

DIGITAL SYSTEMS: Course Objectives and Lecture Plan

Aim: At the end of the course the student will be able to analyze, design, and evaluate digital circuits, of medium complexity, that are based on SSIs, MSIs, and programmable logic devices.

Module 1: Number Systems and Codes (3)

Number systems: Binary, octal, and hexa-decimal number systems, binary arithmetic. Codes: Binary code, excess-3 code, gray code, and error detection and correction codes.

Module 2: Boolean Algebra and Logic Functions (5)

Boolean algebra: Postulates and theorems. Logic functions, minimization of Boolean functions using algebraic, Karnaugh map and Quine – McClausky methods. Realization using logic gates

Module 3: Logic Families (4)

Logic families: Characteristics of logic families. TTL, CMOS, and ECL families.

Module 4: Combinational Functions (8)

Realizing logical expressions using different logic gates and comparing their performance. Hardware aspects logic gates and combinational ICs: delays and hazards. Design of combinational circuits using combinational ICs: Combinational functions: code conversion, decoding, comparison, multiplexing, demultiplexing, addition, and subtraction.

Module 5: Analysis of Sequential Circuits (5)

Structure of sequential circuits: Moore and Melay machines. Flip-flops, excitation tables, conversions, practical clocking aspects concerning flip-flops, timing and triggering considerations. Analysis of sequential circuits: State tables, state diagrams and timing diagrams.

Module 6: Designing with Sequential MSIs (6)

Realization of sequential functions using sequential MSIs: counting, shifting, sequence generation, and sequence detection.

Module 7: PLDs (3)

Programmable Logic Devices: Architecture and characteristics of PLDs,

Module 8: Design of Digital Systems (6)

State diagrams and their features. Design flow: functional partitioning, timing relationships, state assignment, output racing. Examples of design of digital systems using PLDs

Lecture Plan

Modules	Learning Units	Hours per topic	Total Hours
1. Number Systems and Codes	1. Binary, octal and hexadecimal number systems, and conversion of number with one radix to another	1.5	3
	2. Different binary codes	1.5	
2. Logic Functions	3. Boolean algebra and Boolean operators	1.5	5
	4. Logic Functions	1	
	5. Minimization of logic functions using Karnaugh -map	1.5	
	6. Quine-McClusky method of minimization of logic functions	1	
3. Logic Families	7. Introduction to Logic families	0.5	4
	8. TTL family	1	
	9. CMOS family	1.5	
	10. Electrical characteristics of logic families	1	
4. Combinational Circuits	11. Introduction to combinational circuits, logic convention, and realization of simple combinational functions using gates	2	8
	12. Implications of delay and hazard	1	
	13. Realization of adders and subtractors	2	
	14. Design of code converters, comparators, and decoders	2	
	15. Design of multiplexers, demultiplexers,	1	
5. Analysis of Sequential Circuits	16. Introduction to sequential circuits: Moore and Mealy machines	1	5
	17. Introduction to flip-flops like SR, JK, D & T with truth tables, logic diagrams, and timing relationships	1	
	18. Conversion of Flip-Flops, Excitation table	1	
	19. State tables, and realization of state tables	2	
6. Design with Sequential MSIs	20. Design of shift registers and counters	2	6
	21. Design of counters	2	
	22. Design of sequence generators and detectors	2	
7. PLDs	23. Introduction to Programmable Devices	1	3
	24. Architecture of PLDs	2	
8. Design of Digital Systems	25. State diagrams and their features	2	6
	26. Design flow	1	
	27. Design of digital systems using PLDs	3	

Learning Objectives of the Course

1. Recall

- 1.1 List different criteria that could be used for optimization of a digital circuit.
- 1.2 List and describe different problems of digital circuits introduced by the hardware limitations.

2. Comprehension

- 2.1 Describe the significance of different criteria for design of digital circuits.
- 2.2 Describe the significance of different hardware related problems encountered in digital circuits.
- 2.3 Draw the timing diagrams for identified signals in a digital circuit.

3. Application

- 3.1 Determine the output and performance of given combinational and sequential circuits.
- 3.2 Determine the performance of a given digital circuit with regard to an identified optimization criterion.

4. Analysis

- 4.1 Compare the performances of combinational and sequential circuits implemented with SSIs/MSIs and PLDs.
- 4.2 Determine the function and performance of a given digital circuit.
- 4.3 Identify the faults in a given circuit and determine the consequences of the same on the circuit performance.
- 4.4 Draw conclusions on the behavior of a given digital circuit with regard to hazards, asynchronous inputs, and output races.
- 4.5 Determine the appropriateness of the choice of the ICs used in a given digital circuit.
- 4.6 Determine the transition sequence of a given state in a state diagram for a given input sequence.

5. Synthesis

- 5.1 Generate multiple digital solutions to a verbally described problem.
- 5.2 Modify a given digital circuit to change its performance as per specifications.

6. Evaluation

- 6.1 Evaluate the performance of a given digital circuit.
- 6.2 Assess the performance of a given digital circuit with Moore and Melay configurations.
- 6.3 Compare the performance of given digital circuits with respect to their speed, power consumption, number of ICs, and cost.

Digital Systems: Motivation

A digital circuit is one that is built with devices with two well-defined states. Such circuits can process information represented in binary form. Systems based on digital circuits touch all aspects of our present day lives. The present day home products including electronic games and appliances, communication and office automation products, computers with a wide range of capabilities, and industrial instrumentation and control systems, electro-medical equipment, and defence and aerospace systems are heavily dependent on digital circuits. Many fields that emerged later to digital electronics have peaked and levelled off, but the application of digital concepts appears to be still growing exponentially. This unprecedented growth is powered by the semiconductor technology, which enables the introduction of more and more complex integrated circuits. The complexity of an integrated circuit is measured in terms of the number of transistors that can be integrated into a single unit. The number of transistors in a single integrated circuit has been doubling every eighteen months (Moore's Law) for several decades and reached the figure of almost one billion transistors per chip. This allowed the circuit designers to provide more and more complex functions in a single unit.

The introduction of programmable integrated circuits in the form of microprocessors in the 70s completely transformed every facet of electronics. While fixed function integrated circuits and microprocessors coexisted for considerable time, the need to make the equipment smaller and more portable led to replacement of fixed function devices with programmable devices. With the all pervasive presence of the microprocessor and the increasing usage of other programmable circuits like PLDs (Programmable Logic devices), FPGAs (Field Programmable Gate Arrays) and ASICs (Application Specific Integrated Circuits), the very nature of digital systems is continuously changing.

The central role of digital circuits in all our professional and personal lives makes it imperative that every electrical and electronics engineer acquire good knowledge of relevant basic concepts and ability to work with digital circuits.

At present many of the undergraduate programmes offer two to four courses in the area of digital systems, with at least two of them being core courses. The course under consideration constitutes the first course in the area of digital systems. The rate of obsolescence of knowledge, design methods, and design tools is uncomfortably high. Even the first level course in digital electronics is not exempt from this obsolescence.

Any course in electronics should enable the students to design circuits to meet some stated requirements as encountered in real life situations. However, the design approaches should be based on a sound understanding of the underlying principles. The basic feature of all design problems is that all of them admit multiple solutions. The selection of the final solution depends on a variety of criteria that could include the size and cost of the substrate on which the components are assembled, the cost of components, manufacturability,

reliability, speed etc.

The course contents are designed to enable the students to design digital circuits of medium level of complexity taking the functional and hardware aspects in an integrated manner within the context of commercial and manufacturing constraints. However, no compromises are made with regard to theoretical aspects of the subject.

Learning Objectives

Module 1: Number Systems and Codes (3)

Number systems: Binary, octal, and hexa-decimal number systems, binary arithmetic. Codes: Binary code, excess-3 code, gray code, error detection and correction codes.

Recall

1. Describe the format of numbers of different radices?
2. What is parity of a given number?

Comprehension

1. Explain how a number with one radix is converted into a number with another radix.
2. Summarize the advantages of using different number systems.
3. Interpret the arithmetic operations of binary numbers.
4. Explain the usefulness of different coding schemes.
5. Explain how errors are detected and/or corrected using different codes.

Application

1. Convert a given number from one system to an equivalent number in another system.
2. Illustrate the construction of a weighted code.

Analysis: Nil

Synthesis: Nil

Evaluation: Nil



Digital Electronics

Module 1: Number Systems and Codes - Number Systems

N.J. Rao

Indian Institute of Science



Numbers

We use numbers

- to communicate
- to perform tasks
- to quantify
- to measure
- Numbers have become symbols of the present era
- Many consider what is not expressible in terms of numbers is not worth knowing



Number Systems in use

Symbolic number system

- uses Roman numerals (I = 1, V = 5, X = 10, L = 50, C = 100, D = 500 and M = 1000)
- still used in some watches

Weighted position system

- Decimal system is the most commonly used
- Decimal numbers are based on Indian numerals
- Radix used is 10



Other weighted position systems

- Advent of electronic devices with two states created a possibility of working with binary numbers
- Binary numbers are most extensively used
- Binary system uses radix 2
- Octal system uses radix 8
- Hexa-decimal system uses radix 16



Weighted Position Number System

- Value associated with a digit is dependent on its position
- The value of a number is weighted sum of its digits

$$2357 = 2 \times 10^3 + 3 \times 10^2 + 5 \times 10^1 + 7 \times 10^0$$

- Decimal point allows negative and positive powers of 10

$$526.47 = 5 \times 10^2 + 2 \times 10^1 + 6 \times 10^0 + 4 \times 10^{-1} + 7 \times 10^{-2}$$

- 10 is called the *base* or *radix* of the number system



General positional number system

- Any integer ≥ 2 can serve as the radix
- Digit position 'i' has weight r^i .
- The general form of a number is

$$d_{p-1} d_{p-2}, \dots, d_1, d_0 . d_{-1} d_{-2} \dots d_{-n}$$

p digits to the left of the point (*radix point*) and n digits to the right of the point



General positional number system (2)

- The value of the number is

$$D = \sum_{i=-n}^{p-1} d_i r^i$$

- Leading and trailing zeros have no values
- The values d_i s can take are limited by the radix value
- A number like $(357)_5$ is incorrect



Binary Number System

- Uses 2 as its radix
- Has only two numerals, 0 and 1

Example:

$$(N)_2 = (11100110)_2$$

- It is an eight digit binary number
- The binary digits are also known as *bits*
- $(N)_2$ is an 8-bit number



Binary numbers to Decimal Number

$$(N)_2 = (11100110)_2$$

Its decimal value is given by,

$$\begin{aligned}(N)_2 &= 1 \times 2^7 + 1 \times 2^6 + 1 \times 2^5 + 0 \times 2^4 + 0 \times 2^3 \\ &\quad + 1 \times 2^2 + 1 \times 2^1 + 0 \times 2^0 \\ &= 128 + 64 + 32 + 0 + 0 + 4 + 2 + 0 = (230)_{10}\end{aligned}$$



Binary fractional number to Decimal number

- A binary fractional number $(N)_2 = 101.101$
- Its decimal value is given by

$$\begin{aligned}(N)_2 &= 1 \times 2^2 + 0 \times 2^1 + 1 \times 2^0 \\ &\quad + 1 \times 2^{-1} + 0 \times 2^{-2} + 1 \times 2^{-3} \\ &= 4 + 0 + 1 + \frac{1}{2} + 0 + \frac{1}{8} \\ &= 5 + 0.5 + 0.125 = (5.625)_{10}\end{aligned}$$



Some features of Binary Numbers

- Require very long strings of 1s and 0s
- Some simplification can be done through grouping
- 3-bit groupings: Octal (radix 8) groups three binary digits
Digits will have one of the eight values 0, 1, 2, 3, 4, 5, 6 and 7
- 4-digit groupings: Hexa-decimal (radix 16)
Digits will have one of the sixteen values 0 through 15.
Decimal values from 10 to 15 are designated as A (=10), B (=11), C (=12), D (=13), E (=14) and F (=15)



Conversion of binary numbers

Conversion to an octal number

- Group the binary digits into groups of three
- $(11011001)_2 = (011) (011) (001) = (331)_8$

- Conversion to an hexa-decimal number

- Group the binary digits into groups of four
- $(11011001)_2 = (1101) (1001) = (D9)_{16}$



Changing the radix of numbers

- Conversion requires, sometimes, arithmetic operations
- The decimal equivalent value of a number in any radix

$$D = \sum_{i=-n}^{p-1} d_i r^i$$

Examples

$$(331)_8 = 3 \times 8^2 + 3 \times 8^1 + 1 \times 8^0 = 192 + 24 + 1 = (217)_{10}$$

$$(D9)_{16} = 13 \times 16^1 + 9 \times 16^0 = 208 + 9 = (217)_{10}$$

$$(33.56)_8 = 3 \times 8^1 + 3 \times 8^0 + 5 \times 8^{-1} + 6 \times 8^{-2} = (27.69875)_{10}$$

$$(E5.A)_{16} = 14 \times 16^1 + 5 \times 16^0 + 10 \times 16^{-1} = (304.625)_{10}$$



Conversion of decimal numbers to numbers with radix r

Represent a number with radix r as

$$D = ((\dots ((d_{n-1}).r + d_{n-2}) r + \dots).r + d_1).r + d_0$$

To convert a number with radix r to a decimal number

- Divide the right hand side by r
- Remainder: d_0
- Quotient: $Q = ((\dots ((d_{n-1}).r + d_{n-2}) r + \dots).r + d_1$
- Division of Q by r gives d_1 as the remainder
- so on



Example of Conversion

	Quotient	Remainder
$156 \div 2$	78	0
$78 \div 2$	39	0
$39 \div 2$	19	1
$19 \div 2$	9	1
$9 \div 2$	4	1
$4 \div 2$	2	0
$2 \div 2$	1	0
$1 \div 2$	0	1

$$(156)_{10} = (10011100)_2$$



Example of Conversion

	Quotient	Remainder
$678 \div 8$	84	6
$84 \div 8$	10	4
$10 \div 8$	1	2
$1 \div 8$	0	1

$$(678)_{10} = (1246)_8$$

	Quotient	Remainder
$678 \div 16$	42	6
$42 \div 16$	2	A
$2 \div 16$	0	2

$$(678)_{10} = (2A6)_{16}$$



Negative Numbers

Sign-Magnitude representation

- “+” sign before a number indicates it as a positive number
- “-” sign before a number indicates it as a negative number
- Not very convenient on computers
- Replace “+” sign by “0” and “-” by “1”

$$(+1100101)_2 \rightarrow (01100101)_2$$

$$(+101.001)_2 \rightarrow (0101.001)_2$$

$$(-10010)_2 \rightarrow (110010)_2$$

$$(-110.101)_2 \rightarrow (1110.101)_2$$



Representing signed numbers

- Diminished Radix Complement (DRC) or $(r-1)$ - complement
- Radix Complement (RXC) or r -complement

Binary numbers

- DRC is known as “one’s-complement”
- RXC is known as “two’s-complement”

Decimal numbers

- DRC is known as 9’s-complement
- RXC is known as 10’s-complement



One's Complement Representation

The most significant bit (MSD) represents the sign

If MSD is a “0”

- The number is positive
- Remaining $(n-1)$ bits directly indicate the magnitude

If the MSD is “1”

- The number is negative
- Complement of all the remaining $(n-1)$ bits gives the magnitude



Example: One's complement

$1111001 \rightarrow (1)(111001)$

- First (sign) bit is 1: The number is negative
- Ones' Complement of $111001 \rightarrow 000110$
 $\rightarrow (6)_{10}$



Range of n-bit numbers

One's complement numbers:

0111111 + 63

0000110 --> + 6

0000000 --> + 0

1111111 --> + 0

1111001 --> - 6

1000000 --> - 63

- “0” is represented by 000.....0 and 111.....1
- 7- bit number covers the range from +63 to -63.
- n-bit number has a range from $+(2^{n-1} - 1)$ to $-(2^{n-1} - 1)$



One's complement of a number

Complement all the digits

- If A is an integer in one's complement form, then one's complement of A = -A
- This applies to fractions as well.

$$A = 0.101 (+0.625)_{10}$$

$$\text{One's complement of } A = 1.010, (-0.625)_{10}$$

Mixed number

$$B = 010011.0101 (+19.3125)_{10}$$

$$\text{One's complement of } B = 101100.1010 (-19.3125)_{10}$$



Two's Complement Representation

If MSD is a "0"

- The number is positive
- Remaining $(n-1)$ bits directly indicate the magnitude

If the MSD is "1"

- The number is negative
- Magnitude is obtained by complementing all the remaining $(n-1)$ bits and adding a 1



Example: Two's complement

$1111010 \rightarrow (1)(111010)$

- First (sign) bit is 1: The number is negative
- Complement 111010 and add 1 $\rightarrow 000101 + 1$
 $= 000110 = (6)_{10}$



Range of n-bit numbers

Two's complement numbers:

0111111 + 63

0000110 + 6

0000000 + 0

1111010 - 6

1000001 - 63

1000000 - 64

- “0” is represented by 000.....0
- 7- bit number covers the range from +63 to -64.
- n-bit number has a range from $+(2^{n-1} - 1)$ to $-(2^{n-1})$



Two's complement of a number

Complement all the digits and add '1' to the LSB

If A is an integer in one's complement form, then

- Two's complement of A = -A

This applies to fractions as well

- A = 0.101 (+0.625)₁₀
- Two's complement of A = 1.011 → (-0.625)₁₀

Mixed number

- B = 010011.0101 (+19.3125)₁₀
- Two's complement of B = 101100.1011 → (- 9.3125)₁₀

Number Systems

We all use numbers to communicate and perform several tasks in our daily lives. Our present day world is characterized by measurements and numbers associated with everything. In fact, many consider if we cannot express something in terms of numbers is not worth knowing. While this is an extreme view that is difficult to justify, there is no doubt that quantification and measurement, and consequently usage of numbers, are desirable whenever possible. Manipulation of numbers is one of the early skills that the present day child is trained to acquire. The present day technology and the way of life require the usage of several number systems. Usage of decimal numbers starts very early in one's life. Therefore, when one is confronted with number systems other than decimal, some time during the high-school years, it calls for a fundamental change in one's framework of thinking.

There have been two types of numbering systems in use through out the world.

One type is symbolic in nature. Most important example of this symbolic numbering system is the one based on Roman numerals

I = 1, V = 5, X = 10, L = 50, C = 100, D = 500 and M = 1000

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While this system was in use for several centuries in Europe it is completely superseded by the weighted-position system based on Indian numerals. The Roman number system is still used in some places like watches and release dates of movies.

The weighted-positional system based on the use of radix 10 is the most commonly used numbering system in most of the transactions and activities of today's world. However, the advent of computers and the convenience of using devices that have two well defined states brought the binary system, using the radix 2, into extensive use. The use of binary number system in the field of computers and electronics also lead to the use of octal (based on radix 8) and hex-decimal system (based on radix 16). The usage of binary numbers at various levels has become so essential that it is also necessary to have a good understanding of all the binary arithmetic operations.

Here we explore the weighted-position number systems and conversion from one system to the other.

Weighted-Position Number System

In a weighted-position numbering system using Indian numerals the value associated with a digit is dependent on its position. The value of a number is weighted sum of its digits.

Consider the decimal number 2357. It can be expressed as

$$2357 = 2 \times 10^3 + 3 \times 10^2 + 5 \times 10^1 + 7 \times 10^0$$

Each weight is a power of 10 corresponding to the digit's position. A decimal point allows negative as well as positive powers of 10 to be used;

$$526.47 = 5 \times 10^2 + 2 \times 10^1 + 6 \times 10^0 + 4 \times 10^{-1} + 7 \times 10^{-2}$$

Here, 10 is called the *base* or *radix* of the number system. In a general positional number system, the *radix* may be any integer $r \geq 2$, and a digit position i has weight r^i . The general form of a number in such a system is

$$d_{p-1} d_{p-2}, \dots, d_1, d_0 . d_{-1} d_{-2} \dots d_{-n}$$

where there are p digits to the left of the point (called *radix point*) and n digits to the right of the point. The value of the number is the sum of each digit multiplied by the corresponding power of the *radix*.

$$D = \sum_{i=-n}^{p-1} d_i r^i$$

Except for possible leading and trailing zeros, the representation of a number in positional system is unique (00256.230 is the same as 256.23). Obviously the values d_i 's can take are limited by the radix value. For example a number like $(356)_5$, where the suffix 5 represents the radix will be incorrect, as there can not be a digit like 5 or 6 in a weighted position number system with radix 5.

If the radix point is not shown in the number, then it is assumed to be located near the last right digit to its immediate right. The symbol used for the radix point is a point (.). However, a comma is used in some countries. For example 7,6 is used, instead of 7.6, to represent a number having seven as its integer component and six as its fractional.

As much of the present day electronic hardware is dependent on devices that work reliably in two well defined states, a numbering system using 2 as its radix has become necessary and popular. With the radix value of 2, the binary number system

will have only two numerals, namely 0 and 1.

Consider the number $(N)_2 = (11100110)_2$.

It is an eight digit binary number. The binary digits are also known as *bits*. Consequently the above number would be referred to as an 8-bit number. Its decimal value is given by

$$\begin{aligned}(N)_2 &= 1 \times 2^7 + 1 \times 2^6 + 1 \times 2^5 + 0 \times 2^4 + 0 \times 2^3 + 1 \times 2^2 + 1 \times 2^1 + 0 \times 2^0 \\ &= 128 + 64 + 32 + 0 + 0 + 4 + 2 + 0 = (230)_{10}\end{aligned}$$

Consider a binary fractional number $(N)_2 = 101.101$.

Its decimal value is given by

$$\begin{aligned}(N)_2 &= 1 \times 2^2 + 0 \times 2^1 + 1 \times 2^0 + 1 \times 2^{-1} + 0 \times 2^{-2} + 1 \times 2^{-3} \\ &= 4 + 0 + 1 + \frac{1}{2} + 0 + \frac{1}{8} \\ &= 5 + 0.5 + 0.125 = (5.625)_{10}\end{aligned}$$

From here on we consider any number without its radix specifically mentioned, as a decimal number.

With the radix value of 2, the binary number system requires very long strings of 1s and 0s to represent a given number. Some of the problems associated with handling large strings of binary digits may be eased by grouping them into three digits or four digits. We can use the following groupings.

- Octal (radix 8 to group three binary digits)
- Hexadecimal (radix 16 to group four binary digits)

In the octal number system the digits will have one of the following eight values 0, 1, 2, 3, 4, 5, 6 and 7.

In the hexadecimal system we have one of the sixteen values 0 through 15. However, the decimal values from 10 to 15 will be represented by alphabet A (=10), B (=11), C (=12), D (=13), E (=14) and F (=15).

Conversion of a binary number to an octal number or a hexadecimal number is very simple, as it requires simple grouping of the binary digits into groups of three or four. Consider the binary number 11011011. It may be converted into octal or hexadecimal numbers as

$$(11011001)_2 = (011) (011) (001) = (331)_8$$

$$= (1101) (1001) = (D9)_{16}$$

Note that adding a leading zero does not alter the value of the number. Similarly for grouping the digits in the fractional part of a binary number, trailing zeros may be added without changing the value of the number.

Number System Conversions

In general, conversion between numbers with different radices cannot be done by simple substitutions. Such conversions would involve arithmetic operations. Let us work out procedures for converting a number in any radix to radix 10, and vice-versa. The decimal equivalent value of a number in any radix is given by the formula

$$D = \sum_{i=-n}^{p-1} d_i r^i$$

where r is the radix of the number and there are p digits to the left of the radix point and n digits to the right. Decimal value of the number is determined by converting each digit of the number to its radix-10 equivalent and expanding the formula using radix-10 arithmetic.

Some examples are:

$$(331)_8 = 3 \times 8^2 + 3 \times 8^1 + 1 \times 8^0 = 192 + 24 + 1 = (217)_{10}$$

$$(D9)_{16} = 13 \times 16^1 + 9 \times 16^0 = 208 + 9 = (217)_{10}$$

$$(33.56)_8 = 3 \times 8^1 + 3 \times 8^0 + 5 \times 8^{-1} + 6 \times 8^{-2} = (27.69875)_{10}$$

$$(E5.A)_{16} = 14 \times 16^1 + 5 \times 16^0 + 10 \times 16^{-1} = (304.625)_{10}$$

The conversion formula can be rewritten as

$$D = ((\dots ((d_{n-1}) \cdot r + d_{n-2}) r + \dots) \cdot r + d_1) \cdot r + d_0$$

This forms the basis for converting a decimal number D to a number with radix r . If we divide the right hand side of the above formula by r , the remainder will be d_0 , and the quotient will be

$$Q = ((\dots ((d_{n-1}) \cdot r + d_{n-2}) r + \dots) \cdot r + d_1)$$

Thus, d_0 can be computed as the remainder of the long division of D by the radix r . As the quotient Q has the same form as D , another long division by r will give d_1 as the remainder. This process can continue to produce all the digits of the number with radix r . Consider the following examples.

	Quotient	Remainder
$156 \div 2$	78	0
$78 \div 2$	39	0

$39 \div 2$	19	1
$19 \div 2$	9	1
$9 \div 2$	4	1
$4 \div 2$	2	0
$2 \div 2$	1	0
$1 \div 2$	0	1

$$(156)_{10} = (10011100)_2$$

	Quotient	Remainder
$678 \div 8$	84	6
$84 \div 8$	10	4
$10 \div 8$	1	2
$1 \div 8$	0	1

$$(678)_{10} = (1246)_8$$

	Quotient	Remainder
$678 \div 16$	42	6
$42 \div 16$	2	A
$2 \div 16$	0	2

$$(678)_{10} = (2A6)_{16}$$

Representation of Negative Numbers

In our traditional arithmetic we use the "+" sign before a number to indicate it as a positive number and a "-" sign to indicate it as a negative number. We usually omit the sign before the number if it is positive. This method of representation of numbers is called "sign-magnitude" representation. But using "+" and "-" signs on a computer is not convenient, and it becomes necessary to have some other convention to represent the signed numbers. We replace "+" sign with "0" and "-" with "1". These two symbols already exist in the binary system. Consider the following examples:

$$(+1100101)_2 \longrightarrow (01100101)_2$$

$$(+101.001)_2 \longrightarrow (0101.001)_2$$

$$(-10010)_2 \longrightarrow (110010)_2$$

$$(-110.101)_2 \longrightarrow (1110.101)_2$$

In the sign-magnitude representation of binary numbers the first digit is always treated separately. Therefore, in working with the signed binary numbers in sign-magnitude form the leading zeros should not be ignored. However, the leading zeros can be ignored after the sign bit is separated. For example,

$$1000101.11 = -101.11$$

While the sign-magnitude representation of signed numbers appears to be natural extension of the traditional arithmetic, the arithmetic operations with signed numbers in this form are not that very convenient, either for implementation on the computer or for hardware implementation. There are two other methods of representing signed numbers.

- Diminished Radix Complement (DRC) or (r-1)-complement
- Radix Complement (RX) or r-complement

When the numbers are in binary form

- Diminished Radix Complement will be known as "one's-complement"
- Radix complement will be known as "two's-complement".

If this representation is extended to the decimal numbers they will be known as 9's-complement and 10's-complement respectively.

One's Complement Representation

Let A be an n-bit signed binary number in one's complement form.

The most significant bit represents the sign. If it is a "0" the number is positive and if it is a "1" the number is negative.

The remaining (n-1) bits represent the magnitude, but not necessarily as a simple weighted number.

Consider the following one's complement numbers and their decimal equivalents:

0111111		+ 63
0000110	-->	+ 6
0000000	-->	+ 0
1111111	-->	+ 0
1111001	-->	- 6
1000000	-->	- 63

There are two representations of "0", namely 000.....0 and 111.....1.

From these illustrations we observe

- If the most significant bit (MSD) is zero the remaining (n-1) bits directly indicate the magnitude.
- If the MSD is 1, the magnitude of the number is obtained by taking the complement of all the remaining (n-1) bits.

For example consider one's complement representation of -6 as given above.

- Leaving the first bit '1' for the sign, the remaining bits 111001 do not directly represent the magnitude of the number -6.
- Take the complement of 111001, which becomes 000110 to determine the magnitude.

In the example shown above a 7-bit number can cover the range from +63 to -63. In general an n-bit number has a range from $+(2^{n-1} - 1)$ to $-(2^{n-1} - 1)$ with two representations for zero.

The representation also suggests that if A is an integer in one's complement form, then

$$\text{one's complement of } A = -A$$

One's complement of a number is obtained by merely complementing all the digits.

This relationship can be extended to fractions as well.

For example if $A = 0.101 (+0.625)_{10}$, then the one's complement of A is 1.010, which is one's complement representation of $(-0.625)_{10}$. Similarly consider the case of a mixed number.

$$A = 010011.0101 \quad (+19.3125)_{10}$$

$$\text{One's complement of } A = 101100.1010 \quad (-19.3125)_{10}$$

This relationship can be used to determine one's complement representation of negative decimal numbers.

Example 1: What is one's complement binary representation of decimal number -75?

Decimal number 75 requires 7 bits to represent its magnitude in the binary form. One additional bit is needed to represent the sign. Therefore,

one's complement representation of 75 = 01001011

one's complement representation of -75 = 10110100

Two's Complement Representation

Let A be an n-bit signed binary number in two's complement form.

- The most significant bit represents the sign. If it is a "0", the number is positive, and if it is "1" the number is negative.
- The remaining (n-1) bits represent the magnitude, but not as a simple weighted number.

Consider the following two's complement numbers and their decimal equivalents:

0111111 → + 63

0000110 → + 6

0000000 → + 0

1111010 → - 6

1000001 → - 63

1000000 → - 64

There is only one representation of "0", namely 000...0.

From these illustrations we observe

If most significant bit (MSD) is zero the remaining (n-1) bits directly indicate the magnitude.

If the MSD is 1, the magnitude of the number is obtained by taking the complement of all the remaining (n-1) bits and adding a 1.

Consider the two's complement representation of -6.

- We assume we are representing it as a 7-bit number.
- Leave the sign bit.
- The remaining bits are 111010. These have to be complemented (that is 000101) and a 1 has to be added (that is 000101 + 1 = 000110 = 6).

In the example shown above a 7-bit number can cover the range from +63 to -64. In general an n-bit number has a range from $+(2^{n-1} - 1)$ to $-(2^{n-1})$ with one representation for zero.

The representation also suggests that if A is an integer in two's complement form, then

$$\text{Two's complement of } A = -A$$

Two's complement of a number is obtained by complementing all the digits and adding '1' to the LSB.

This relationship can be extended to fractions as well.

If $A = 0.101 (+0.625)_{10}$, then the two's complement of A is 1.011, which is two's complement representation of $(-0.625)_{10}$.

Similarly consider the case of a mixed number.

$$A = 010011.0101 \quad (+19.3125)_{10}$$

$$\text{Two's complement of } A = 101100.1011 \quad (-19.3125)_{10}$$

This relationship can be used to determine two's complement representation of negative decimal numbers.

Example 2: What is two's complement binary representation of decimal number -75?

Decimal number 75 requires 7 bits to represent its magnitude in the binary form. One additional bit is needed to represent the sign. Therefore,

$$\text{Two's complement representation of } 75 = 01001011$$

$$\text{Two's complement representation of } -75 = 10110101$$

M1L1: Number Systems

Multiple Choice Questions

1. Which number system is understood easily by the computer?
(a) Binary (b) Decimal (c) Octal (d) Hexadecimal
2. How many symbols are used in the decimal number system?
(a) 2 (b) 8 (c) 10 (d) 16
3. How are number systems generally classified?
 - a. Conditional or non conditional
 - b. Positional or non positional
 - c. Real or imaginary
 - d. Literal or numerical
4. What does $(10)_{16}$ represent in decimal number system?
(a) 10 (b) 0A (c) 16 (d) 15
5. How many bits have to be grouped together to convert the binary number to its corresponding octal number?
(a) 2 (b) 3 (c) 4 (d) 5
6. Which bit represents the sign bit in a signed number system?
 - a. Left most bit
 - b. Right most bit
 - c. Left centre
 - d. Right centre
7. The ones complement of 1010 is
(a) 1100 (b) 0101 (c) 0111 (d) 1011
8. How many bits are required to cover the numbers from +63 to -63 in one's complement representation?
(a) 6 (b) 7 (c) 8 (d) 9

M1L1: Number Systems

Problems

1. Perform the following number system conversions:

- (a) $10110111_2 = ?_{10}$ (b) $5674_{10} = ?_2$
(c) $10011100_2 = ?_8$ (d) $2453_8 = ?_2$
(e) $111100010_2 = ?_{16}$ (f) $68934_{10} = ?_2$
(g) $10101.001_2 = ?_{10}$ (h) $6FAB7_{16} = ?_{10}$
(i) $11101.101_2 = ?_8$ (j) $56238_{16} = ?_2$

2. Convert the following hexadecimal numbers into binary and octal numbers

- (a) 78AD (b) DA643 (c) EDC8
(d) 3245 (e) 68912 (f) AF4D

3. Convert the following octal numbers into binary and hexadecimal numbers

- (a) 7643 (b) 2643 (c) 1034
(d) 3245 (e) 6712 (f) 7512

4. Convert the following numbers into binary:

- (a) 1236_{10} (b) 2349_{10} (c) 345.275_{10}
(d) 4567_8 (e) 45.65_8 (f) 145.23_8
(g) $ADF5_{16}$ (h) $AD.F3_{16}$ (i) $12.DA_{16}$

5. What is the range of unsigned decimal values that can be represented by 8 bits?

6. What is the range of signed decimal values that can be represented by 8 bits?

7. How many bits are required to represent decimal values ranging from 75 to -75?

8. Represent each of the following values as a 6-bit signed binary number in one's complement and two's complement forms.

- (a) 28 (b) -21 (c) -5 (d) -13

9. Determine the decimal equivalent of two's complement numbers given below:

- (a) 1010101 (b) 0111011 (c) 11100010



Digital Electronics

Module 1: Number Systems and Codes - Codes

N.J. Rao

Indian Institute of Science



Need for Coding

Information sent over a noisy channel is likely to be distorted

Information is coded to facilitate

- Efficient transmission
- Error detection
- Error correction



Coding

- Coding is the process of altering the characteristics of information to make it more suitable for intended application
- Coding schemes depend on
 - Security requirements
 - Complexity of the medium of transmission
 - Levels of error tolerated
 - Need for standardization



Decoding

- Decoding is the process of reconstructing source information from the received encoded information
- Decoding can be more complex than coding if there is no prior knowledge of coding schemes



Bit combinations

- Bit - a binary digit 0 or 1
- Nibble - a group of four bits
- Byte - a group of eight bits
- Word - a group of sixteen bits;
(Sometimes used to designate 32 bit or 64 bit groups of bits)



Binary coding

Assign each item of information a unique combination of 1s and 0s

- n is the number of bits in the code word
- x be the number of unique words

If $n = 1$, then $x = 2$ (0, 1)

$n = 2$, then $x = 4$ (00, 01, 10, 11)

$n = 3$, then $x = 8$ (000, 001, 010 ... 111)

$n = j$, then $x = 2^j$



Number of bits in a code word

x : number of elements to be coded binary coded format

$$x \leq 2^j$$

or $j \geq \log_2 x$

$$\geq 3.32 \log_{10} x$$

j is the number of bits in a code word.



Example: Coding of alphanumeric information

- Alphanumeric information: 26 alphabetic characters + 10 decimals digits = 36 elements
$$j \geq 3.32 \log_{10} 36$$
$$j \geq 5.16 \text{ bits}$$
- Number of bits required for coding = 6
- Only 36 code words are used out of the 64 possible code words



Some codes for consideration

- Binary coded decimal codes
- Unit distance codes
- Error detection codes
- Alphanumeric codes



Binary coded decimal codes

Simple Scheme

- Convert decimal number inputs into binary form
- Manipulate these binary numbers
- Convert resultant binary numbers back into decimal numbers

However, it

- requires more hardware
- slows down the system



Binary coded decimal codes

- Encode each decimal symbol in a unique string of 0s and 1s
- Ten symbols require at least four bits to encode
- There are sixteen four-bit groups to select ten groups.
- There can be 30×10^{10} (${}^{16}C_{10} \cdot 10!$) possible codes
- Most of these codes will not have any special properties



How do we select a coding scheme?

It should have some desirable properties

- ease of coding
- ease in arithmetic operations
- minimum use of hardware
- error detection property
- ability to prevent wrong output during transitions



Weighted Binary Coding

Decimal number $(A)_{10}$

Encoded in the binary form as 'a3 a2 a1 a0'

w_3, w_2, w_1 and w_0 are the weights selected for a given code

$$(A)_{10} = w_3a_3 + w_2a_2 + w_1a_1 + w_0a_0$$

The more popularly used codes have these weights as

w_3	w_2	w_1	w_0
8	4	2	1
2	4	2	1
8	4	-2	-1



Binary codes for decimal numbers

Decimal digit	Weight	Weights	Weights
	8 4 2 1	2 4 2 1	8 4 -2 -1
0	0 0 0 0	0 0 0 0	0 0 0 0
1	0 0 0 1	0 0 0 1	0 1 1 1
2	0 0 1 0	0 0 1 0	0 1 1 0
3	0 0 1 1	0 0 1 1	0 1 0 1
4	0 1 0 0	0 1 0 0	0 1 0 0
5	0 1 0 1	1 0 1 1	1 0 1 1
6	0 1 1 0	1 1 0 0	1 0 1 0
7	0 1 1 1	1 1 0 1	1 0 0 1
8	1 0 0 0	1 1 1 0	1 0 0 0
9	1 0 0 1	1 1 1 1	1 1 1 1



Binary coded decimal numbers

- The unused six combinations are illegal
- They may be utilised for error detection purposes.
- Choice of weights in a BCD codes
 1. Self-complementing codes
 2. Reflective codes



Self complementing codes

Logical complement of a coded number is also its arithmetic complement

Example: 2421 code

Nine's complement of $(4)_{10} = (5)_{10}$

2421 code of $(4)_{10} = 0100$

Complement of $0100 = 1011 = 2421$ code for $(5)_{10}$
 $= (9 - 4)_{10}$.

A necessary condition: Sum of its weights should be 9.



Other self complementing codes

Excess-3 code (not weighted)

Add 0011 (3) to all the 8421 coded numbers

Another example is 631-1 weighted code



Examples of self-complementary codes

Decimal Digit	Excess-3 Code	631-1 Code	2421 Code
0	0011	0011	0000
1	0100	0010	0001
2	0101	0101	0010
3	0110	0111	0011
4	0111	0110	0100
5	1000	1001	1011
6	1001	1000	1100
7	1010	1010	1101
8	1011	1101	1110
9	1100	1100	1111



Reflective code

- Imaged about the centre entries with one bit changed

Example

- 9's complement of a reflected BCD code word is formed by changing only one of its bits



Examples of reflective BCD codes

Decimal Digit	Code-A	Code-B
0	0000	0100
1	0001	1010
2	0010	1000
3	0011	1110
4	0100	0000
5	1100	0001
6	1011	1111
7	1010	1001
8	1001	1011
9	1000	0101



Unit Distance Codes

Adjacent codes differ only in one bit

- “Gray code” is the most popular example
- Some of the Gray codes have also the reflective properties



3-bit and 4-bit Gray codes

Decimal Digit	3-bit Gray Code	4-bit Gray Code
0	000	0000
1	001	0001
2	011	0011
3	010	0010
4	110	0110
5	111	0111
6	101	0101
7	100	0100
8	-	1100
9	-	1101

Decimal Digit	3-bit Gray Code	4-bit Gray Code
10	-	1111
11	-	1110
12	-	1010
13	-	1011
14	-	1001
15	-	1000

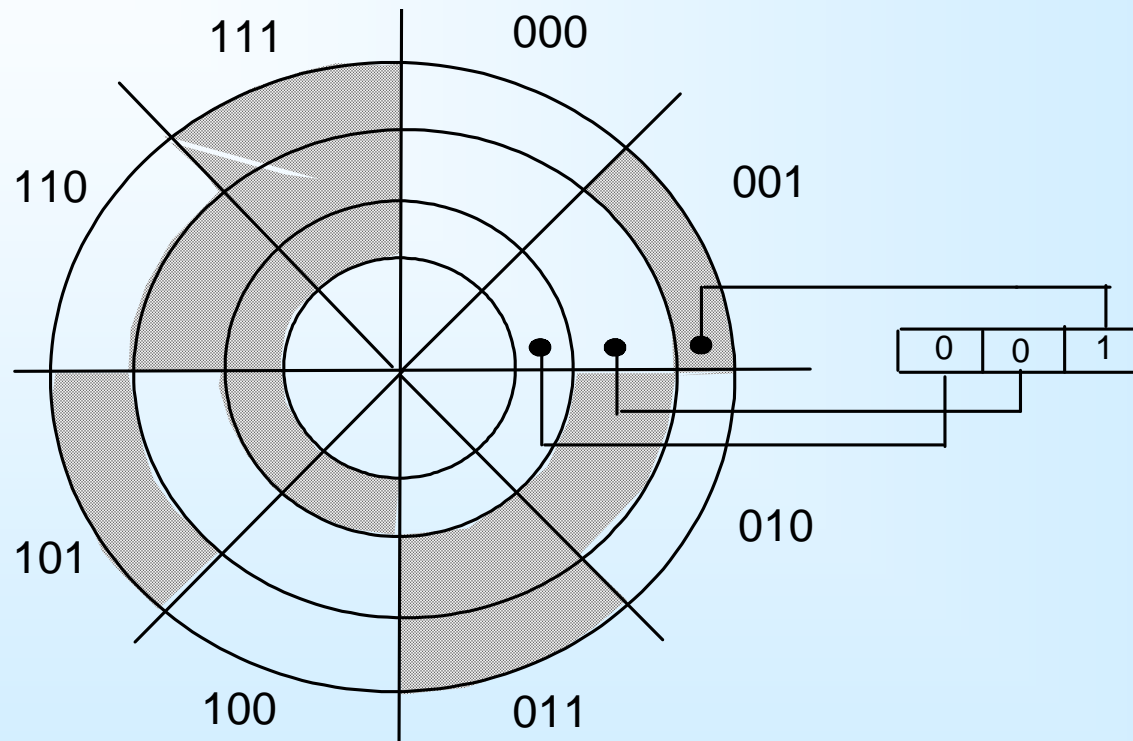


More examples of Unit Distance Codes

Decimal Digit	UDC-1	UDC-2	UDC-3
0	0000	0000	0000
1	0100	0001	1000
2	1100	0011	1001
3	1000	0010	0001
4	1001	0110	0011
5	1011	1110	0111
6	1111	1111	1111
7	0111	1101	1011
8	0011	1100	1010
9	0001	0100	0010



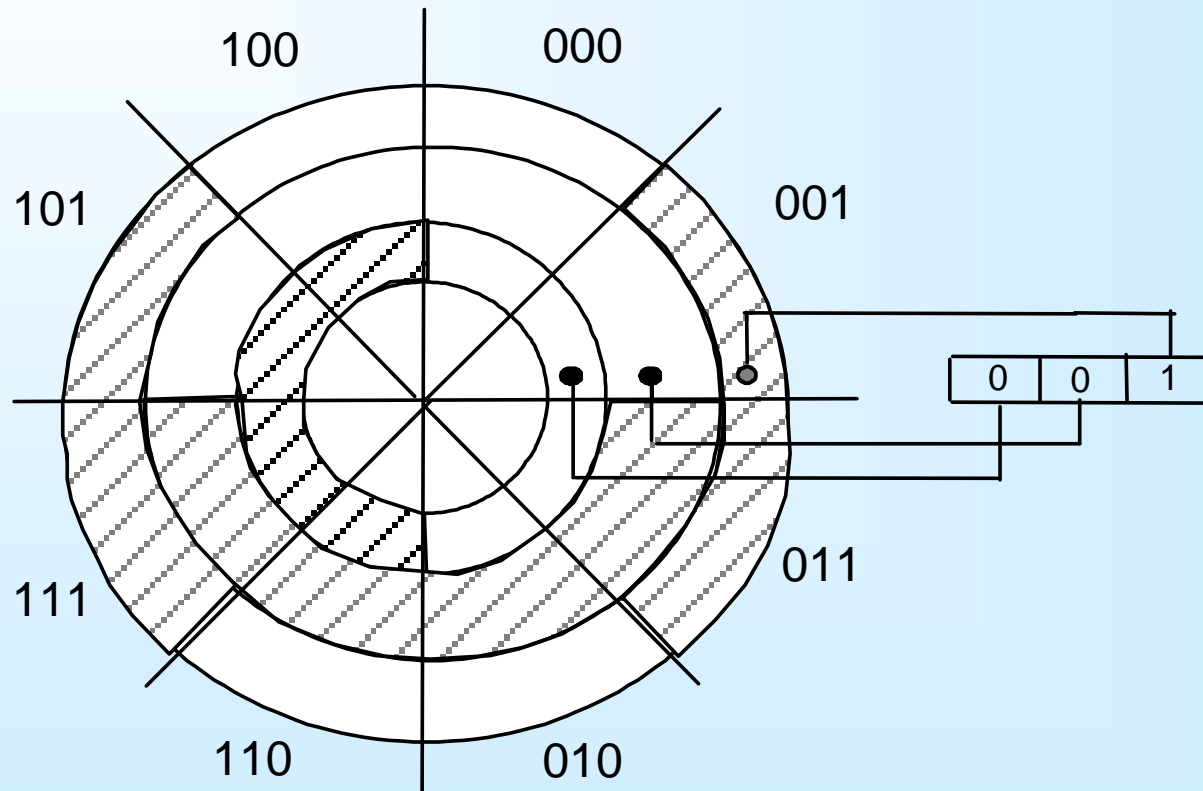
3-bit simple binary coded shaft encoder



Can lead to errors (001 → 011 → 010)



Shaft encoder disk using 3-bit Gray code





Constructing Gray Code

- The bits of Gray code words are numbered from right to left, from 0 to $n-1$.
- Bit i is 0 if bits i and $i+1$ of the corresponding binary code word are the same, else bit i is 1
- When $i+1 = n$, bit n of the binary code word is considered to be 0

Example: Consider the decimal number 68.

$$(68)_{10} = (1000100)_2$$

Binary code : 1 0 0 0 1 0 0

Gray code : 1 1 0 0 1 1 0



Convert a Gray coded number to a straight binary number

- Scan the Gray code word from left to right
- All the bits of the binary code are the same as those of the Gray code until the first 1 is encountered, including the first 1
- 1's are written until the next 1 is encountered, in which case a 0 is written.
- 0's are written until the next 1 is encountered, in which case a 1 is written.

Examples

Gray code : 1 1 0 1 1 0

Binary code: 1 0 0 1 0 0

Gray code : 1 0 0 0 1 0 1 1

Binary code: 1 1 1 1 0 0 1 0



Alphanumeric Code (ASCII)

b4	b3	b2	b1	b7 b6 b5							
				000	001	010	011	100	101	110	111
0	0	0	0	NUL	DLE	SP	0	@	P	'	p
0	0	0	1	SOH	DC1	!	1	A	Q	a	q
0	0	1	0	STX	DC2	“	2	B	R	b	r
0	0	1	1	ETX	DC3	#	3	C	S	c	s
0	1	0	0	EOT	DC4	\$	4	D	T	d	t
0	1	0	1	ENQ	NAK	%	5	E	U	e	u
0	1	1	0	ACK	SYN	&	6	F	V	f	v
0	1	1	1	BEL	ETB	,	7	G	W	g	w
1	0	0	0	BS	CAN	(	8	H	X	h	x
1	0	0	1	HT	EM	)	9	I	Y	i	y
1	0	1	0	LF	SUB	*	:	J	Z	j	z
1	0	1	1	VT	ESC	+	;	K	[	k	{
1	1	0	0	FF	FS	,	<	L	\	l	|
1	1	0	1	CR	GS	-	=	M	]	m	}
1	1	1	0	SO	RS	.	>	N	^	n	~
1	1	1	1	SI	US	/	?	O	-	o	DEL



Other alphanumeric codes

- EBCDIC (Extended Binary Coded Decimal Interchange Code)
 - 12-bit Hollerith code
- are in use for some applications



Error Detection and Correction

- Error rate cannot be reduced to zero
- We need a mechanism of correcting the errors that occur
- It is not always possible or may prove to be expensive
- It is necessary to know if an error occurred
- If an occurrence of error is known, data may be retransmitted
- Data integrity is improved by encoding
- Encoding may be done for error correction or merely for error detection.



Encoding for data integrity

- Add a special code bit to a data word
- It is called the 'Parity Bit'
- Parity bit can be added on an 'odd' or 'even' basis



Parity

Odd Parity

- The number of 1's, including the parity bit, should be odd

Example: S in ASCII code is

$$(S) = (1010011)_{\text{ASCII}}$$

S, when coded for odd parity, would be shown as

$$(S) = (11010011)_{\text{ASCII with odd parity}}$$

Even Parity

- The number of 1's, including the parity bit, should be even

When S is encoded for even parity

$$(S) = (01010011)_{\text{ASCII with even parity}}$$



Error detection with parity bits

- If odd number of 1's occur in the received data word coded for even parity then an error occurred
- Single or odd number bit errors can be detected
- Two or even number bit errors will not be detected



Error Correction

- Parity bit allows us only to detect the presence of one bit error in a group of bits
- It does not enable us to exactly locate the bit that changed
- Parity bit scheme can be extended to locate the faulty bit in a block of information



Parity-check block codes

Detect and correct more than one-bit errors

These are known as (n, k) codes

- They have $r (= n - k)$ parity check bits, formed by linear operations on the k data bits
- R bits are appended to each block of k bits to generate an n -bit code word

A $(15, 11)$ code has $r = 4$ parity-check bits for every 11 data bits

- As r increases it should be possible to correct more and more errors
- With $r = 1$ error correction is not possible
- Long codes with a relatively large number of parity-check bits should provide better performance.



Single-error correcting code

(7, 3) code

Data bits	Code words
0 0 0	0 0 0 0 0 0 0
0 0 1	0 0 1 1 1 1 1
0 1 0	0 1 0 0 1 1 0
0 1 1	0 1 1 1 0 0 1
1 0 0	1 0 0 1 1 0 0
1 0 1	1 0 1 0 0 1 1
1 1 0	1 1 0 1 0 1 0
1 1 1	1 1 1 0 1 0 1

- Code words differ in at least three positions.
- Any one error is correctable since the resultant code word will still be closer to the correct one



Hamming distance

- Difference in the number of positions between any two code words
- For two errors to be correctable, the Hamming distance d should be at least 5
- For t errors correctable, $d \geq 2t+1$ or $t = \lfloor (d-1)/2 \rfloor$
[$\lfloor \cdot \rfloor$] refers to the integer less than or equal to x .



Codes with different properties

Codes exist for

- correcting independently occurring errors
- correcting burst errors
- providing relatively error-free synchronization of binary data
- etc.

Coding Theory is very important to communication systems.
It is a discipline by itself.

CODES: Introduction

When we wish to send information over long distances unambiguously it becomes necessary to modify (encoding) the information into some form before sending, and convert (decode) at the receiving end to get back the original information. This process of encoding and decoding is necessary because the channel through which the information is sent may distort the transmitted information. Much of the information is sent as numbers. While these numbers are created using simple weighted-positional numbering systems, they need to be encoded before transmission. The modifications to numbers were based on changing the weights, but predominantly on some form of binary encoding. There are several codes in use in the context of present day information technology, and more and more new codes are being generated to meet the new demands.

Coding is the process of altering the characteristics of information to make it more suitable for intended application

By assigning each item of information a unique combination of 1s and 0s we transform some given information into binary coded form. The bit combinations are referred to as "words" or "code words". In the field of digital systems and computers different bit combinations have different designations.

Bit - a binary digit 0 or 1

Nibble - a group of four bits

Byte - a group of eight bits

Word - a group of sixteen bits;

a word has two bytes or four nibbles

Sometimes 'word' is used to designate a larger group of bits also, for example 32 bit or 64 bit words.

We need and use coding of information for a variety of reasons

- to increase efficiency of transmission,
- to make it error free,
- to enable us to correct it if errors occurred,
- to inform the sender if an error occurred in the received information etc.

- for security reasons to limit the accessibility of information
- to standardise a universal code that can be used by all

Coding schemes have to be designed to suit the security requirements and the complexity of the medium over which information is transmitted.

Decoding is the process of reconstructing source information from the encoded information. Decoding process can be more complex than coding if we do not have prior knowledge of coding schemes.

In view of the modern day requirements of efficient, error free and secure information transmission coding theory is an extremely important subject. However, at this stage of learning digital systems we confine ourselves to familiarising with a few commonly used codes and their properties.

We will be mainly concerned with binary codes. In binary coding we use binary digits or bits (0 and 1) to code the elements of an information set. Let n be the number of bits in the code word and x be the number of unique words.

If $n = 1$, then $x = 2$ (0, 1)

$n = 2$, then $x = 4$ (00, 01, 10, 11)

$n = 3$, then $x = 8$ (000,001,010 ...111)

.

$n = j$, then $x = 2^j$

From this we can conclude that if we are given elements of information to code into binary coded format,

$$x \leq 2^j$$

or $j \geq \log_2 x$

$$\geq 3.32 \log_{10} x$$

where j is the number of bits in a code word.

For example, if we want to code alphanumeric information (26 alphabetic characters + 10 decimals digits = 36 elements of information), we require

$$j \geq 3.32 \log_{10} 36$$

$$j \geq 5.16 \text{ bits}$$

Since bits are not defined as fractional parts, we take $j = 6$. In other words a minimum six-bit code would be required to code 36 alphanumeric elements of information. However, with a six-bit code only 36 code words are used out of the 64 code words possible.

In this Learning Unit we consider a few commonly used codes including

1. Binary coded decimal codes
2. Unit distance codes
3. Error detection codes
4. Alphanumeric codes

Binary Coded Decimal Codes

The main motivation for binary number system is that there are only two elements in the binary set, namely 0 and 1. While it is advantageous to perform all computations on hardware in binary forms, human beings still prefer to work with decimal numbers. Any electronic system should then be able to accept decimal numbers, and make its output available in the decimal form.

One method, therefore, would be to

- convert decimal number inputs into binary form
- manipulate these binary numbers as per the required functions, and
- convert the resultant binary numbers into the decimal form

However, this kind of conversion requires more hardware, and in some cases considerably slows down the system. Faster systems can afford the additional circuitry, but the delays associated with the conversions would not be acceptable. In case of smaller systems, the speed may not be the main criterion, but the additional circuitry may make the system more expensive.

We can solve this problem by encoding decimal numbers as binary strings, and use them for subsequent manipulations.

There are ten different symbols in the decimal number system: 0, 1, 2, . . . , 9. As there are ten symbols we require at least four bits to represent them in the binary form. Such a representation of decimal numbers is called **binary coding of decimal numbers**.

As four bits are required to encode one decimal digit, there are sixteen four-bit groups to select ten groups. This would lead to nearly 30×10^{10} (${}^{16}C_{10} \cdot 10!$) possible codes. However, most of them will not have any special properties that would be useful in hardware design. We wish to choose codes that have some desirable properties like

- ease of coding
- ease in arithmetic operations
- minimum use of hardware
- error detection property
- ability to prevent wrong output during transitions

In a **weighted code** the decimal value of a code is the algebraic sum of the weights of 1s appearing in the number. Let $(A)_{10}$ be a decimal number encoded in the binary form as $a_3a_2a_1a_0$. Then

$$(A)_{10} = w_3a_3 + w_2a_2 + w_1a_1 + w_0a_0$$

where w_3, w_2, w_1 and w_0 are the weights selected for a given code, and a_3, a_2, a_1 and a_0 are either 0s or 1s. The more popularly used codes have the weights as

w_3	w_2	w_1	w_0
8	4	2	1
2	4	2	1
8	4	-2	-1

The decimal numbers in these three codes are

Decimal digit	Weights				Weights				Weights			
	8	4	2	1	2	4	2	1	8	4	-2	-1
0	0	0	0	0	0	0	0	0	0	0	0	0
1	0	0	0	1	0	0	0	1	0	1	1	1
2	0	0	1	0	0	0	1	0	0	1	1	0
3	0	0	1	1	0	0	1	1	0	1	0	1
4	0	1	0	0	0	1	0	0	0	1	0	0
5	0	1	0	1	1	0	1	1	1	0	1	1
6	0	1	1	0	1	1	0	0	1	0	1	0
7	0	1	1	1	1	1	0	1	1	0	0	1
8	1	0	0	0	1	1	1	0	1	0	0	0
9	1	0	0	1	1	1	1	1	1	1	1	1

In all the cases only ten combinations are utilized to represent the decimal digits. The remaining six combinations are illegal. However, they may be utilized for error detection purposes.

Consider, for example, the representation of the decimal number 16.85 in Natural Binary Coded Decimal code (NBCD)

$$(16.85)_{10} = (\underline{0001} \ \underline{0110} \cdot \underline{1000} \ \underline{0101})_{NBCD}$$

1
6
8
5

There are many possible weights to write a number in BCD code. Some codes have desirable properties, which make them suitable for specific applications. Two such desirable properties are:

1. Self-complementing codes

2. Reflective codes

When we perform arithmetic operations, it is often required to take the “complement” of a given number. If the logical complement of a coded number is also its arithmetic complement, it will be convenient from hardware point of view. In a **self-complementing coded** decimal number, $(A)_{10}$, if the individual bits of a number are complemented it will result in $(9 - A)_{10}$.

Example: Consider the 2421 code.

- The 2421 code of $(4)_{10}$ is 0100.
- Its complement is 1011 which is 2421 code for $(5)_{10} = (9 - 4)_{10}$.

Therefore, 2421 code may be considered as a self-complementing code. A necessary condition for a self-complementing code is that the sum of its weights should be 9.

A self-complementing code, which is not weighted, is excess-3 code. It is derived from 8421 code by adding 0011 to all the 8421 coded numbers.

Another self-complementing code is 631-1 weighted code.

Three self-complementing codes are

Decimal Digit	Excess-3 Code	631-1 Code	2421 Code
0	0011	0011	0000
1	0100	0010	0001
2	0101	0101	0010
3	0110	0111	0011
4	0111	0110	0100
5	1000	1001	1011
6	1001	1000	1100
7	1010	1010	1101
8	1011	1101	1110
9	1100	1100	1111

A **reflective code** is characterized by the fact that it is imaged about the centre entries with one bit changed. For example, the 9's complement of a reflected BCD code word is formed by changing only one its bits. Two such examples of reflective BCD codes are

Decimal	Code-A	Code-B
0	0000	0100
1	0001	1010
2	0010	1000
3	0011	1110
4	0100	0000
5	1100	0001
6	1011	1111
7	1010	1001
8	1001	1011
9	1000	0101

The BCD codes are widely used and the reader should become familiar with reasons for using them and their application. The most common application of NBCD codes is in the calculator.

Unit Distance Codes

There are many applications in which it is desirable to have a code in which the adjacent codes differ only in one bit. Such codes are called Unit distance Codes. "Gray code" is the most popular example of unit distance code. The 3-bit and 4-bit Gray codes are

Decimal	3-bit Gray	4-bit Gray
0	000	0000
1	001	0001
2	011	0011
3	010	0010
4	110	0110
5	111	0111
6	101	0101
7	100	0100
8	-	1100
9	-	1101
10	-	1111
11	-	1110
12	-	1010
13	-	1011
14	-	1001
15	-	1000

These Gray codes listed here have also the reflective properties. Some additional examples of unit distance codes are

Decimal Digit	UDC-1	UDC-2	UDC-3
0	0000	0000	0000
1	0100	0001	1000
2	1100	0011	1001
3	1000	0010	0001
4	1001	0110	0011
5	1011	1110	0111
6	1111	1111	1111
7	0111	1101	1011
8	0011	1100	1010
9	0001	0100	0010

The most popular use of Gray codes is in the position sensing transducer known as shaft encoder. A shaft encoder consists of a disk in which concentric circles have alternate sectors with reflective surfaces while the other sectors have non-reflective

surfaces. The position is sensed by the reflected light from a light emitting diode. However, there is choice in arranging the reflective and non-reflective sectors. A 3-bit binary coded disk will be as shown in the figure 1.

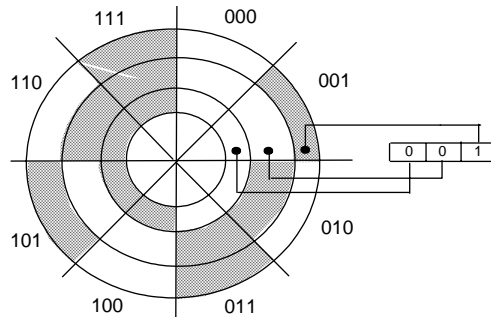


FIG.1: 3-bit binary coded shaft encoder

From this figure we see that straight binary code can lead to errors because of mechanical imperfections. When the code is transiting from 001 to 010, a slight misalignment can cause a transient code of 011 to appear. The electronic circuitry associated with the encoder will receive 001 --> 011 -> 010. If the disk is patterned to give Gray code output, the possibilities of wrong transient codes will not arise. This is because the adjacent codes will differ in only one bit. For example the adjacent code for 001 is 011. Even if there is a mechanical imperfection, the transient code will be either 001 or 011. The shaft encoder using 3-bit Gray code is shown in the figure 2.

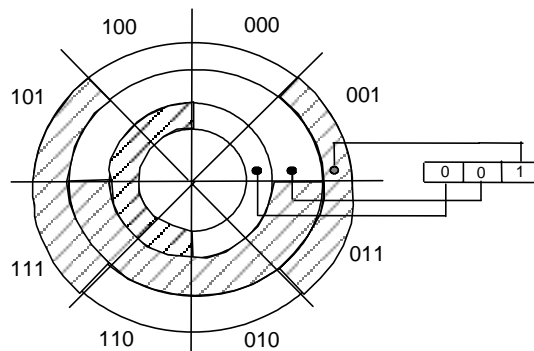


FIG. 2: Shaft encoder disk using a 3-bit Gray code

There are two convenient methods to construct Gray code with any number of desired bits. The first method is based on the fact that Gray code is also a reflective code. The following rule may be used to construct Gray code:

- A one-bit Gray code had code words, 0 and 1

- The first 2^n code words of an $(n+1)$ -bit Gray code equal the code words of an n -bit Gray code, written in order with a leading 0 appended.
- The last 2^n code words of a $(n+1)$ -bit Gray code equal the code words of an n -bit Gray code, written in reverse order with a leading 1 appended.

However, this method requires Gray codes with all bit lengths less than 'n' also be generated as a part of generating n -bit Gray code. The second method allows us to derive an n -bit Gray code word directly from the corresponding n -bit binary code word:

- The bits of an n -bit binary code or Gray code words are numbered from right to left, from 0 to $n-1$.
- Bit i of a Gray-code word is 0 if bits i and $i+1$ of the corresponding binary code word are the same, else bit i is 1. When $i+1 = n$, bit n of the binary code word is considered to be 0.

Example: Consider the decimal number 68.

$$(68)_{10} = (1000100)_2$$

Binary code: 1 0 0 0 1 0 0

Gray code : 1 1 0 0 1 1 0

The following rules can be followed to convert a Gray coded number to a straight binary number:

- Scan the Gray code word from left to right. All the bits of the binary code are the same as those of the Gray code until the first 1 is encountered, including the first 1.
- 1's are written until the next 1 is encountered, in which case a 0 is written.
- 0's are written until the next 1 is encountered, in which case a 1 is written.

Consider the following examples of Gray code numbers converted to binary numbers

Gray code : 1 1 0 1 1 0 1 0 0 0 1 0 1 1

Binary code: 1 0 0 1 0 0 1 1 1 1 0 0 1 0

Alphanumeric Codes

When information to be encoded includes entities other than numerical values, an expanded code is required. For example, alphabetic characters (A, B, ...Z) and special operation symbols like +, -, /, *, (,) and other special symbols are used in digital systems. Codes that include alphabetic characters are commonly referred to as Alphanumeric Codes. However, we require adequate number of bits to encode all the characters. As there was a need for alphanumeric codes in a wide variety of applications in the early era of computers, like teletype, punched tape and punched cards, there has always been a need for evolving a standard for these codes. Alphanumeric keyboard has become ubiquitous with the popularization of personal computers and notebook computers. These keyboards use ASCII (American Standard Code for Information Interchange) code

b4	b3	b2	b1	b7 b6 b5							
				000	001	010	011	100	101	110	111
0	0	0	0	NUL	DLE	SP	0	@	P	'	p
0	0	0	1	SOH	DC1	!	1	A	Q	a	q
0	0	1	0	STX	DC2	"	2	B	R	b	r
0	0	1	1	ETX	DC3	#	3	C	S	c	s
0	1	0	0	EOT	DC4	\$	4	D	T	d	t
0	1	0	1	ENQ	NAK	%	5	E	U	e	u
0	1	1	0	ACK	SYN	&	6	F	V	f	v
0	1	1	1	BEL	ETB	,	7	G	W	g	w
1	0	0	0	BS	CAN	(	8	H	X	h	x
1	0	0	1	HT	EM	)	9	I	Y	i	y
1	0	1	0	LF	SUB	*	:	J	Z	j	z
1	0	1	1	VT	ESC	+	;	K	[	k	{
1	1	0	0	FF	FS	,	<	L	\	l	|
1	1	0	1	CR	GS	-	=	M	]	m	}
1	1	1	0	SO	RS	.	>	N		n	~
1	1	1	1	SI	US	/	?	O	-	o	DEL

Alphanumeric codes like EBCDIC (Extended Binary Coded Decimal Interchange Code) and 12-bit Hollerith code are in use for some applications. However, ASCII code is now the standard code for most data communication networks. Therefore, the reader is urged to become familiar with the ASCII code.

Error Detection and Correcting Codes

When data is transmitted in digital form from one place to another through a transmission channel/medium, some data bits may be lost or modified. This loss of data integrity occurs due to a variety of electrical phenomena in the transmission channel. As there are needs to transmit millions of bits per second, the data integrity should be very high. The error rate cannot be reduced to zero. Then we would like to ideally have a mechanism of correcting the errors that occur. If this is not possible or proves to be expensive, we would like to know if an error occurred. If an occurrence of error is known, appropriate action, like retransmitting the data, can be taken. One of the methods of improving data integrity is to encode the data in a suitable manner. This encoding may be done for error correction or merely for error detection.

A simple process of adding a special code bit to a data word can improve its integrity. This extra bit will allow detection of a single error in a given code word in which it is used, and is called the 'Parity Bit'. This parity bit can be added on an odd or even basis. The odd or even designation of a code word may be determined by actual number of 1's in the data (including the added parity bit) to which the parity bit is added. For example, the S in ASCII code is

$$(S) = (1010011)_{\text{ASCII}}$$

S, when coded for odd parity, would be shown as

$$(S) = (11010011)_{\text{ASCII with odd parity}}$$

In this encoded 'S' the number of 1's is five, which is odd.

When S is encoded for even parity

$$(S) = (01010011)_{\text{ASCII with even parity}}$$

In this case the coded word has even number (four) of ones.

Thus the parity encoding scheme is a simple one and requires only one extra bit. If the system is using even parity and we find odd number of ones in the received data word we know that an error has occurred. However, this scheme is meaningful only for single errors. If two bits in a data word were received incorrectly the parity bit scheme will not detect the faults. Then the question arises as to the level of improvement in the data integrity if occurrence of only one bit error is detectable. The improvement in the reliability can be mathematically determined.

Adding a parity bit allows us only to detect the presence of one bit error in a group of bits. But it does not enable us to exactly locate the bit that changed. Therefore, addition of one parity bit may be called an error detecting coding scheme. In a digital system detection of error alone is not sufficient. It has to be corrected as well. Parity bit scheme can be extended to locate the faulty bit in a block of information. The information bits are conceptually arranged in a two-dimensional array, and parity bits are provided to check both the rows and the columns.

If we can identify the code word that has an error with the parity bit, and the column in which that error occurs by a way of change in the column parity bit, we can both detect and correct the wrong bit of information. Hence such a scheme is single error detecting and single error correcting coding scheme.

This method of using parity bits can be generalized for detecting and correcting more than one-bit error. Such codes are called parity-check block codes. In this class known as (n, k) codes, $r (= n-k)$ parity check bits, formed by linear operations on the k data bits, are appended to each block of k bits to generate an n -bit code word. An encoder outputs a unique n -bit code word for each of the 2^k possible input k -bit blocks. For example a $(15, 11)$ code has $r = 4$ parity-check bits for every 11 data bits. As r increases it should be possible to correct more and more errors.

With $r = 1$ error correction is not possible, as such a code will only detect an odd number of errors.

It can also be established that as k increases the overall probability of error should also decrease. Long codes with a relatively large number of parity-check bits should thus provide better performance. Consider the case of $(7, 3)$ code

Data bits	Code words
0 0 0	0 0 0 0 0 0 0
0 0 1	0 0 1 1 1 1 1
0 1 0	0 1 0 0 1 1 0
0 1 1	0 1 1 1 0 0 1
1 0 0	1 0 0 1 1 0 0
1 0 1	1 0 1 0 0 1 1
1 1 0	1 1 0 1 0 1 0
1 1 1	1 1 1 0 1 0 1

A close look at these indicates that they differ in at least three positions. Any *one* error should then be correctable since the resultant code word will still be closer to the correct one, in the sense of the number of bit positions in which they agree, than to any other. This is an example of *single-error-correcting-code*. The difference in the number of positions between any two code words is called the *Hamming distance*, named after R.W.Hamming who, in 1950, described a general method for constructing codes with a minimum distance of 3. The Hamming distance plays a key role in assessing the error-correcting capability of codes. For two errors to be correctable, the Hamming distance d should be at least 5. In general, for t errors to be correctable, $d \geq 2t+1$ or $t = \lfloor (d-1)/2 \rfloor$, where the $\lfloor x \rfloor$ notation refers to the integer less than or equal to x .

Innumerable varieties of codes exist, with different properties. There are various types of codes for correcting independently occurring errors, for correcting burst errors, for providing relatively error-free synchronization of binary data etc. The theory of these codes, methods of generating the codes and decoding the coded data, is a very important subject of communication systems, and need to be studied as a separate discipline.

Problems

M1L2: Codes

- Write the following decimal number in Excess-3, 2421, 84-2-2 BCD codes:
(a) 563 (b) 678 (c) 1465
- What is the use of self-complementing property? Demonstrate 631-1 BCD code is self-complementary.
- Develop two different 4-bit unit distance codes.
- Prove that Gray code is both a reflective and unit distance code?
- Determine the Gray code for (a) 37_{10} and (b) 97_{10} .
- Write your address in ASCII code.
- Write 8-bit ASCII code sequence of the name of your town/city with even parity.
- (a) Write the following statements in ASCII
 $A = 4.5 \times B$
 $X = 75/Y$
(b) Attach an even parity bit to each code word of the ASCII strings written for the above statements
- Find and correct the error in the following code sequence

```
0 1 0 1 0
0 1 1 0 0
1 1 0 1 1
1 0 1 1 0
1 0 0 0 1
0 0 0 1 1
1 1 0 0 0
0 1 0 0 1
0 1 0 1 0 --- Parity word
```

|_____ Parity bit



Digital Electronics

Module 2: Boolean Algebra and Boolean Operators: Boolean Algebra

N.J. Rao

Indian Institute of Science



Switching Signals

We encounter situations where the choice is binary

Move - Stop

On - Off

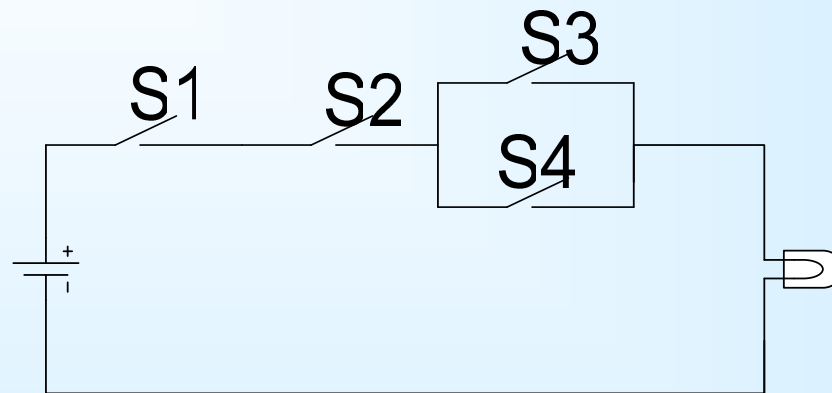
Yes - No

- An intended action takes place or does not take place
- Signals with two possible states are called “switching signals”
- We need to work with a large number of such signals
- There is a need for formal methods of handling such signals



Examples of switching signals

A control circuit for an electric bulb



Four switches control the operation of the bulb

'the bulb is switched on if the switches **S1 and S2** are closed, **and S3 or S4** is also closed, otherwise the bulb will not be switched on'

Relay operations in telephone exchanges is another example



George Boole

English mathematician (1854)

Wrote “An Investigation of the Laws of Thought”

Examined the truth or falsehood of language statements

Used special algebra of logic - Boole's Algebra (Boolean Algebra)

- assigned a value 1 to statements that are completely correct
- assigned a value 0 to statements that are completely false

Statements are referred to digital variables

We consider logical or digital variables to be synonymous



Claude Shannon

Master's Thesis at Massachusetts Institute of Technology
in 1938

“A Symbolic Analysis of Relay and Switching Circuits”

- He applied Boolean algebra to the analysis and design of electrical switching circuits



Realisation of switching circuits

Bipolar and MOS transistors are used as switches in building integrated circuits

Need to understand the electrical aspects of these circuits



Learning Objectives

- To know the basic axioms of Boolean algebra
- To simplify logic functions (Boolean functions) using the basic properties of Boolean Algebra



Boolean Algebra

A Boolean algebra consists of

- a finite set BS
- subject to equivalence relation " $=$ "
- one unary operator "not" (symbolised by an over bar)
- two binary operators " $+$ " and " \cdot "

such that for every element x and $y \in BS$, the operations \overline{x} (not x), $x + y$ and $x \cdot y$ are uniquely defined



Boolean Algebra (2)

- The unary operator '*not*' is defined by the relation

$$\bar{1} = 0; \bar{0} = 1$$

- The *not* operator is also called the complement
 \bar{x} is the complement of x



Binary operator “and”

The “*and*” operator is defined by

$$0 \cdot 0 = 0$$

$$0 \cdot 1 = 0$$

$$1 \cdot 0 = 0$$

$$1 \cdot 1 = 1$$



Binary operator “or”

The “or” operator is defined by

$$0 + 0 = 0$$

$$0 + 1 = 1$$

$$1 + 0 = 1$$

$$1 + 1 = 1$$



Huntington's (1909) postulates

P1. The operations are closed

For all x and $y \in BS$,

- $x + y \in BS$
- $x \cdot y \in BS$

P2. For each operation there exists an identity element.

- There exists an element $0 \in BS$ such that for all $x \in BS$, $x + 0 = x$
- There exists an element $1 \in BS$ such that for all $x \in BS$, $x \cdot 1 = x$



Huntington's postulates (2)

P3. The operations are commutative

For all x and $y \in BS$,

- $x + y = y + x$
- $x \cdot y = y \cdot x$

P4. The operations are distributive

For all x, y and $z \in BS$,

- $x + (y \cdot z) = (x + y) \cdot (x + z)$
- $x \cdot (y + z) = (x \cdot y) + (x \cdot z)$



Huntington's postulates (3)

P5. For every element $x \in BS$ there exists an element

$\bar{x} \in BS$ (called the complement of x) such that

$$\bullet x + \bar{x} = 1$$

$$\bullet x \cdot \bar{x} = 0$$

P6. There exist at least two elements x and $y \in BS$ such that $x \neq y$.



Useful properties

Property 1: Special law of 0 and 1

For all $x \in BS$

a. $x \cdot 0 = 0$

b. $x + 1 = 1$

Proof : $x \cdot 0 = (x \cdot 0) + 0$ (postulate 2a)

$$= (x \cdot 0) + (x \cdot \bar{x}) \quad (\text{postulate 5b})$$

$$= x \cdot (0 + \bar{x}) \quad (\text{postulate 4b})$$

$$= x \cdot \bar{x} \quad (\text{postulate 2a})$$

$$= 0 \quad (\text{postulate 5b})$$

Part b can be proved by applying the law of duality



Useful properties (2)

Property 2:

- The element 0 is unique.
- The element 1 is unique.

Proof for Part b by contradiction:

Assume that there are two 1s denoted 1_1 and 1_2 .

$$x \cdot 1_1 = x \text{ and } y \cdot 1_2 = y \text{ (Postulate 2b)}$$

$$x \cdot 1_1 = x \text{ and } 1_2 \cdot y = y \text{ (Postulate 3b)}$$



Useful properties (3)

Letting $x = 1_2$ and $y = 1_1$

$$1_2 \cdot 1_1 = 1_2 \text{ and } 1_2 \cdot 1_1 = 1_1$$

$$1_1 = 1_2 \text{ (transitivity property)}$$

which becomes a contradiction of initial assumption

Property 'a' can be established by applying the principle of duality.



Useful properties (3)

Property 3

a. The complement of 0 is $\bar{0}=1$

b. The complement of 1 is $\bar{1}=0$

Proof : $x + 0 = x$ (postulate 2a)

$$\bar{0} + 0 = \bar{0}$$

$$\bar{0} + 0 = 1 \quad (\text{postulate 5a})$$

$$\bar{0} = 1$$

Part b is valid by the application of principle of duality



Useful properties (4)

Property 4: Idempotency law

For all $x \in BS$

a. $x + x = x$

b. $x \cdot x = x$

Proof : $x + x = (x + x) \cdot 1$ (postulate 2b)

$$= (x + x) \cdot (x + \overline{x})$$
 (postulate 5a)
$$= x + (x \cdot \overline{x})$$
 (postulate 4a)
$$= x + 0$$
 (postulate 5b)
$$= x$$
 (postulate 2a)

$x \cdot x = x$ (by duality)



Useful properties (5)

Property 5 : Adjacency law

For all x and $y \in BS$

$$\text{a. } x \cdot y + x \cdot \bar{y} = x$$

$$\text{b. } (x + y) \cdot (x + \bar{y}) = x$$

Proof : $x \cdot y + x \cdot \bar{y} = x \cdot (y + \bar{y})$ (postulate 4b)

$$= x \cdot 1 \quad (\text{postulate 5a})$$

$$= x \quad (\text{postulate 2b})$$

$$(x + y) \cdot (x + \bar{y}) = x \quad (\text{by duality})$$

Useful in simplifying logical expressions



Useful properties (6)

Property 6: First law of absorption.

For all x and $y \in BS$,

$$x + (x \cdot y) = x$$

$$x \cdot (x + y) = x$$

Proof : $x \cdot (x + y) = (x + 0) \cdot (x + y)$ (postulate 2a)
 $= x + (0 \cdot y)$ (postulate 4a)
 $= x + 0$ (property 2.1a)
 $= x$ (postulate 2a)

$x + (x \cdot y) = x$ (by duality)



Useful properties (7)

Property 7 : Second law of absorption

For all x and $y \in BS$

$$a. x + (\bar{x} \cdot y) = x + y$$

$$b. x \cdot (\bar{x} + y) = x \cdot y$$

$$\begin{aligned} \text{Proof : } x + (\bar{x} \cdot y) &= (x + \bar{x}) \cdot (x + y) && \text{(postulate 4a)} \\ &= 1 \cdot (x + y) && \text{(postulate 5a)} \\ &= x + y && \text{(postulate 2b)} \\ x \cdot (\bar{x} + y) &= x \cdot y && \text{(by duality)} \end{aligned}$$



Useful properties (8)

Property 8 : Consensus law

For all $x, y, z \in BS$

$$a. x \cdot y + \bar{x} \cdot z + y \cdot z = x \cdot y + \bar{x} \cdot z$$

$$b. (x + y) \cdot (\bar{x} \cdot z) \cdot (y + z) = (x + y) \cdot (\bar{x} + z)$$

Proof : $x \cdot y + \bar{x} \cdot z + y \cdot z$

$$= x \cdot y + \bar{x} \cdot z + 1 \cdot y \cdot z \quad (\text{postulate 2b})$$

$$= x \cdot y + \bar{x} \cdot z + (x + \bar{x}) \cdot y \cdot z \quad (\text{postulate 5a})$$

$$= x \cdot y + x \cdot y \cdot z + \bar{x} \cdot z + \bar{x} \cdot y \cdot z \quad (\text{postulate 4b})$$

$$= x \cdot y \cdot (1 + z) + \bar{x} \cdot z \cdot (1 + y) \quad (\text{postulate 4b})$$

$$= x \cdot y \cdot 1 + \bar{x} \cdot z \cdot 1 \quad (\text{postulate 2.1 b})$$

$$= x \cdot y + \bar{x} \cdot z \quad (\text{postulate 2b})$$

$$(x + y) \cdot (\bar{x} + z) \cdot (y + z) = (x + y) \cdot (\bar{x} + z) \quad (\text{by duality})$$



Useful properties (9)

For all x and $y \in BS$,

If (a) $x + y = y$ and (b) $x \cdot y = y$, then $x = y$

Proof: Substituting (a) into the left-hand side of (b), we have

$$x \cdot (x + y) = y$$

However by the first law of absorption

$$x \cdot (x + y) = x \quad (\text{property 6})$$

Therefore, by transitivity $x = y$



Useful properties (10)

Property 10 : The law of involution

For all $x \in BS$, $\overline{\overline{x}} = x$

Proof : We need to show that the law of identity (property 2.9) holds, that is,

$$\overline{\overline{x + x}} = x \quad \text{and} \quad \overline{\overline{x \cdot x}} = \overline{\overline{x}}$$

$$\overline{\overline{x}} = \overline{\overline{x}} + 0 \quad (\text{postulate 2a})$$

$$= \overline{\overline{x}} + (\overline{x \cdot \overline{x}}) \quad (\text{postulate 5b})$$

$$= (\overline{\overline{x + x}}) \cdot (\overline{\overline{x}} + \overline{\overline{x}}) \quad (\text{postulate 4a})$$

$$= (\overline{\overline{x + x}}) \cdot 1 = \overline{\overline{x}} \cdot x \quad (\text{postulate 5a})$$



Useful properties (10) (contd.)

Also $\overline{\overline{x}} = \overline{x} \cdot 1$

$$= \overline{x} \cdot (\overline{x} + \overline{\overline{x}}) \quad (\text{postulate 2b})$$

$$= \overline{x} \cdot \overline{x} + \overline{x} \cdot \overline{\overline{x}} \quad (\text{postulate 5a})$$

$$= \overline{x} \cdot \overline{x} + 0 \quad (\text{postualte 5b})$$

$$= \overline{x} \cdot \overline{x} \quad (\text{postulate 2a})$$

Therefore, by the law of identity, we have $\overline{\overline{x}} = \overline{x}$



Useful properties (11)

Property 11: DeMorgan's Law

For all $x, y \in BS$

$$\text{a. } \overline{x + y} = \bar{x} \cdot \bar{y}$$

$$\text{b. } \overline{x \cdot y} = \bar{x} + \bar{y}$$

$$\begin{aligned} \text{Proof : } (x + y) \cdot (\bar{x} \cdot \bar{y}) &= (x \cdot \bar{x} \cdot \bar{y}) + (y \cdot \bar{x} \cdot \bar{y}) \quad (\text{postulate 4b}) \\ &= 0 + 0 = 0 \quad (\text{postulate 2a}) \\ (x + y) + (\bar{x} \cdot \bar{y}) &= (x + \bar{x} \cdot \bar{y}) + y \quad (\text{postulate 3a}) \\ &= x + \bar{y} + y \quad (\text{property 2.7a}) \\ &= x + 1 \quad (\text{postulate 5a}) \\ &= 1 \quad (\text{property 2.16}) \end{aligned}$$

Therefore, $(\bar{x} \cdot \bar{y})$ is the complement of $x + y$

$$\overline{x \cdot y} = \bar{x} + \bar{y} \quad (\text{by duality})$$



DeMorgan's law

- bridges the AND and OR operations
- establishes a method for converting one form of a Boolean function into another
- allows the formation of complements of expressions with more than one variable
- can be extended to expressions of any number of variables through substitution



Example of DeMorgan's Law

$$\overline{x + y + z} = \bar{x} . \bar{y} . \bar{z}$$

Let $y + z = w$, then $x + y + z = x + w$

Since $\overline{x + w} = \bar{x} . \bar{w}$ (by DeMorgan's law)

Therefore $\overline{x + w} = \overline{x + y + z}$ (by substitution)

$$= \bar{x} . \overline{y + z} \quad (\text{by DeMorgan's law})$$

$$= \bar{x} . \bar{y} . \bar{z}$$



Boolean Operators

$BS = \{0, 1\}$

Resulting Boolean algebra is more suited to working with switching circuits

Variables associated with electronic switching circuits take only one of the two possible values.

The operations "+" and "." also need to be given appropriate meaning



Binary Variables

Definition: A binary variable is one that can assume one of the two values 0 and 1.

These two values are meant to express two exactly opposite states.

If $A \neq 0$, then $A = 1$.

If $A \neq 1$, then $A = 0$

Examples:

- if switch A is not open then it is closed
- if switch A is not closed then it is open

Statement like

"0 is less than 1" or "1 is greater than 0" are invalid in Boolean algebra



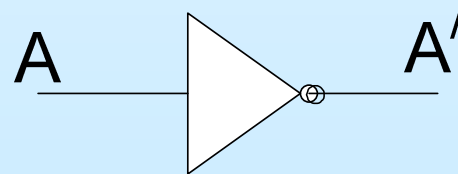
NOT Operator

- The Boolean operator NOT, also known as complement operator
- NOT operator is represented by " " (overbar) on the variable, or " / " (a superscript slash) after the variable

Definition: Not operator is defined by

A	A'
0	1
1	0

- " / " symbol is preferred for convenience in typing and writing programs
- Circuit representation:



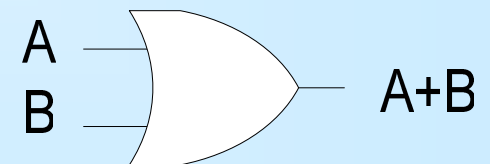


OR Operator

Definition: The Boolean operator "+" known as OR operator is defined by

A	B	A+B
0	0	0
0	1	1
1	0	1
1	1	1

The circuit symbol for logical OR operation



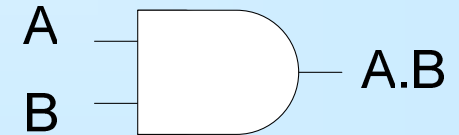


And Operator

- **Definition:** The Boolean operator "." known as AND operator is defined by

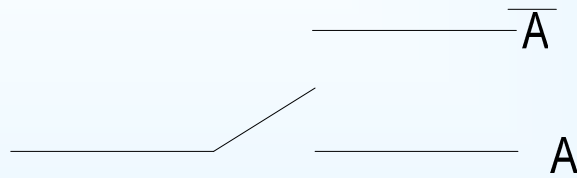
A	B	A.B
0	0	0
0	1	0
1	0	0
1	1	1

Circuit symbol for the logical AND operation



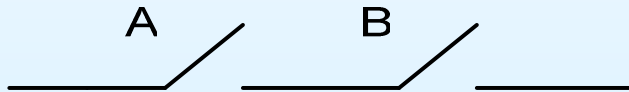


Boolean Operators and Switching Circuits

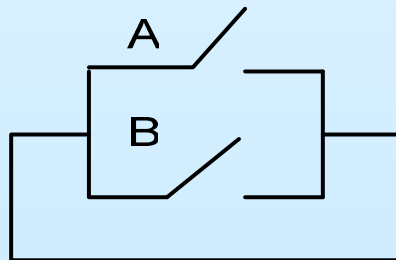


\bar{A}	A
Open	Closed
Closed	Open

AND operator



OR operator



A	B	A+B	A.B
0	0	0	0
0	1	1	0
1	0	1	0
1	1	1	1



Additional Boolean Operators

- NAND,
- NOR,
- Exclusive-OR (Ex-OR)
- Exclusive-NOR (Ex-NOR)

Definitions

A	B	$(AB)'$	$(A+B)'$	$A \oplus B$	$A \odot B$
0	0	1	1	0	1
0	1	1	0	1	0
1	0	1	0	1	0
1	1	0	0	0	1



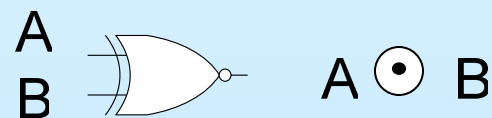
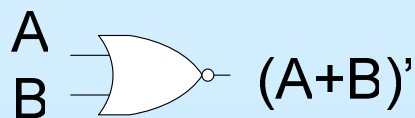
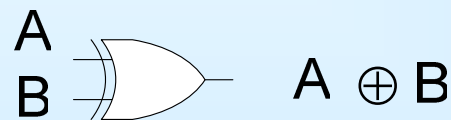
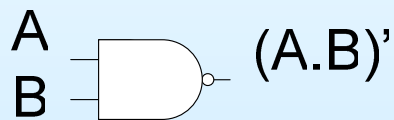
Additional Operations (2)

NAND operation is just the complement of AND operation

NOR operation is the complement of OR operation

Exclusive-NOR is the complement of Exclusive-OR operation

Circuit Symbols



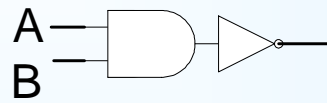


Functionally complete sets of operations

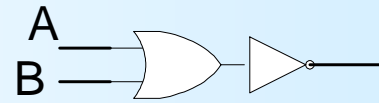
- OR, AND and NOT
- OR and NOT
- AND and NOT
- NAND
- NOR



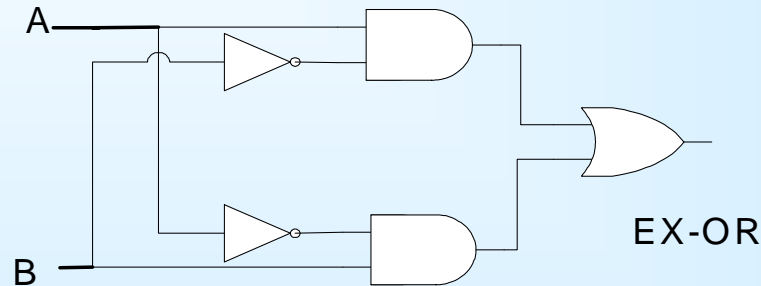
Completeness of AND, OR and NOT



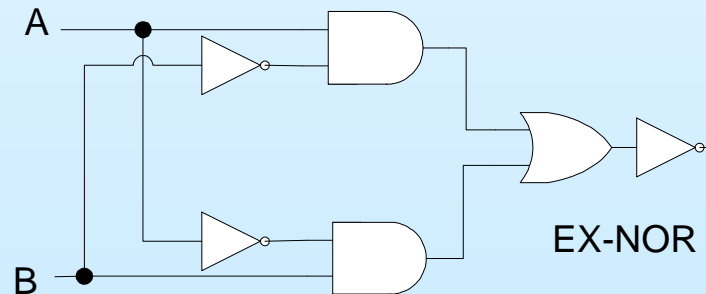
NAND



NOR



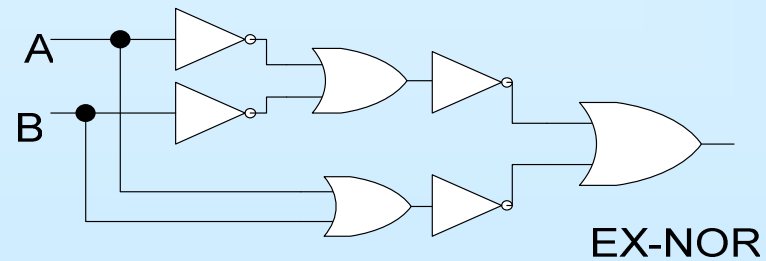
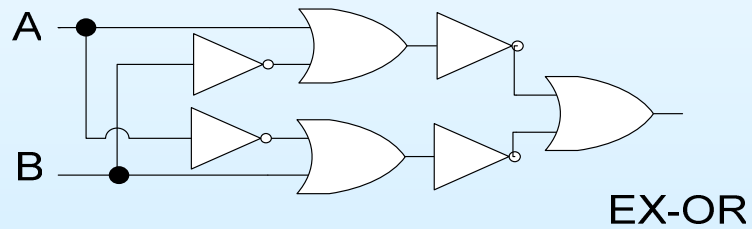
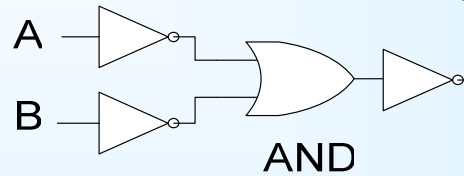
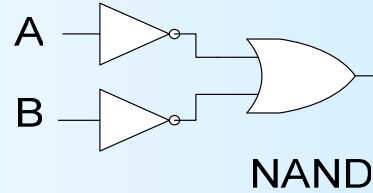
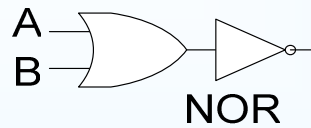
EX-OR



EX-NOR

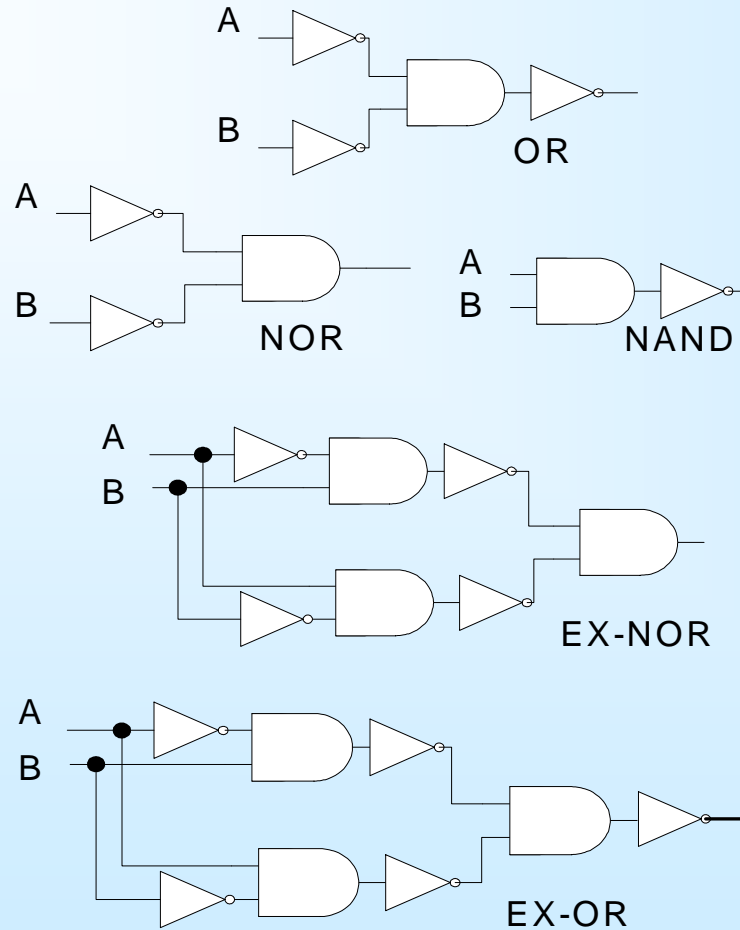


Completeness of OR and NOT operations



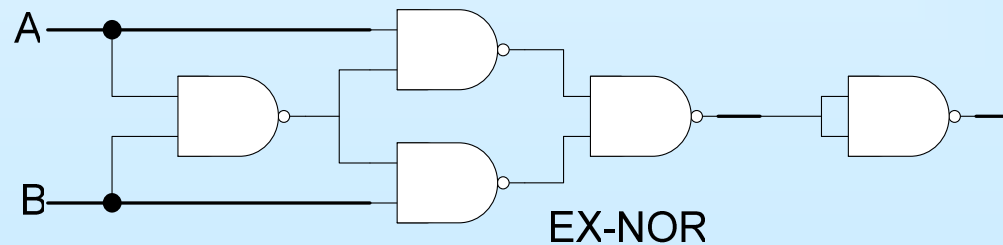
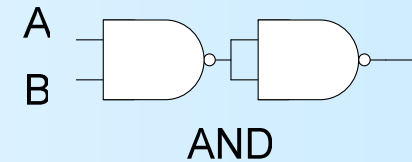
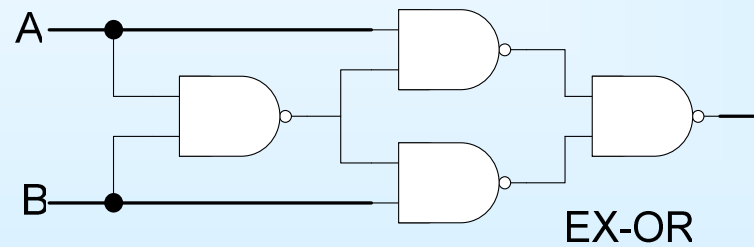
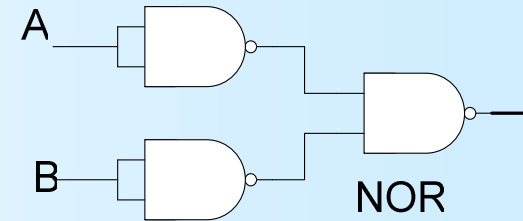
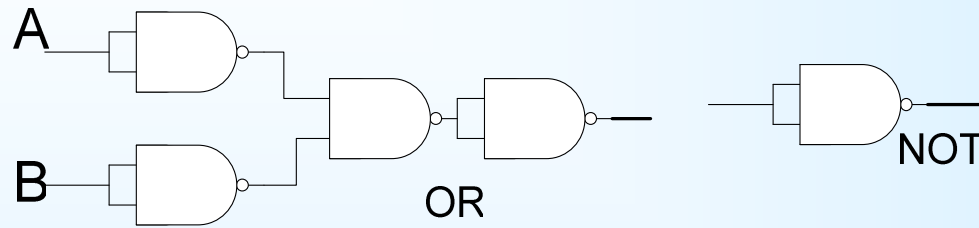


Completeness of AND and NOT



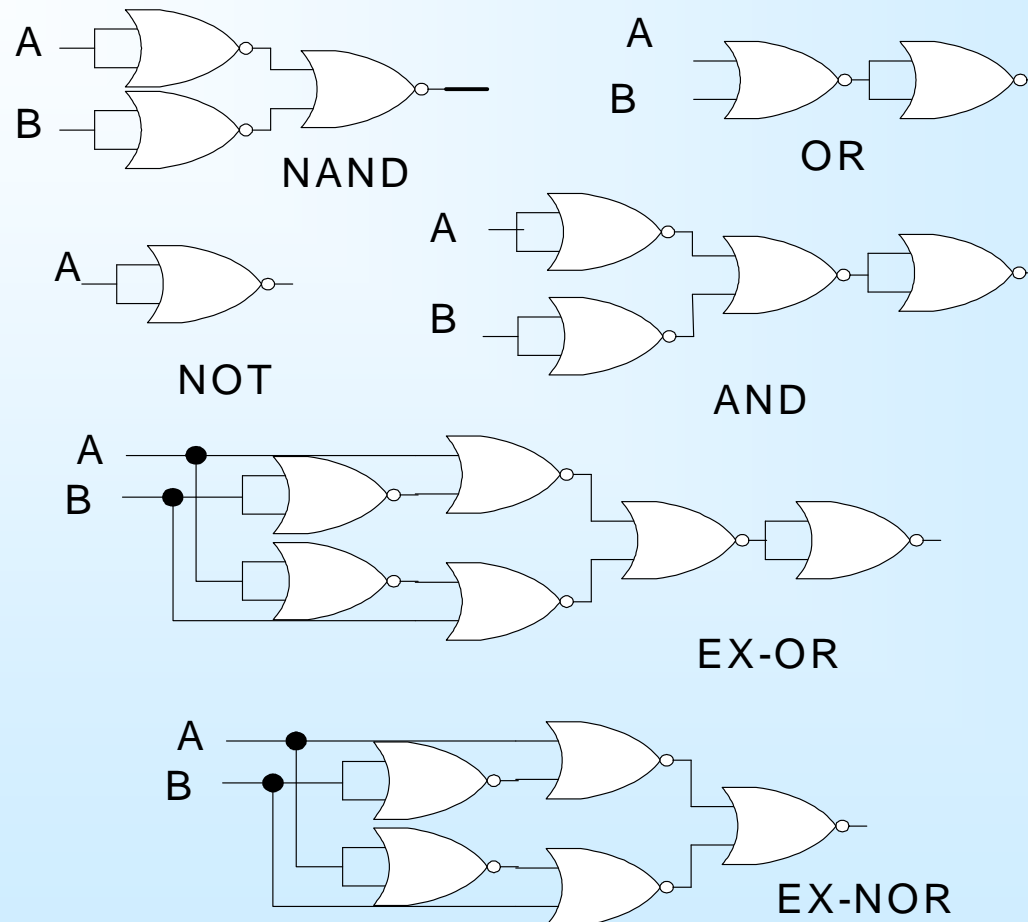


Completeness of NAND



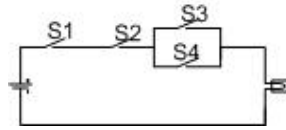


Completeness of NOR



WHAT IS BOOLEAN ALGEBRA?

Consider the electrical circuit that controls the lighting of a bulb.



Four switches control the operation of the bulb. The manner in which the operation of the bulb is controlled can be stated as

The bulb switches on if the switches S1 and S2 are closed, and S3 or S4 is also closed, otherwise the bulb will not switch on

From this statement one can make the following observations:

- Any switch has two states: "closed" or "open"
- The bulb is switched on only when the switches are in some well defined combination of states.
- The possible combinations are expressed through two types of relationships: "and" and "or".
- The two possible combinations are
 - "S1 and S2 and S3 are closed"
 - "S1 and S2 and S4 are closed"

There are many situations of engineering interest where the variables take only a small number of possible values.

Some examples:

- Relay network used in telephone exchanges of earlier era
- Testing through multiple choice questions
- Mechanical display boards in airports and railway stations
- Choices available at road junctions.

Can you identify a situation of significance where the variables can take only a small number of distinctly defined states?

How do we implement functions similar to the example shown above? We need devices that have finite number states. It seems to be easy to create devices with two well defined states. It is more difficult and more expensive to create devices with more than two states.

Let us consider devices with two well defined states. We should also have the ability to switch the state of the device from one state to the other. We call devices having two well defined states as “two-valued switching devices”.

Some examples of devices with two states

- A bipolar transistor in either fully-off or fully-on state
- A MOS transistor in either fully off or fully on state
- Simple relays
- Electromechanical switch

If we learn to work with two-valued variables, we acquire the ability to implement functions of such variables using two-state devices. We call them “binary variables”.

Very complex functions can be represented using several binary variables. As we can also build systems using millions of electronic two-state devices at very low costs, the mathematics of binary variables becomes very important.

An English mathematician, George Boole, introduced the idea of examining the truth or falsehood of language statements through a special algebra of logic. His work was published in 1854, in a book entitled “An Investigation of the Laws of Thought”. Boole's algebra was applied to statements that are either completely correct or completely false. A value 1 is assigned to those statements that are completely correct and a value 0 is assigned to statements that are completely false. As these statements are given numerical values 1 or 0, they are referred to as digital variables.

In our study of digital systems, we use the words switching variables, logical variables, and digital variables interchangeably.

Boole's algebra is referred to as Boolean algebra. Originally Boolean algebra was mainly applied to establish the **validity** or **falsehood** of logical statements.

In 1938, Claude Shannon of Department of Electrical Engineering at Massachusetts Institute of Technology in (his master's thesis) provided the first applications of the principles of Boolean algebra to the design of electrical switching circuits. The title of the paper, which was an abstract of his thesis, is “A Symbolic Analysis of Relay and Switching Circuits”. Shannon established Boole's algebra to switching circuits is what ordinary algebra is to analogue circuits.

Logic designers of today use Boolean algebra to functionally design a large variety of electronic equipment such as

- hand-held calculators,
- traffic light controllers,

- personal computers,
- super computers,
- communication systems
- aerospace equipment
- etc.

We next explore Boolean algebra at the axiomatic level. However, we do not worry about the devices that would be used to implement them and their limitations.

Boolean Algebra and Huntington Postulates

Any branch of mathematics starts with a set of self-evident statements known as postulates, axioms or maxims. These are stated without any proof.

Boolean algebra is a specific instance of Algebra of Propositional Logic.

E.V.Huntington presented basic postulates of Boolean Algebra in 1904 in his paper "Sets of Independent Postulates for the Algebra of Logic". He defined a multi-valued Boolean algebra on a set of finite number of elements.

In Boolean algebra as applied to the switching circuits, all variables and relations are two-valued. The two values are normally chosen as 0 and 1, with 0 representing *false* and 1 representing *true*. If x is a Boolean variable, then

$x = 1$ means x is true

$x = 0$ means x is false

When we apply Boolean algebra to digital circuits we will find that the qualifications "*asserted*" and "*not-asserted*" are better names than "*true*" and "*false*". That is when $x = 1$ we say x is asserted, and when $x = 0$ we say x is not-asserted.

You are expected to be familiar with

- Concept of a set
- Meaning of equivalence relation
- The principle of substitution

Definition: A Boolean algebra consists of a finite set of elements BS subject to

- Equivalence relation "=",
- One unary operator "not" (symbolised by an over bar),
- Two binary operators "." and "+",
- For every element x and $y \in BS$ the operations \bar{x} (not x), $x.y$ and $x + y$ are uniquely defined.

The unary operator '*not*' is defined by the relation

$$\bar{1} = 0; \quad \bar{0} = 1$$

The *not* operator is also called the complement, and consequently \bar{x} is the complement of x .

The binary operator 'and' is symbolized by a dot. The 'and' operator is defined by the relations

$$0 \cdot 0 = 0$$

$$0 \cdot 1 = 0$$

$$1 \cdot 0 = 0$$

$$1 \cdot 1 = 1$$

The binary operator 'or' is represented by a plus (+) sign. The 'or' operator is defined by the relations

$$0 + 0 = 0$$

$$0 + 1 = 1$$

$$1 + 0 = 1$$

$$1 + 1 = 1$$

Huntington's postulates apply to the Boolean operations

P1. The operations are closed.

For all x and $y \in BS$,

a. $x + y \in BS$

b. $x \cdot y \in BS$

P2. For each operation there exists an identity element.

a. There exists an element $0 \in BS$ such that for all $x \in BS$, $x + 0 = x$

b. There exists an element $1 \in BS$ such that for all $x \in BS$, $x \cdot 1 = x$

P3. The operations are commutative.

For all x and $y \in BS$,

a. $x + y = y + x$

b. $x \cdot y = y \cdot x$

P4. The operations are distributive.

For all x, y and $z \in BS$,

a. $x + (y \cdot z) = (x + y) \cdot (x + z)$

b. $x \cdot (y + z) = (x \cdot y) + (x \cdot z)$

P5. For every element $x \in BS$ there exists an element $\bar{x} \in BS$ (called the complement of x) such that $x + \bar{x} = 1$ and $x \cdot \bar{x} = 0$

P6. There exist at least two elements x and $y \in BS$ such that $x \neq y$.

Propositions from Huntington's Postulates

We derive several new propositions using the basic Huntington's postulates. Through these propositions we will be able to explore the structures and implications of that branch of mathematics. Such propositions are called theorems. A theorem gives a relationship among the variables.

Definition: A Boolean expression is a constant, 1 or 0, a single Boolean variable or its complement, or several constants and/or Boolean variables and/or their complements used in combination with one or more binary operators.

According to this definition 0, 1, x and \bar{x} are Boolean expressions. If A and B are Boolean expressions, then \bar{A} , \bar{B} , A+B and A.B are also Boolean expressions.

Duality: Many of the Huntington's postulates are given as pairs, and differ only by the simultaneous interchange of operators "+" and "." and the elements "0" and "1". This special property is called duality.

The property of duality can be utilized effectively to establish many useful properties of Boolean algebra.

The duality principle

"If two expressions can be proven equivalent by applying a sequence of basic postulates, then the dual expressions can be proven equivalent by simply applying the sequence of dual postulates"

This implies that for each Boolean property, which we establish, the dual property is also valid without needing additional proof.

Let us derive some useful properties:

Property 1: Special law of 0 and 1

For all $x \in BS$,

a. $x \cdot 0 = 0$

b. $x + 1 = 1$

Proof: $x \cdot 0 = (x \cdot 0) + 0$ (postulate 2a)

$= (x \cdot 0) + (x \cdot \bar{x})$ (postulate 5b)

$= x \cdot (0 + \bar{x})$ (postulate 4b)

$= x \cdot \bar{x}$ (postulate 2a)

$= 0$ (postulate 5b)

Property: **b** can be proved by applying the law of duality, that is, by interchanging "." and "+", and "1" and "0".

Property 2:

- a. The element 0 is unique.
- b. The element 1 is unique.

Proof for Part b by contradiction: Let us assume that there are two 1s denoted 1_1 and 1_2 . Postulate 2b states that

$$x. 1_1 = x \text{ and } y. 1_2 = y$$

Applying the postulate 3b on commutativity to the second relationship, we get

$$1_1 . x = x \text{ and } 1_2 . y = y$$

Letting $x = 1_2$ and $y = 1_1$, we obtain

$$1_1 . 1_2 = 1_2 \text{ and } 1_2 . 1_1 = 1_1$$

Using the transitivity property of any equivalence relationship we obtain $1_1 = 1_2$, which becomes a contradiction of our initial assumption.

Property **a** can be established by applying the principle of duality.

Property 3

- a. The complement of 0 is $\bar{0} = 1$.
- b. The complement of 1 is $\bar{1} = 0$.

Proof: $x + 0 = x$ (postulate 2a)

$$0 + \bar{0} = \bar{0}$$

$$0 + \bar{0} = 1 \quad \text{(postulate 5a)}$$

$$\bar{0} = 1$$

Part b is valid by the application of principle of duality.

Property 4: Idempotency law

For all $x \in BS$,

$$a. x + x = x$$

$$b. x . x = x$$

Proof: $x + x = (x + x) . 1$ (postulate 2b)

$$= (x + x) . (x + \bar{x}) \quad \text{(postulate 5a)}$$

$$= x + (x . \bar{x}) \quad \text{(postulate 4a)}$$

$$= x + 0 \quad \text{(postulate 5b)}$$

$$= x \quad \text{(postulate 2a)}$$

$$x \cdot x = x \quad (\text{by duality})$$

Property 5: Adjacency law

For all x and $y \in \text{BS}$,

$$\text{a. } x \cdot y + x \cdot \bar{y} = x$$

$$\text{b. } (x + y) \cdot (x + \bar{y}) = x$$

$$\text{Proof: } x \cdot y + x \cdot \bar{y} = x \cdot (y + \bar{y}) \quad (\text{postulate 4b})$$

$$= x \cdot 1 \quad (\text{postulate 5a})$$

$$= x \quad (\text{postulate 2b})$$

$$(x + y) \cdot (x + \bar{y}) = x \quad (\text{by duality})$$

The adjacency law is very useful in simplifying logical expressions encountered in the design of digital circuits. This property will be extensively used in later learning units.

Property 6: First law of absorption

For all x and $y \in \text{BS}$,

$$\text{a. } x + (x \cdot y) = x$$

$$\text{b. } x \cdot (x + y) = x$$

$$\text{Proof } x \cdot (x + y) = (x + 0) \cdot (x + y) \quad (\text{postulate 2a})$$

$$= x + (0 \cdot y) \quad (\text{postulate 4a})$$

$$= x + 0 \quad (\text{property 2.1a})$$

$$= x \quad (\text{postulate 2a})$$

$$x + (x \cdot y) = x \quad (\text{by duality})$$

Property 7: Second law of absorption

For all x and $y \in \text{BS}$,

$$\text{a. } x + (\bar{x} \cdot y) = x + y$$

$$\text{b. } x \cdot (\bar{x} + y) = x \cdot y$$

$$\text{Proof: } x + (\bar{x} \cdot y) = (x + \bar{x}) \cdot (x + y) \quad (\text{postulate 4a})$$

$$= 1 \cdot (x + y) \quad (\text{postulate 5a})$$

$$= x + y \quad (\text{postulate 2b})$$

$$x \cdot (\bar{x} + y) = x \cdot y \quad (\text{by duality})$$

Property 8: Consensus law

For all x, y and $z \in \text{BS}$,

$$\text{a. } x \cdot y + \bar{x} \cdot z + y \cdot z = x \cdot y + \bar{x} \cdot z$$

$$b. (x + y) \cdot (\bar{x} + z) \cdot (y + z) = (x + y) \cdot (\bar{x} + z)$$

Proof: $x \cdot y + \bar{x} \cdot z + y \cdot z$

$$= x \cdot y + \bar{x} \cdot z + 1 \cdot y \cdot z \quad (\text{postulate 2b})$$

$$= x \cdot y + \bar{x} \cdot z + (x + \bar{x}) \cdot y \cdot z \quad (\text{postulate 5a})$$

$$= x \cdot y + \bar{x} \cdot z + x \cdot y \cdot z + \bar{x} \cdot y \cdot z \quad (\text{postulate 4b})$$

$$= x \cdot y + x \cdot y \cdot z + \bar{x} \cdot z + \bar{x} \cdot y \cdot z \quad (\text{postulate 3a})$$

$$= x \cdot y \cdot (1 + z) + \bar{x} \cdot z \cdot (1 + y) \quad (\text{postulate 4b})$$

$$= x \cdot y \cdot 1 + \bar{x} \cdot z \cdot 1 \quad (\text{property 2.1b})$$

$$= x \cdot y + \bar{x} \cdot z \quad (\text{postulate 2b})$$

$$(x + y) \cdot (\bar{x} + z) \cdot (y + z) = (x + y) \cdot (\bar{x} + z) \quad (\text{by duality})$$

Property 9: Law of identity

For all x and $y \in BS$, if

- a. $x + y = y$
- b. $x \cdot y = y$, then $x = y$

Proof: Substituting (a) into the left-hand side of (b), we have

$$x \cdot (x + y) = y$$

However by the first law of absorption

$$x \cdot (x + y) = x \quad (\text{property 6})$$

Therefore, by transitivity $x = y$

Property 10: The law of involution

For all $x \in BS$, $\overline{\overline{x}} = x$

Proof: We need to show that the law of identity (property 2.9) holds, that is,

$$(\overline{\overline{x}} + x) = \overline{\overline{x}} \quad \text{and} \quad \overline{\overline{x}} \cdot x = \overline{\overline{x}}$$

$$\overline{\overline{x}} = \overline{\overline{x}} + 0 \quad (\text{postulate 2a})$$

$$= \overline{\overline{x}} + (\overline{x \cdot x}) \quad (\text{postulate 5b})$$

$$= (\overline{\overline{x}} + x) \cdot (\overline{\overline{x}} + \overline{x}) \quad (\text{postulate 4a})$$

$$= (\overline{\overline{x}} + x) \cdot 1 \quad (\text{postulate 5a})$$

Thus $\overline{\overline{x}} = \overline{x + x}$

Also $\overline{\overline{x}} = \overline{\overline{x} \cdot 1}$ (postulate 2b)

$$= \overline{\overline{x} \cdot (\overline{x + \overline{x}})} \quad (\text{postulate 5a})$$

$$= \overline{\overline{x} \cdot \overline{x} + \overline{x} \cdot \overline{\overline{x}}} \quad (\text{postulate 4b})$$

$$= \overline{\overline{x} \cdot \overline{x} + 0} \quad (\text{postulate 5b})$$

$$= \overline{\overline{x} \cdot \overline{x}} \quad (\text{postulate 2a})$$

Therefore by the law of identity, we have $\overline{\overline{x}} = x$

Property 11: DeMorgan's Law

For all $x, y \in BS$,

a. $\overline{\overline{x + y}} = \overline{\overline{\overline{x} \cdot \overline{y}}}$

b. $\overline{\overline{\overline{x} \cdot \overline{y}}} = \overline{\overline{x + y}}$

Proof: $(x + y) \cdot \overline{\overline{\overline{x} \cdot \overline{y}}} = (x \cdot \overline{\overline{\overline{x} \cdot \overline{y}}}) + (y \cdot \overline{\overline{\overline{x} \cdot \overline{y}}})$ (postulate 4b)

$$= 0 + 0$$

$$= 0 \quad (\text{postulate 2a})$$

$$(x + y) + \overline{\overline{\overline{x} \cdot \overline{y}}} = (x + \overline{\overline{\overline{x} \cdot \overline{y}}}) + y \quad (\text{postulate 3a})$$

$$= x + \overline{\overline{y}} + y \quad (\text{property 2.7a})$$

$$= x + 1 \quad (\text{postulate 5a})$$

$$= 1 \quad (\text{property 2.16})$$

Therefore, $(\overline{\overline{x}} \cdot \overline{\overline{y}})$ is the complement of $(x + y)$.

$$\overline{\overline{\overline{x} \cdot \overline{y}}} = \overline{\overline{x + y}} \quad (\text{by duality})$$

DeMorgan's law bridges the AND and OR operations, and establishes a method for converting one form of a Boolean function into another. More particularly it gives a method to form complements of expressions involving more than one variable. By employing the property of substitution, DeMorgan's law can be extended to expressions of any number of variables. Consider the following example:

$$\overline{\overline{\overline{x + y + z}}} = \overline{\overline{\overline{\overline{x} \cdot \overline{y} \cdot \overline{z}}}}$$

Let $y + z = w$, then $x + y + z = x + w$.

$$\overline{\overline{\overline{x + w}}} = \overline{\overline{\overline{\overline{x} \cdot \overline{w}}}} \quad (\text{by DeMorgan's law})$$

$$\begin{aligned} \overline{x + w} &= \overline{x + y + z} && \text{(by substitution)} \\ &= \overline{\overline{x} \cdot y + z} && \text{(by DeMorgan's law)} \\ &= \overline{\overline{x} \cdot \overline{y \cdot z}} && \text{(by DeMorgan's law)} \end{aligned}$$

At the end of this Section the reader should remind himself that all the postulates and properties of Boolean algebra are valid when the number of elements in the BS is finite. The case of the set BS having only two elements is of more interest here and in the topics that follow in this course on Design of Digital systems.

All the identities derived in this Section are listed in the Table 1 to serve as a ready reference.

TABLE: Useful Identities of Boolean Algebra

Complementation	$x \cdot \overline{x} = 0$ $x + \overline{x} = 1$
0 - 1 law	$x \cdot 0 = 0$ $x + 1 = 1$ $x + 0 = x$ $x \cdot 1 = x$
Idempotency	$x \cdot x = x$ $x + x = x$
Involution	$\overline{\overline{x}} = x$
Commutative law	$x \cdot y = y \cdot x$ $x + y = y + x$
Associative law	$(x \cdot y) \cdot z = x \cdot (y \cdot z)$ $(x + y) + z = x + (y + z)$
Distributive law	$x + (y \cdot z) = (x + y) \cdot (x + z)$ $x \cdot (y + z) = x \cdot y + x \cdot z$
Adjacency law	$x \cdot y + x \cdot \overline{y} = x$ $(x + y) \cdot (x + \overline{y}) = x$
Absorption law	$x + x \cdot y = x$

$$x \cdot (x+y) = x$$

$$x + \bar{x} \cdot y = x + y$$

$$x \cdot (\bar{x} + y) = x \cdot y$$

Consensus law

$$x \cdot y + \bar{x} \cdot z + y \cdot z = x \cdot y + \bar{x} \cdot z$$

$$(x + y) \cdot (\bar{x} + z) \cdot (y + z) = (x + y) \cdot (\bar{x} + z)$$

DeMorgan's law

$$\overline{x + y} = \bar{x} \cdot \bar{y}$$

$$\overline{x \cdot y} = \bar{x} + \bar{y}$$

The properties of Boolean algebra when the set BS has two elements, namely 0 and 1, will be explored next.

BOOLEAN OPERATORS

Recall that Boolean Algebra is defined over a set (BS) with finite number of elements. If the set BS is restricted to two elements $\{0, 1\}$ then the Boolean variables can take only one of the two possible values. As all switches take only two possible positions, for example ON and OFF, Boolean Algebra with two elements is more suited to working with switching circuits. In all the switching circuits encountered in electronics, the variables take only one of the two possible values.

Definition: A binary variable is one that can assume one of the two values, 0 or 1.

These two values, however, are meant to express two exactly opposite states. It means, if a binary variable $A \neq 0$ then $A = 1$. Similarly if $A \neq 1$, then $A = 0$.

Note that it agrees with our intuitive understanding of electrical switches we are familiar with.

- a. if switch A is not open then it is closed
- b. if switch A is not closed then it is open

The values 0 and 1 should not be treated numerically, such as to say "0 is less than 1" or "1 is greater than 0".

Definition: The Boolean operator NOT, also known as complement operator represented by " $\bar{\quad}$ " (overbar) on the variable, or " \prime " (a superscript slash) after the variable, is defined by the following table.

A	A'
0	1
1	0

Though it is more popular to use the symbol " $\bar{\quad}$ " (overbar) in most of the text-books, we will adopt the " \prime " to represent the complement of a variable, for convenience of typing.

The circuit representation of the NOT operator is shown in the following:



Definition: The Boolean operator "+" known as OR operator is defined by the table given in the following.

A	B	A+B
0	0	0
0	1	1
1	0	1
1	1	1

The circuit symbol for logical OR operation is given in the following.



Definition: The Boolean operator "." known as AND operator is defined by the table given below

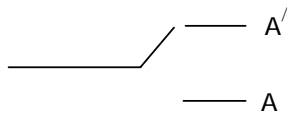
A	B	A.B
0	0	0
0	1	0
1	0	0
1	1	1

The circuit symbol for the logical AND operation is given in the following.



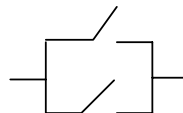
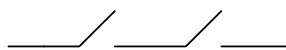
The relationship of these operators to the electrical switching circuits can be seen from the equivalent circuits given in the following.

Consider the NOT operator



A'	A
open	closed
closed	open

Consider the OR and AND operators



A	B	A + B	A.B
Open	Open	Open	Open
Open	Closed	Closed	Open
Closed	Open	Closed	Open
Closed	Closed	Closed	Closed

We can define several other logic operations besides these three basic logic operations. These include

- NAND
- NOR
- Exclusive-OR (Ex-OR for short)
- Exclusive-NOR (Ex-NOR)

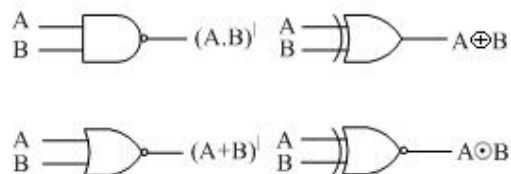
These are defined in terms of different combinations of values the variables assume, as indicated in the following table:

A	B	$(A.B)'$ NAND	$(A+B)'$ NOR	$A \oplus B$ EX-OR	$A \odot B$ EX-NOR
0	0	1	1	0	1
0	1	1	0	1	0
1	0	1	0	1	0
1	1	0	0	0	1

Observe the following:

- NAND operation is just the complement of AND operation
- NOR operation is the complement of OR operation.
- Exclusive-OR operation is similar to OR operation except that EX-OR operation leads to 0, when the two variables take the value of 1.
- Exclusive-NOR is the complement of Exclusive-OR operation.

These functions can also be represented graphically as shown in the figure.



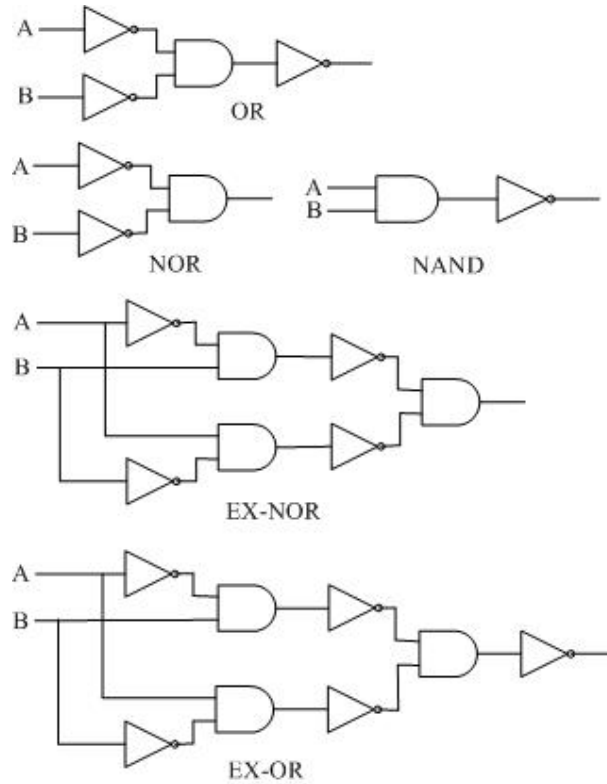
A set of Boolean operations is called functionally complete set if all Boolean expressions can be expressed by that set of operations. AND, OR and NOT constitute a functionally complete set. However, it is possible to have several combinations of Boolean operations as functionally complete sets.

- OR, AND and NOT
- OR and NOT
- AND and NOT

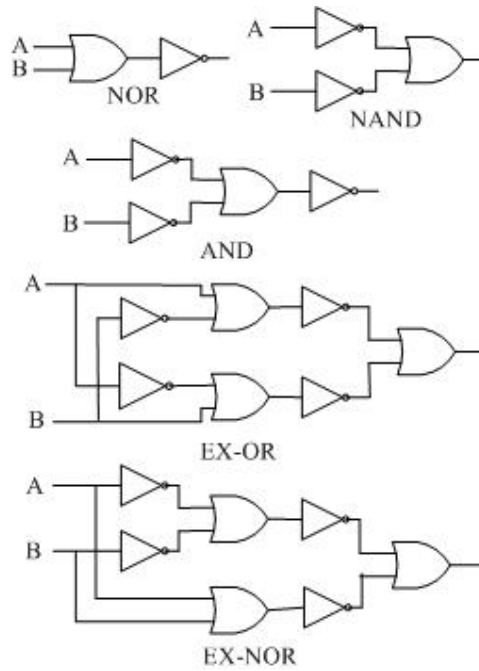
- NAND
- NOR

The completeness of these combinations is shown in the following.

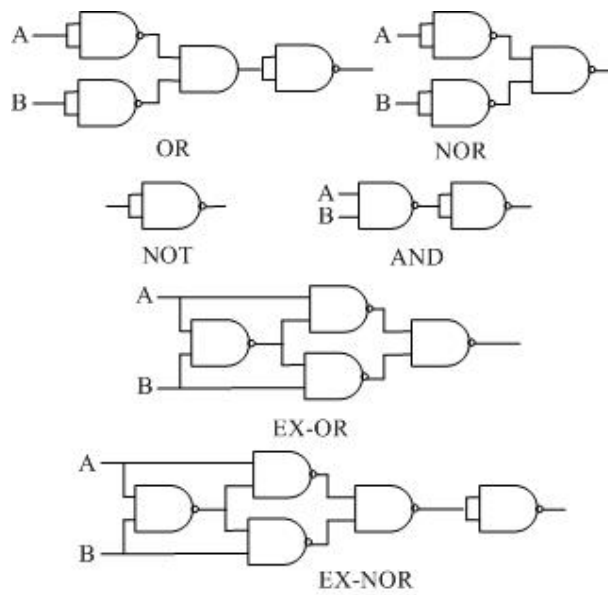
All Boolean functions through AND and NOT operations



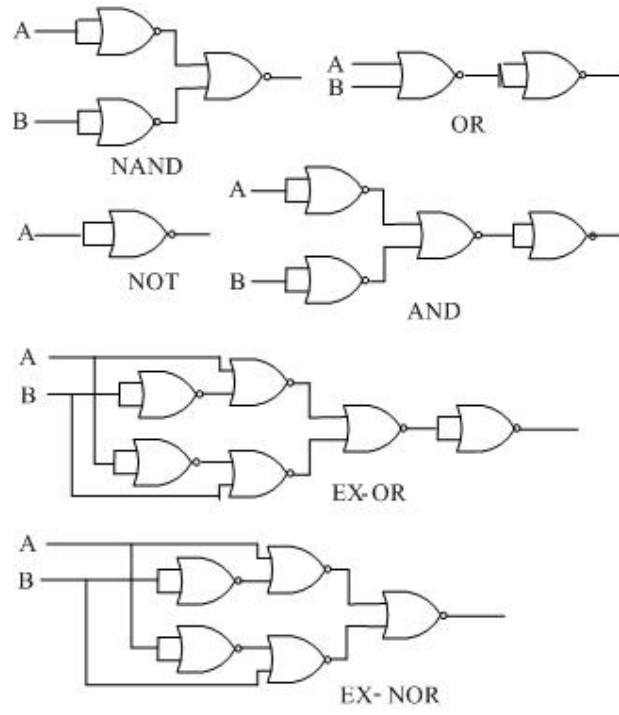
All Boolean functions through OR and NOT operations



All Boolean functions through NAND function



All Boolean functions through NOR function





Digital Electronics

Module 2: Boolean Algebra and Boolean Operators: Logic Functions

N.J. Rao

Indian Institute of Science



Logic Functions

- Electrical and electronic circuits can be built with devices that have two states
- Variables with only two values are called Logic variables or Switching variables
- We defined several Boolean/Logic operators
- A large variety of situations and problems can be described using logic variables and logic operators.
- The description is done through “logic functions”



Descriptions of logic functions

- Algebraic
- Truth-table
- Logic circuit
- Hardware description language
- Maps

Each form of representation is convenient in a different context.



Logic Functions in Algebraic Form

Let A_1, A_2, \dots, A_n be logic variables defined on the set $BS = \{0, 1\}$.

A logic function of n variables associates a value 0 or 1 to every one of the possible 2^n combinations of the n variables.

$$F_1 = A_1.A_2/.A_3.A_4 + A_1/.A_2.A_3/.A_4 + A_1.A_2/.A_3.A_4/$$

- F_1 is a function of 4 variables

It is not necessary to have all the variables in all the terms.

$$F_2 = A_1.A_2 + A_1/.A_2.A_3/ + A_1/.A_2.A_4/.A_5$$



Properties of logic functions

- If $F1(A1, A2, \dots, A_n)$ is a logic function, then $(F1(A1, A2, \dots, A_n))'$ is also a Boolean function.
- If $F1$ and $F2$ are two logic functions, then $F1+F2$ and $F1.F2$ are also Boolean functions.
- Any function that is generated by the finite application of the above two rules is also a logic function.

There are a total of 2^{2^n} distinct logic functions of n variables.



Terms to get familiarized

- **Literal:** not-complemented or complemented version of a variable (A and A' are literals)
- **Product term:** A series of literals related to one another through an AND operator.
Ex: $A.B'.D$, $A.B.D'.E$, etc.
- **Sum term:** A series of literals related to one another through an OR operator.
Ex: $A+B'+D$, $A+B+D'+E$, etc.



Truth Table

- It is a tabular representation of a logic function.
- It gives the value of the function for all possible combinations of the values of the variables
- For each combination, the function takes either 1 or 0
- These combinations are listed in a table, which constitute the truth table for the given function.
- The information contained in the truth table and in the algebraic representation of the function are the same.



Example of a truth-table

$$F(A, B) = A.B + A.B'$$

Truth table

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



Truth and Truth Table

- The term truth table came into usage long before Boolean algebra came to be associated with digital electronics.
- Boolean functions were originally used to establish truth or falsehood of a statement.
- When statement is true the "1" is associated with it
- When it is false "0" is associated.
- This usage got extended to the variables associated with digital circuits



Inappropriateness of truth and falsity

- All variables in digital systems are indicative of actions. Examples: "CLEAR", "LOAD", "SHIFT", "ENABLE", and "COUNT"
- They are suggestive of actions.
- When a variable is asserted, the intended action takes place
- When a variable is not asserted the intended action does not take place
- Associate "1" with the assertion of a variable, and "0" with the non-assertion of that variable.



Assertion and Non-assertion

$$F = A.B + A.B'$$

- Read it as "F is asserted when A **and** B are asserted **or** A is asserted **and** B is not asserted".
- We will continue to use the term "truth table" for historical reasons

We understand it as

an input-output table associated with a logic function but not as something that is concerned with the establishment of truth.



Size of the Truth-Table

- A five variable function would require 32 entries
- A six-variable function would require 64 entries

When the number of variables increase a simple artefact may be adopted.

- A truth table will have entries only for those terms for which the value of the function is "1", without loss of any information.
- This is particularly effective when the function has smaller number of terms.



Simpler Truth Table

$$F = A.B.C.D'.E' + A.B'.C.D'.E + A'.B'.C.D.E + A.B'.C'.D.E$$

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



English Sentences \rightarrow Logic Functions

Anil freaks out with his friends if it is Saturday and



he completed his assignments



- $F = 1$ if “Anil freaks out with his friends”; otherwise $F = 0$
- $A = 1$ if “it is Saturday”; otherwise $A = 0$
- $B = 1$ if “he completed his assignments”; otherwise $B = 0$

F is asserted if A is asserted and B is asserted.

The sentence, therefore, can be translated into a logic equation as

$$F = A.B$$



Rahul will attend the Networks class F

if and only if his friend Shaila is attending the class A

and the topic being covered in class is important from B
examination point of view

or there is no interesting matinee show in the city C/
and

the assignment is to be submitted D

$$F = A.B + C/.D$$



Minterms

- A logic function has product terms.
- Product terms that consist of all the variables of a function are called "canonical product terms", "fundamental product terms" or "minterms".
- The term $A.B.C'$ is a minterm in a three variable logic function, but will be a non-minterm in a four variable logic function.



Maxterms

- Sum terms which contain all the variables of a Boolean function are called "canonical sum terms", "fundamental sum terms" or "maxterms".
- $(A+B/C)$ is an example of a maxterm in a three variable logic function.



Minterms and Maxterms of 3 variables

Term No.	A	B	C	Minterms	Maxterms
0	0	0	0	$A'B'C' = m_0$	$A + B + C = M_0$
1	0	0	1	$A'B'C = m_1$	$A + B + C' = M_1$
2	0	1	0	$A'BC' = m_2$	$A + B' + C = M_2$
3	0	1	1	$A'BC = m_3$	$A + B' + C' = M_3$
4	1	0	0	$AB'C' = m_4$	$A + B + C = M_4$
5	1	0	1	$AB'C = m_5$	$A + B + C' = M_5$
6	1	1	0	$ABC' = m_6$	$A' + B' + C = M_6$
7	1	1	1	$ABC = m_7$	$A' + B' + C' = M_7$



Logic function as a sum of minterms

Consider a function of three variables

$$F = m_0 + m_3 + m_5 + m_6$$

This is equivalent to

$$F = A'B'C' + A'BC + A'BC' + ABC'$$

A logic function that is expressed as an OR of several product terms is considered to be in "sum-of-products" or SOP form.



Logic function as a product of Maxterms

F is a function of three variables

$$F = M_0 \cdot M_3 \cdot M_5 \cdot M_6$$

When F expressed as an AND of several sum terms, it is considered to be in "product-of-sums" or POS form.



Canonical form

If all the terms in an expression or function are canonical in nature, then it is considered to be in canonical form.

- minterms in the case of SOP form
- maxterms in the case of POS form



Canonical form (2)

Consider the function

$$F = A.B + A.B'.C + A'.B.C$$

It is not in canonical form

It can be converted into canonical form:

$$\begin{aligned} A.B &= A.B.1 && \text{(postulate 2b)} \\ &= A.B.(C + C') && \text{(postulate 5a)} \\ &= A.B.C + A.B.C' && \text{(postulate 4b)} \end{aligned}$$

The canonical version of F

$$F = A.B.C + A.B.C' + A.B'.C + A'.B.C$$



Priorities in a logical expression

- NOT (') operation has the highest priority,
- AND (.) has the next priority
- OR (+) has the last priority

in

$$F = A.B + A.B'.C + A'.B.C$$



Sequence of operations

$$F = A.B + A.B'.C + A'.B.C$$

- NOT operation on B and A
- AND terms: $A.B$, $A.B'.C$, $A'.B.C$
- OR operation on AB , $A.B'.C$ and $A'.B.C$

The order of priority can be modified through using parentheses.

$$F1 = A.(B+C') + A'.(C+D)$$

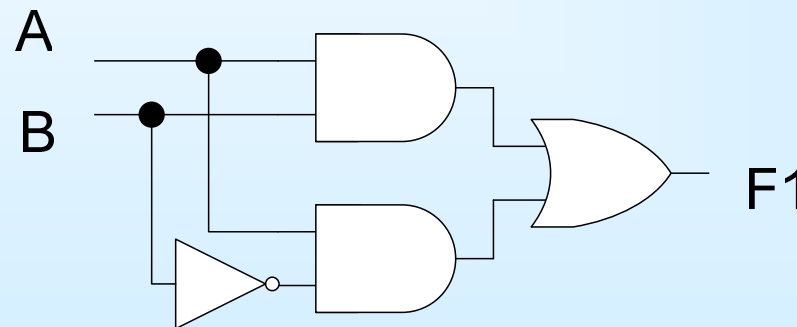
By applying the distributive law, these expressions can be brought into the SOP form



Circuit Representation of Logic Functions

A logic function can be represented in a circuit form using these circuit symbols

$$F1 = A.B + A.B'$$

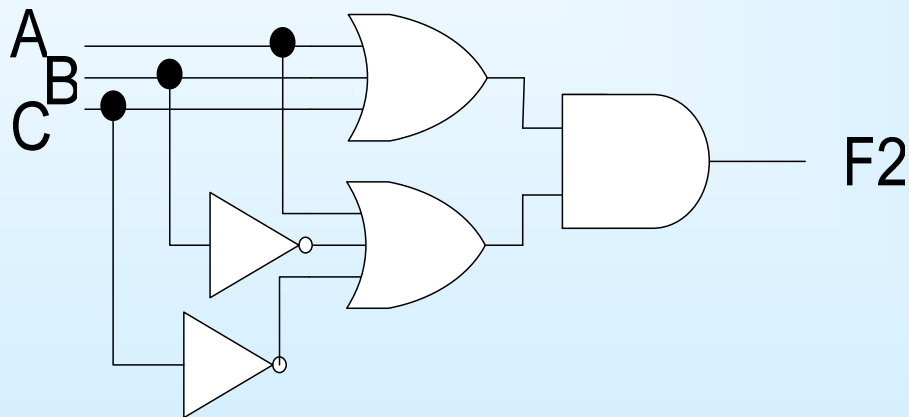




Other forms

Boolean function in POS form

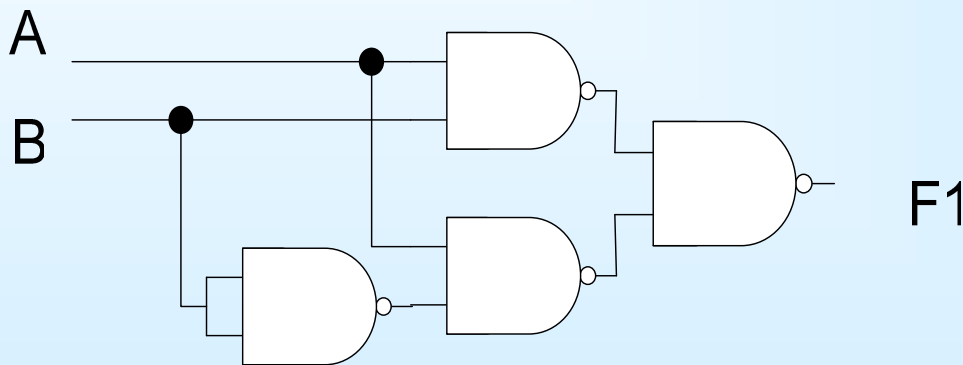
$$F2 = (A+B+C) \cdot (A+B'+C')$$





Other forms

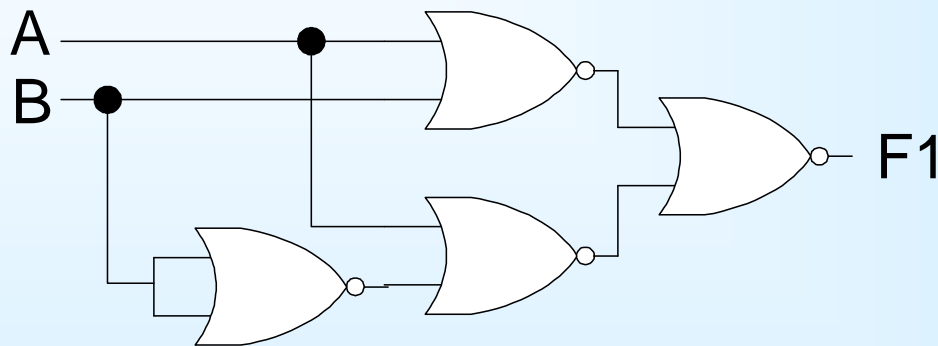
Logical function in terms of other functionally complete set of logical operations
NAND is one such functionally complete set.





Other forms

NOR is another functionally complete set.



Logic Functions

Many types of electrical and electronic circuits can be built with devices that have two possible states. We are, therefore interested in working with variables, which can take only two values. Such two valued variables are called Logic variables or Switching variables.

We defined several Boolean operators, which can also be called Logic operators. We will find that it is possible to describe a wide variety of situations and problems using logic variables and logic operators. This is done through defining a “logic function” of logic variables.

We can describe logic functions in several ways. These include

- Algebraic
- Truth-table
- Logic circuit
- Hardware description language
- Maps

We use all these forms to express logic functions in working with digital circuits. Each form of representation is convenient in some context. Initially we will work with algebraic, truth-table, and logic circuit representation of logic functions.

The objectives of this learning unit are

1. Writing the output of a logic network, whose word description is given, as a function of the input variables either as a logic function, a truth-table, or a logic circuit.
2. Create a truth-table if the description of a logic circuit is given in terms of a logic function or as a logic circuit.
3. Write a logic function if the description of a logic circuit is given in terms of a truth-table or as a logic circuit.
4. Create a logic circuit if its description is given in terms of a truth-table or as a logic function.
5. Expand a given logic function in terms of its minterms or maxterms.
6. Convert a given truth-table into a logic function into minterm or maxterm forms.
7. Explain the nature and role of “don’t care” terms

Logic Functions in Algebraic Form

Let A_1, A_2, \dots, A_n be logic variables defined on the set $BS = \{0,1\}$. A logic function of n variables associates a value 0 or 1 to every one of the possible 2^n combinations of the n variables. Let us consider a few examples of such functions.

$$F1 = A1.A2'.A3.A4 + A1'.A2.A3'.A4 + A1.A2'.A3.A4'$$

$F1$ is a function of 4 variables. You notice that all terms in the function have all the four variables. It is not necessary to have all the variables in all the terms. Consider the following example.

$$F2 = A1.A2 + A1'.A2.A3' + A1'.A2.A4'.A5$$

$F2$ happens to be simplified version of a function, which has a much larger number of terms, where each term has all the variables. We will explore ways and means to generate such simplifications from a given logic expression.

The logic functions have the following properties:

1. If $F1(A_1, A_2, \dots, A_n)$ is a logic function, then $(F1(A_1, A_2, \dots, A_n))'$ is also a Boolean function.
2. If $F1$ and $F2$ are two logic functions, then $F1+F2$ and $F1.F2$ are also Boolean functions.
3. Any function that is generated by the finite application of the above two rules is also a logic function

Try to understand the meaning of these properties by solving the following examples.

If $F1 = A.B.C + A.B'.C + A.B.C'$ what is the logic function that represents $F1'$?

If $F1 = A.B + A'.C$ and $F2 = A.B' + B.C$ write the logic functions $F1 + F2$ and $F1.F2$?

As each one of the combinations can take value of 0 or 1, there are a total of 2^{2^n} distinct logic functions of n variables.

It is necessary to introduce a few terms at this stage.

"Literal" is a not-complemented or complemented version of a variable. A and A' are literals

"Product term" or "product" refers to a series of literals related to one another through an AND operator. Examples of product terms are $A.B'.D$, $A.B.D'.E$, etc.

"Sum term" or "sum" refers to a series of literals related to one another through an OR operator. Examples of sum terms are $A+B'+D$, $A+B+D'+E$, etc.

The choice of terms "product" and "sum" is possibly due to the similarity of OR and AND operator symbols "+" and "." to the traditional arithmetic addition and multiplication operations.

Truth Table Description of Logic Functions

The truth table is a tabular representation of a logic function. It gives the value of the function for all possible combinations of values of the variables. If there are three variables in a given function, there are $2^3 = 8$ combinations of these variables. For each combination, the function takes either 1 or 0. These combinations are listed in a table, which constitutes the truth table for the given function. Consider the expression,

$$F(A, B) = A.B + A.B'$$

The truth table for this function is given by,

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

The information contained in the truth table and in the algebraic representation of the function are the same.

The term 'truth table' came into usage long before Boolean algebra came to be associated with digital electronics. Boolean functions were originally used to establish truth or falsehood of statements. When statement is true the symbol "1" is associated with it, and when it is false "0" is associated. This usage got extended to the variables associated with digital circuits. However, this usage of adjectives "true" and "false" is not appropriate when associated with variables encountered in digital systems. All variables in digital systems are indicative of actions. Typical examples of such signals are "CLEAR", "LOAD", "SHIFT", "ENABLE", and "COUNT". These are suggestive of actions. Therefore, it is appropriate to state that a variable is ASSERTED or NOT ASSERTED than to say that a variable is TRUE or FALSE. When a variable is asserted, the intended action takes place, and when it is not asserted the intended action does not take place. In this context we associate "1" with the assertion of a variable, and "0" with the non-assertion of that variable. Consider the logic function,

$$F = A.B + A.B'$$

It should now be read as "F is asserted when A **and** B are asserted **or** A is asserted **and** B is not asserted". This convention of using "assertion" and "non-assertion" with the logic variables will be used in all the Learning Units of this course on Digital Systems.

The term 'truth table' will continue to be used for historical reasons. But we understand it as an input-output table associated with a logic function, but not as something that is concerned with the establishment of truth.

As the number of variables in a given function increases, the number of entries in the truth table increases exponentially. For example, a five variable expression would require 32 entries and a six-variable function would require 64 entries. It, therefore, becomes inconvenient to prepare the truth table if the number of variables increases beyond four. However, a simple artefact may be adopted. A truth table can have entries only for those terms for which the value of the function is "1", without loss of any information. This is particularly effective when the function has only a small number of terms. Consider the Boolean function with six variables

$$F = A.B.C.D'.E' + A.B'.C.D'.E + A'.B'.C.D.E + A.B'.C'.D.E$$

The truth table will have only four entries rather than 64, and the representation of this function is

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

Truth table is a very effective tool in working with digital circuits, especially when the number of variables in a function is small, less than or equal to five.

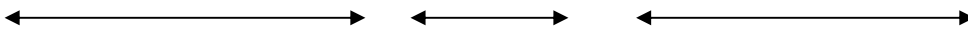
Conversion of English Sentences to Logic Functions

Some of the problems that can be solved using digital circuits are expressed through one or more sentences. For example,

- At the traffic junction the amber light should come on 60 seconds after the red light, and get switched off after 5 seconds.
- If the number of coins put into the vending machine exceed five rupees it should dispense a Thums Up bottle.
- The lift should start moving only if the doors are closed and a floor number is chosen.

These sentences should initially be translated into logic equations. This is done through breaking each sentence into phrases and associating a logic variable with each phrase. As stated earlier many of these phrases will be indicative of actions or directly represent actions. We first mark each action related phrase in the sentence. Then we associate a logic variable with it. Consider the following sentence, which has three phrases:

Anil freaks out with his friends if it is Saturday and he completed his assignments



We will now associate logic variables with each phrase. The words "if" and "and" are not included in any phrase and they show the relationship among the phrases.

$F = 1$ if "Anil freaks out with his friends"; otherwise $F = 0$

$A = 1$ if "it is Saturday"; otherwise $A = 0$

$B = 1$ if "he completed his assignments"; otherwise $B = 0$

F is asserted if A is asserted and B is asserted. The sentence, therefore, can be translated into a logic equation as

$$F = A.B$$

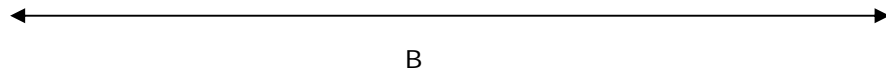
For simple problems it may be possible to directly write the logic function from the word description. In more complex cases it is necessary to properly define the variables and draw a truth-table before the logic function is prepared. Sometimes the given sentences may have some vagueness, in which case clarifications need to be sought from the source of the sentence. Let us consider another sentence with more number of phrases.

Rahul will attend the Networks class if and only if his friend Shaila is attending the class and the topic being covered in class is important from examination point of view or there is no interesting matinee show in the city and the assignment is to be submitted. Let us associate different logic variables with different phrases.

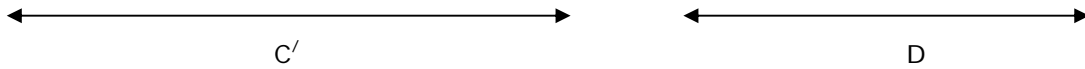
Rahul will attend the Networks class if and only if his friend Shaila is attending the class



and the topic being covered in class is important from examination point of view or



there is no interesting matinee show in the city and the assignment is to be submitted



With the above assigned variables the logic function can be written as

$$F = A.B + C'.D$$

Minterms and Maxterms

A logic function has product terms. Product terms that consist of all the variables of a function are called "canonical product terms", "fundamental product terms" or "minterms". For example the logic term $A.B.C'$ is a minterm in a three variable logic function, but will be a non-minterm in a four variable logic function. Sum terms which contain all the variables of a Boolean function are called "canonical sum terms", "fundamental sum terms" or "maxterms". $(A+B'+C)$ is an example of a maxterm in a three variable logic function.

Consider the Table which lists all the minterms and maxterms of three variables. The minterms are designated as m_0, m_1, \dots, m_7 , and maxterms are designated as M_0, M_1, \dots, M_7 .

Term No.	A	B	C	Minterms	Maxterms
0	0	0	0	$A'B'C' = m_0$	$A + B + C = M_0$
1	0	0	1	$A'B'C = m_1$	$A + B + C' = M_1$
2	0	1	0	$A'BC' = m_2$	$A + B' + C = M_2$
3	0	1	1	$A'BC = m_3$	$A + B' + C' = M_3$
4	1	0	0	$AB'C' = m_4$	$A + B + C = M_4$
5	1	0	1	$AB'C = m_5$	$A + B + C' = M_5$
6	1	1	0	$ABC' = m_6$	$A' + B' + C = M_6$
7	1	1	1	$ABC = m_7$	$A' + B' + C' = M_7$

A logic function can be written as a sum of minterms. Consider F , which is a function of three variables.

$$F = m_0 + m_3 + m_5 + m_6$$

This is equivalent to

$$F = A'B'C' + A'BC + AB'C + ABC'$$

A logic function that is expressed as an OR of several product terms is considered to be in "sum-of-products" or SOP form. If it is expressed as an AND of several sum terms, it is considered to be in "product-of-sums" or POS form. Examples of these two forms are given in the following:

$$F1 = A.B + A.B'.C + A'.B.C \quad (\text{SOP form})$$

$$F2 = (A+B+C') . (A+B'+C') . (A'+B'+C) \quad (\text{POS form})$$

If all the terms in an expression or function are canonical in nature, that is, as minterms in the case of SOP form, and maxterms in the case of POS form, then it is considered to be in canonical form. For example, the function in the equation (1) is not in canonical form. However it can be converted into its canonical form by expanding the term $A.B$ as

$$A.B = A . B . 1 \quad (\text{postulate 2b})$$

$$= A . B . (C + C') \quad (\text{postulate 5a})$$

$$= A . B . C + A . B . C' \quad (\text{postulate 4b})$$

The canonical version of F1 is,

$$F1 = A.B.C + A.B.C' + A.B'.C + A'.B.C$$

The Boolean function F2 is in canonical form, as all the sum terms are in the form of maxterms.

The SOP and POS forms are also referred to as two-level forms. In the SOP form, AND operation is performed on the variables at the first level, and OR operation is performed at the second level on the product terms generated at the first level.

Similarly, in the POS form, OR operation is performed at the first level to generate sum terms, and AND operation is performed at the second level on these sum terms.

In any logical expression, the right hand side of a logic function, there are certain priorities in performing the logical operations.

- NOT (') operation has the highest priority,
- AND (.) has the next priority
- OR (+) has the last priority.

In the expression for F1 the operations are to be performed in the following sequence

- NOT operation on B and A
- AND terms: A.B, A.B'.C, A'.B.C
- OR operation on AB, AB'C and A'BC

However, the order of priority can be modified through using parentheses. It is also common to express logic functions through multi-level expressions using parentheses. A simple example is shown in the following.

$$F1 = A.(B+C') + A'.(C+D)$$

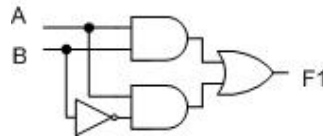
These expressions can be brought into the SOP form by applying the distributive law. More detailed manipulation of algebraic form of logic functions will be explored in another Learning Unit.

Circuit Representation of Logic Functions

Representation of basic Boolean operators through circuits was already presented in the earlier Learning Unit. A logic function can be represented in a circuit form using these circuit symbols. Consider the logic function

$$F1 = A.B + A.B'$$

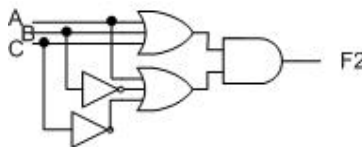
Its circuit form is



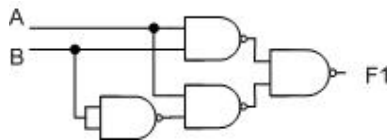
Consider another example of a Boolean function given in POS form.

$$F2 = (A+B+C) . (A+B'+C')$$

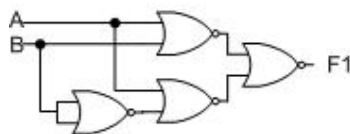
The circuit form of the logical expression F2 is



F1 can also be represented in terms of other functionally complete set of logical operations. NAND is one such functionally complete set. NAND representation of logic expression F2 is



NOR is another functionally complete set. NOR representation of the same function F1 is





Digital Electronics

Module 2: Boolean Algebra and Boolean Operators: Karnaugh Map Method

N.J. Rao

Indian Institute of Science



Karnaugh Map

- Key to minimizing a logic expression is identification of logic adjacency
- Graphic representation of logic expression can facilitate identification of adjacency
- M. Karnaugh introduced (1953) a map to pictorially represent a logical expression.
- It is known as Karnaugh Map abbreviated as K-map.



Karnaugh Map

- K-Map is a pictorial form of the truth-table.
- The inherent structure of the map facilitates systematic minimization
- K-map uses the ability of human perception to identify patterns and relationships when the information is presented graphically



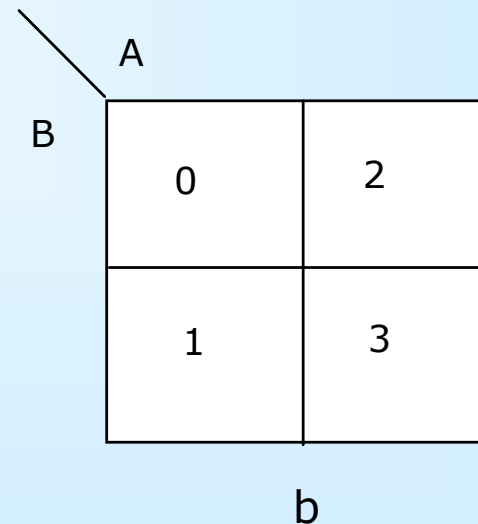
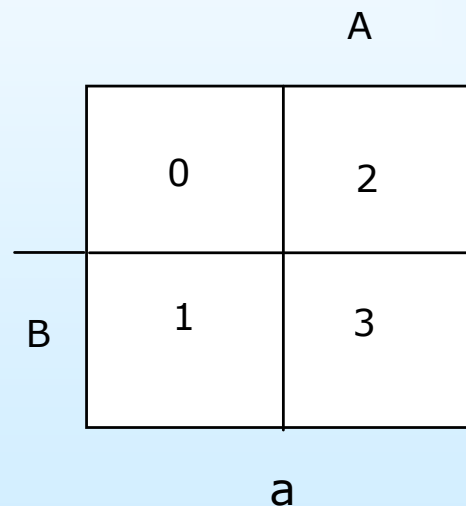
Logical Adjacency

- Two terms are logically adjacent if they differ with respect any one variable.
- ABC is logically adjacent to $A'BC$, $AB'C$ and ABC'
- ABC is not logically adjacent to $A'B'C$, $A'BC'$, $A'B'C'$, $AB'C'$
- The entries that are adjacent in a truth-table are not necessarily logically adjacent
- K-map arranges the logically adjacent terms to be physically adjacent



Representation of a K-map

- There are two popular ways
- K-maps of a two variable function (representation 'a' is preferred)





Cells in a K-Map

The four cells (squares) represent four minterms

Cell 0 \rightarrow minterm m_0

Cell 1 \rightarrow minterm m_1

Cell 2 \rightarrow minterm m_2

Cell 3 \rightarrow minterm m_3

Cell 1 (minterm m_1) is adjacent to cell 0 (minterm m_0) and cell 3 (minterm m_3)

		A
	0	2
B	1	3



Example 1

Consider a two-variable logic function

$$F = A'B + AB'$$

The truth table

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

$A'B$ (01) and AB' (10) are not logically adjacent



Example 1(2)

K-map of F

	F	A
	0	1
B	1	0

The two cells in which "1" is entered are not positionally adjacent and hence are not logically adjacent



Example 2

$$F = A/B + AB$$

K-map

		A
	0	0
B	1	1

Cells in which "1" is entered are positionally adjacent and hence logically adjacent



Three-Variable Karnaugh Map

A three-variable (A, B and C) K-map has $2^3 = 8$ cells

		A		
	0	2	6	4
C	1	3	7	5
		B		

- The numbering followed assures logical adjacency
- Cell 0 (000) and the cell 4 (100) are also adjacent (cyclic adjacency)
- The boundaries on the opposite sides of a K-map are considered to be one common side for the associated two cells



Group of Terms

Adjacency is not merely between two cells

$$\begin{aligned} F &= \Sigma (1, 3, 5, 7) \\ &= A/B/C + A/BC + AB/C + ABC \\ &= A/C(B'+B) + AC(B'+B) \\ &= A/C + AC = (A'+A)C = C \end{aligned}$$

			A	
	0	0	0	0
C	1	1	1	1
			B	



Cyclic Adjacency

A cyclic relationship among the cells 1, 3, 5 and 7 can be observed on the map

In a three-variable map other groups of cells that are cyclically adjacent are

- 0, 1, 3 and 2
- 2, 3, 7 and 6
- 6, 7, 5 and 4
- 4, 5, 1 and 0
- 0, 2, 6 and 4

			A	
	0	2	6	4
C	1	3	7	5
			B	



Four-variable K-Map

		A				
	0	4	12	8		
	1	5	13	9	D	
C	3	7	15	11		
	2	6	14	10		
		B				

Groups with cyclic adjacency:

- 0, 1, 5 and 4
- 1, 5, 7, and 3 etc.
- 0, 1, 3, 2, 10, 11, 9 and 8
- 4, 12, 13, 15, 14, 6, 7 and 5 etc.



Function of four variables

$$F = \Sigma (2, 3, 8, 9, 11, 12)$$

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



5-Variable K-Map

			B	A		B		
	0	4	12	8	16	20	28	24
	1	5	13	9	17	21	29	25
E	3	7	15	11	19	23	31	27
	2	6	14	10	18	22	30	26
			C			C		
								D



5-Variable K-Map (2)

- Simple and cyclic adjacencies are applicable to this map
- They need to be applied separately to the two sections of the map
- Cell 8 and cell 0 are adjacent.
- Taking the assertion and non-assertion of A into account, cell 0 and cell 16 are adjacent.
- Similarly there are 15 more adjacent cell pairs (4-20, 12-28, 8-24, 1-17, 5-21, 13-29, 9-25, 3-19, 7-23, 15-31, 11-27, 2-18, 6-22, 14-30, and 10-26).



5-Variable Function

$$F = A'BC'DE' + A'BCDE' + A'BC'DE + ABCDE + A'BC'D'E + ABC'DE' + ABCDE' + ABC'DE + ABC'D'E + ABC'D'E'$$

				A				
			B			B		
	0	0	0	0	0	0	1	
	0	0	1	1	0	0	1	
	0	0	0	1	0	0	0	D
E	0	0	0	1	0	0	0	1
			C			C		



K-Map Properties

- Karnaugh Map's main feature is to convert logic adjacency into positional adjacency
- Every K-map has 2^n cells corresponding to 2^n minterms
- Combinations are arranged in a special order so as to keep the equivalence of logic adjacency to positional adjacency
- There are three kinds of positional adjacency, namely simple, cyclic and symmetric



Function not in canonical POS form

- If the Boolean function is available in the canonical SOP form, a "1" is entered in all those cells representing the minterms of the expression, and "0" in all the other cells
- If it is not available in the canonical form, convert the non-canonical form into canonical SOP form
- Convert the function into the standard SOP form and directly prepare the K-map.



Example

$$F = A/B + A/B/C' + ABC/D + ABCD'$$

There are four variables in the expression

A/B , containing two variables represents four minterms

$A/B/C'$ represents two minterms

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



Function in POS form

$$F = \Pi (0, 4, 6, 7, 11, 12, 14, 15)$$

0s are filled in the cells represented by the maxterms

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



Function in standard POS form

- Initially convert the standard POS form of the expression into its canonical form, and enter 0s in the cells representing the maxterms
- Enter 0s directly into the map by observing the sum terms one after the other



Example in the POS form

$$F = (A+B+D').(A' +B+C' +D).(B' +C) \quad /$$

Convert into canonical POS form

$$\begin{aligned} F &= (A+B+C+D').(A+B+C' +D')(A' +B+C' +D). (A+B' +C+D). \\ &\quad (A' +B' +C+D).(A+B' +C+D'). (A' +B' +C+D') \\ &= M1 . M3 . M10 . M4 . M12 . M5 . M13 \end{aligned}$$

The cells 1, 3, 4, 5, 10, 12 and 13 can have 0s entered in them while the remaining cells are filled with 1s



Example in the POS form

$$F = (A+B+D').(A'+B+C'+D).(B'+C)$$

- $(A+B+D')$ has A and B asserted and D non-asserted. The two maxterms associated with this sum term are 0001 (M1) and 0011 (M3)
- $(A'+B+C'+D)$ is in canonical form and the maxterm associated with is 1010 (M10)
- Maxterms associated with $(B'+C)$ are 0100 (M4), 1100 (M12), 0101 (M5) and 1101 (M13)

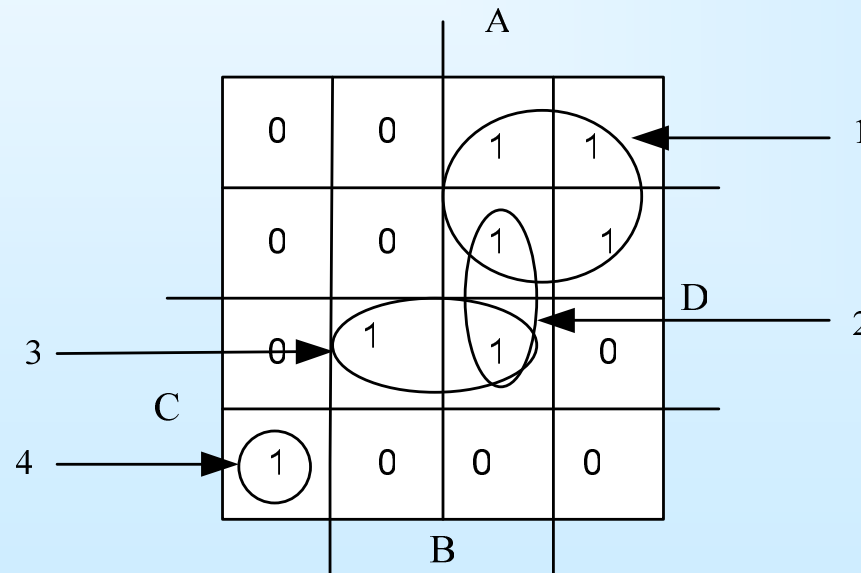
			A	
	1	0	0	1
	0	0	0	1
C	0	1	1	1
	1	1	1	0
		B		



Essential, Prime and Redundant Implicants

The patterns of adjacency of 1-entered cells are referred to as implicants.

An implicant is a group of 2^i ($i = 0, 1, \dots, n$) minterms (1-entered cells) that are logically (positionally) adjacent.





Implicants and Product Terms

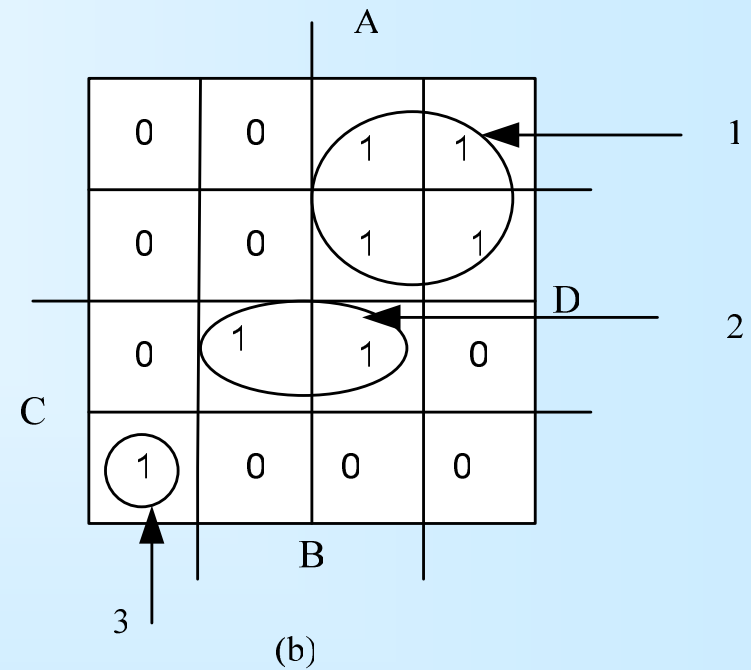
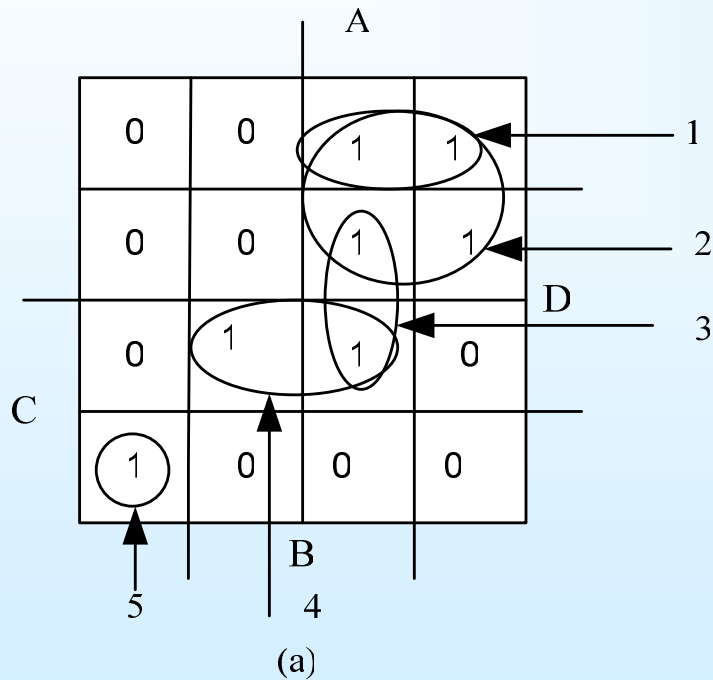
An implicant represents a product term

- Implicant 1 represents the product term AC'
- Implicant 2 represents ABD
- Implicant 3 represents BCD
- Implicant 4 represents $A'B'CD'$

Smaller the number of implicants the smaller the number of product terms in the simplified Boolean expression.



Many ways of identifying implicants





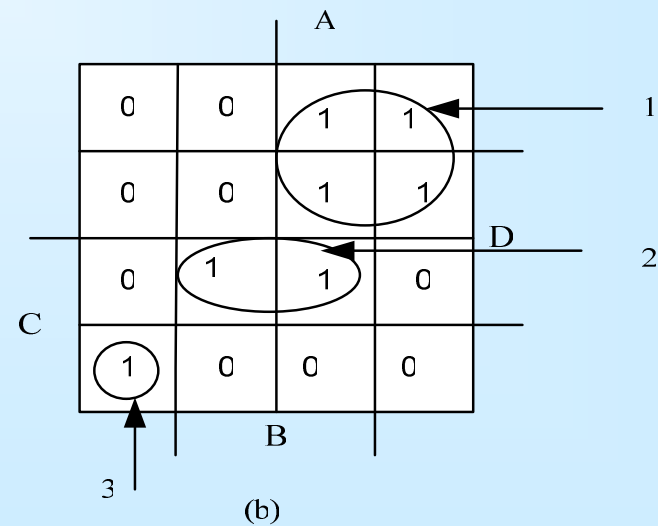
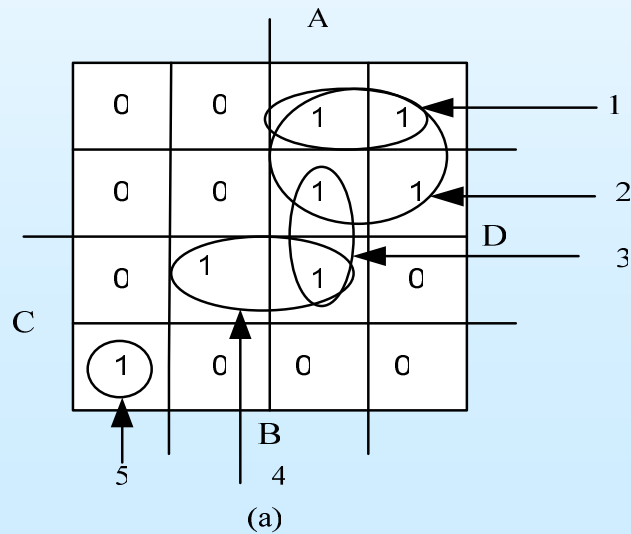
Implicants with properties

- A **prime implicant** is one that is not a subset of any other implicant
- A prime implicant which includes a 1-entered cell that is not included in any other prime implicant is called an **essential prime implicant**.
- A **redundant implicant** is one in which all the 1-entered cells are covered by other implicants



Example

- Implicants 2, 3, 4 and 5 in (a), and 1, 2 and 3 in (b) are prime implicants
- Implicants 2, 4 and 5 in (a), and 1, 2 and 3 in (b) are essential prime implicants
- Implicants 1 and 3 in (a) are redundant implicants
- No redundant implicants in (b)





K-map minimisation

- Find the smallest set of prime implicants that includes all the essential prime implicants
- If there is a choice, the simpler prime implicant should be chosen.



Example 1

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

Implicants

$$X1 = C'D'$$

$$X2 = B'C'$$

$$X3 = BD'$$

$$X4 = ACD$$

$$X5 = AB'C'$$

$$X6 = BCD'$$

$$X7 = A'B'C'$$

$$X8 = BC'D'$$

$$X9 = B'C'D'$$

$$X10 = A'C'D'$$

$$X11 = AC'D'$$

$$X12 = AB'D$$

$$X13 = ABC$$

$$X14 = A'BD'$$

$$X15 = ABD'$$

$$X16 = B'C'D$$

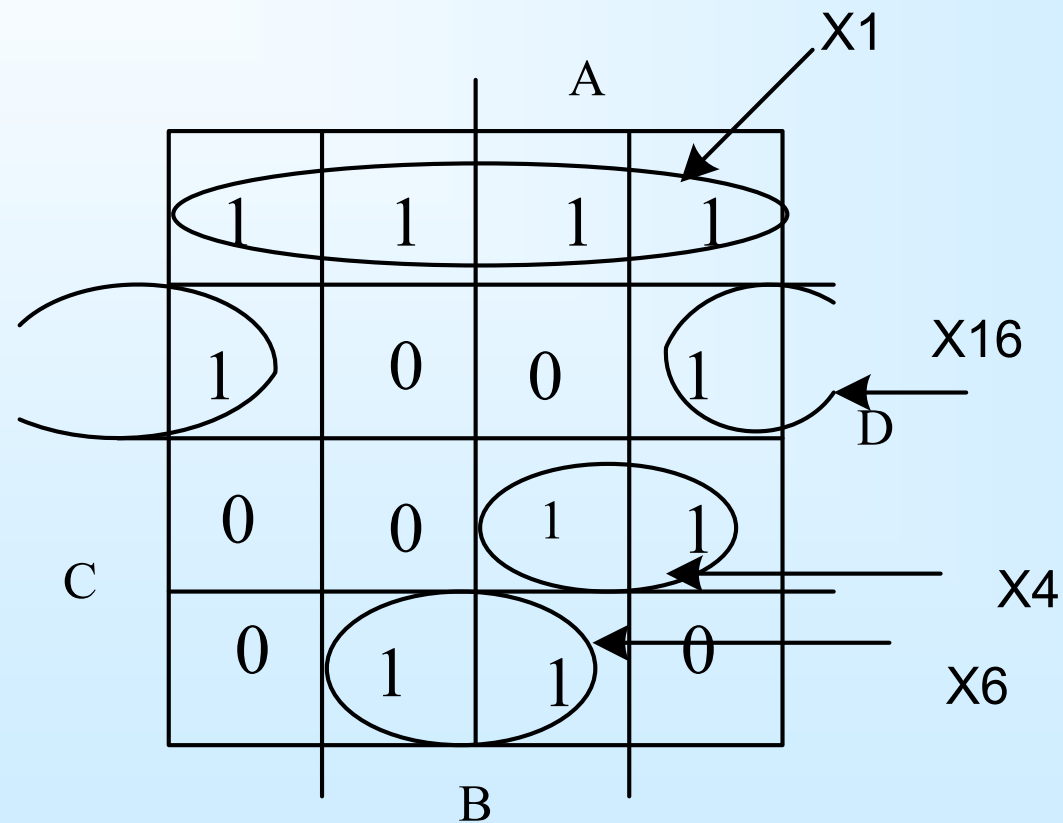
All are not prime implicants

X2, X3 and X4 are essential prime implicants



Combination 1

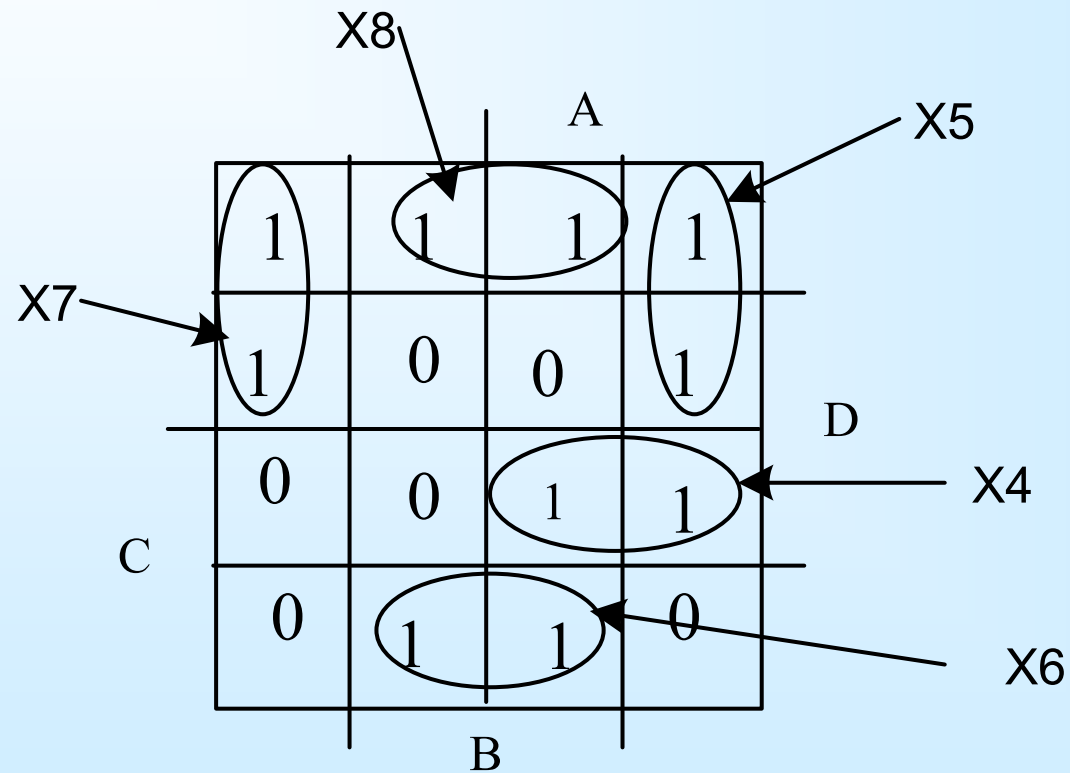
$$F1 = X1 + X4 + X6 + X16$$





Combination 2

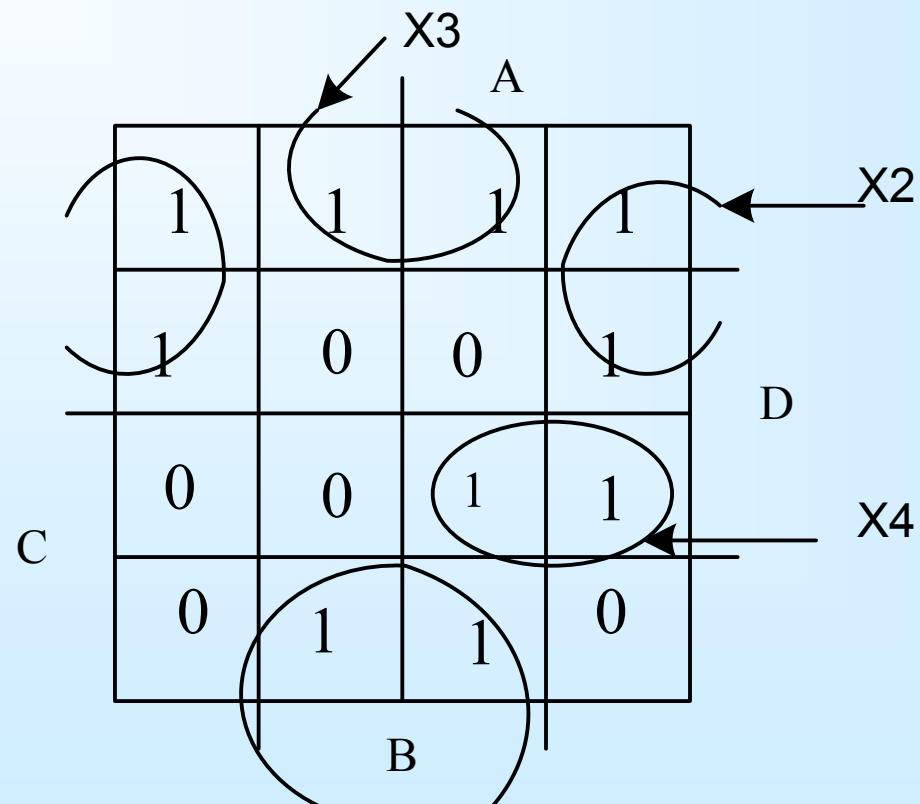
$$F1 = X4 + X5 + X6 + X7 + X8$$





Combination 3

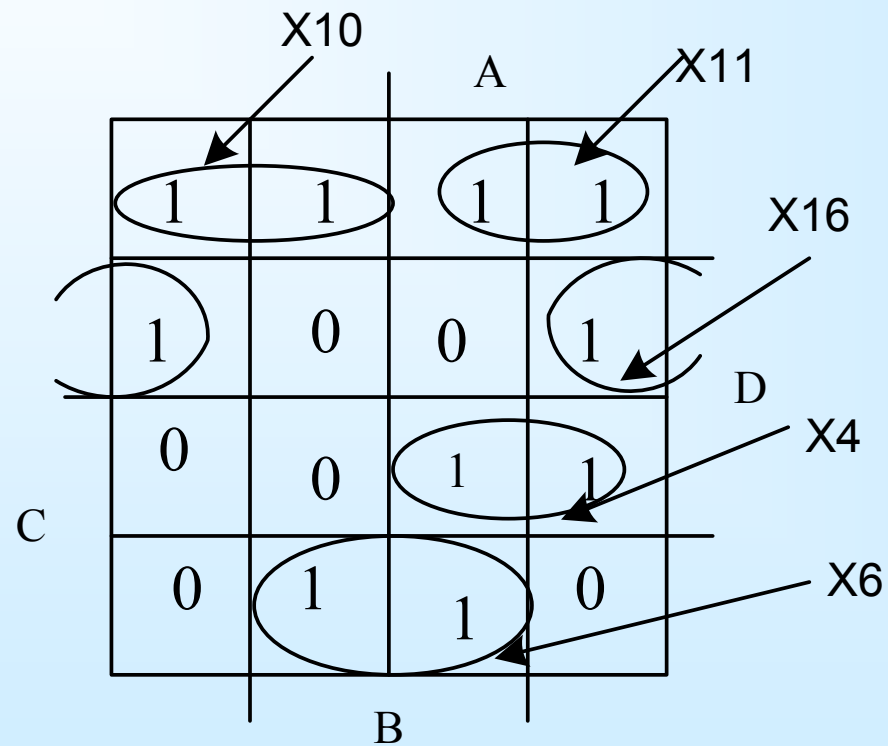
$$F1 = X2 + X3 + X4$$





Combination 4

$$F1 = X10 + X11 + X8 + X4 + X6$$





Example 1: Minimization

Smallest set of prime implicants that includes all the essential prime implicants

$$F1 = X2 + X3 + X4$$



Example

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

Three sets of prime implicants

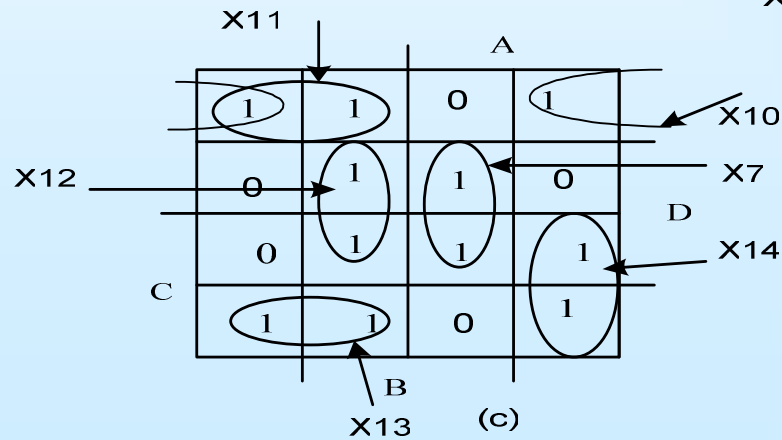
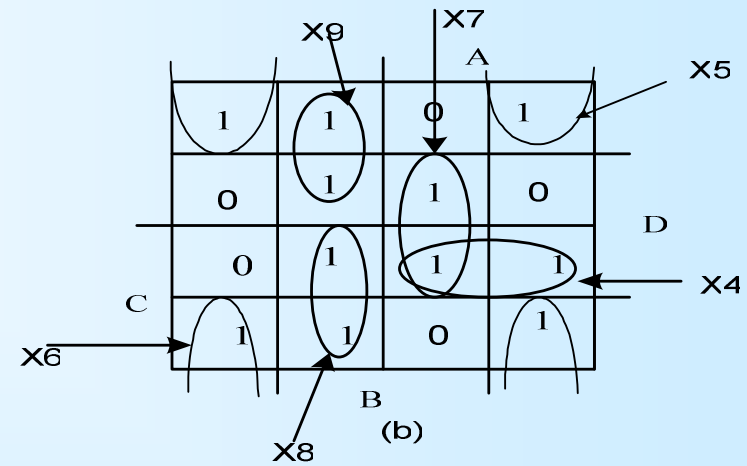
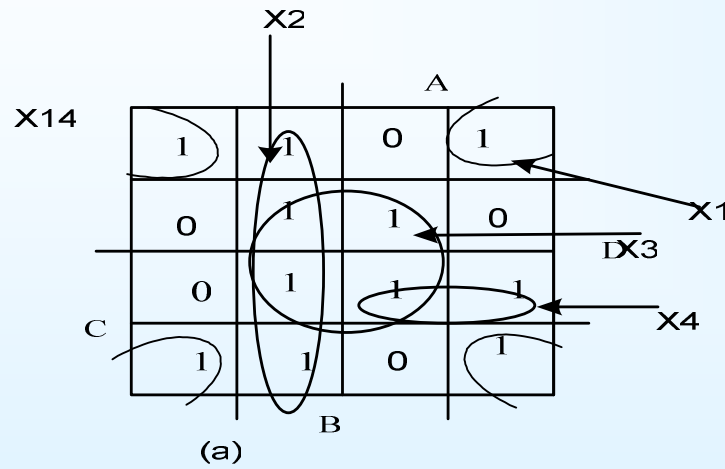
(a) $X1 = B'D'$ $X2 = A'B$ $X3 = BD$ $X4 = ACD$

(b) $X4 = ACD$ $X5 = AB'D'$ $X6 = A'B'D'$ $X7 = ABD$ $X8 = A'BC$
 $X9 = A'BC'$

(c) $X7 = ABD$ $X10 = B'C'D'$ $X11 = A'C'D'$ $X12 = A'BD$
 $X13 = A'C'D'$ $X14 = AB'C$



Example (2)



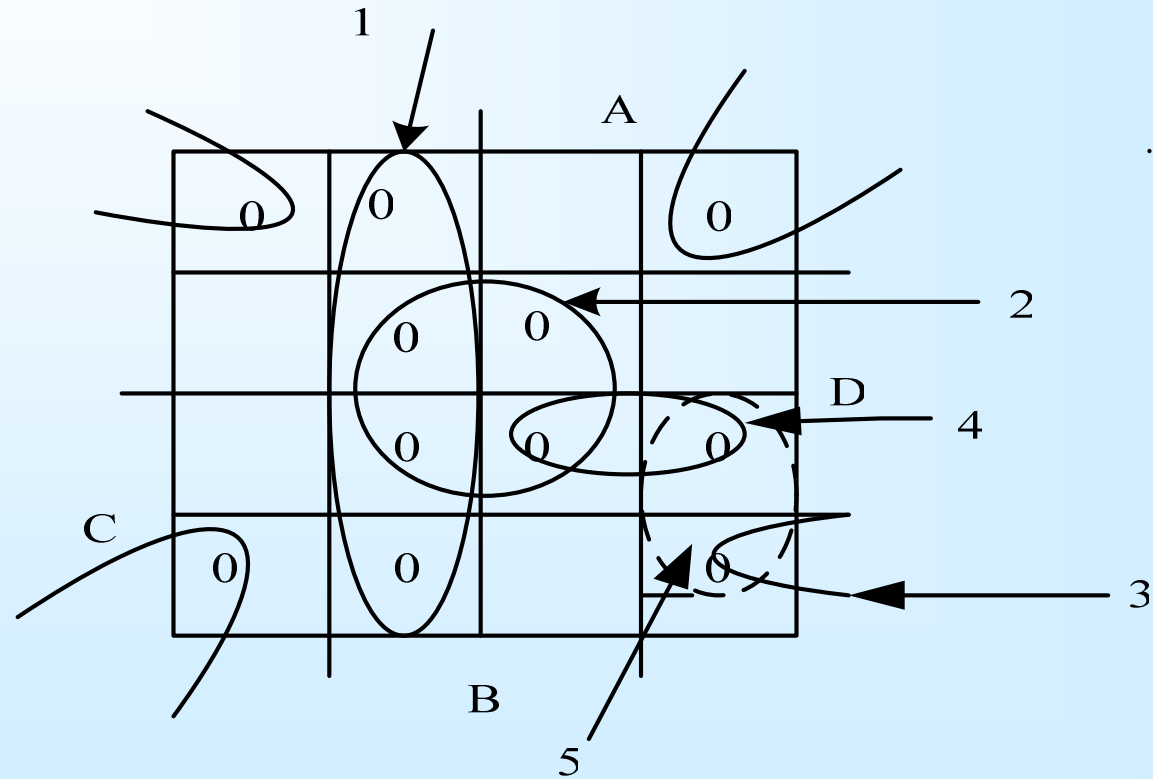


Some simplified expressions

$$\begin{aligned} F &= X1 + X2 + X3 + X4 \\ &= X4 + X6 + X7 + X8 + X9 \\ &= X7 + X10 + X11 + X12 + X13 + X14 \end{aligned}$$



Standard POS form from K- map (Example)





Four implicants are identified

- Implicant 1 and it is represented by $(A + B')$
- Implicant 2 is represented by $(B' + D')$
- Implicant 3 is represented by $(B + D)$
- Implicant 4 is represented by $(A' + C' + D')$

The simplified expression in the POS form is given by;

$$F = (A + B') \cdot (B' + D') \cdot (B + D) \cdot (A' + C' + D')$$

If we choose the implicant 5 instead of 4, the simplified expression

$$F = (A + B') \cdot (B' + D') \cdot (B + D) \cdot (A' + B + C')$$



Minimization procedure

1. Draw the K-map with 2^n cells, where n is the number of variables in a Boolean function.
2. Fill in the K-map with 1s and 0s as per the function given in the algebraic form (SOP or POS) or truth-table form.



Minimization procedure (2)

3. Determine the set of prime implicants that consist of all the essential prime implicants as per the criteria:
 - All the 1-entered or 0-entered cells are covered by a set of implicants, while making the number of cells covered by each implicant as large as possible.
 - Eliminate the redundant implicants.
 - Identify all the essential prime implicants.
 - Whenever there is a choice among the prime implicants select the prime implicant with the smaller number of literals.



Minimization procedure (3)

4. If the final expression is to be generated in SOP form, the prime implicants should be identified by suitably grouping the positionally adjacent 1-entered cells, and converting each of the prime implicant into a product term. The final SOP expression is the OR of all the product terms.



Minimization procedure (4)

5. If the final simplified expression is to be given in the POS form, the prime implicants should be identified by suitably grouping the positionally adjacent 0-entered cells, and converting each of the prime implicant into a sum term. The final POS expression is the AND of all sum terms.



Incompletely specified functions

All Boolean functions are not always completely specified

Consider the BCD decoder,

- Only 10 outputs are decoded from 16 possible input combinations
- The six invalid combinations of the inputs never occur
- We don't-care what the output is for any of these combinations that should never occur
- These don't-care situations can be used advantageously in generating a simpler Boolean expression
- Such don't-care combinations of the variables are represented by an "X" in the appropriate cell of the K-map



Example

The decoder has three inputs A, B and C and an output F

Mode No	Input Code	Output	Description
1	0 0 1	0	Input from keyboard
2	0 1 0	0	Input from mouse
3	0 1 1	0	Input from light-pen
4	1 0 0	1	Output to printer
5	1 0 1	1	Output to plotter



Truth-table and K-map with don't cares

Using the three don't care conditions

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

K-map

		A	
		0	1
C	0	X	0
	1	0	X



SOP and POS forms

$$F = S(4, 5) + d(0, 6, 7)$$

$$F = P(1, 2, 3) \cdot d(0, 6, 7)$$

- The term $d(0, 6, 7)$ represent the don't-care terms.
- Xs can be treated either as 0s or as 1s depending on the convenience

		A		
	0	0	1	1
C	0	0	1	1
		B		

		A		
	0	0	0	1
C	0	0	0	1
		B		

$$F = A$$
$$F = AB'$$



Example

$$F = S(0,1,4,8,10,11,12) + d(2,3,6,9,15)$$

		A			
		0	1	2	3
C	0	1	1	1	1
	1	1	0	0	X
	2	X	0	X	1
	3	X	X	0	1
		B			

The Karnaugh map shows a 4x4 grid with variables A (columns 0-3) and B (rows 0-3). The cells contain values: (0,0)=1, (0,1)=1, (0,2)=1, (0,3)=1, (1,0)=1, (1,1)=0, (1,2)=0, (1,3)=X, (2,0)=X, (2,1)=0, (2,2)=X, (2,3)=1, (3,0)=X, (3,1)=X, (3,2)=0, (3,3)=1. A horizontal oval groups the top row (A=0). A vertical oval groups the rightmost column (B=3). A large curved line groups the leftmost column (B=0) and the rightmost column (B=3).

The simplified expression $F = B' + C'D'$



Multiple functions in same set of variables

$$F1(A,B,C) = \Sigma(0, 3, 4, 5, 6); F2(A,B,C) = \Sigma(1, 2, 4, 6, 7);$$

$$F3(A,B,C) = \Sigma(1, 3, 4, 5, 6)$$

F1

		A	
		1	1
C	B	0	1
		0	1

F2

		A	
		1	1
C	B	1	0
		1	0

F3

		A	
		1	1
C	B	1	1
		0	1

The resultant minimal expressions

$$F1 = B/C/ + AC/ + AB/ + A/BC$$

$$F2 = BC/ + AC/ + AB + A/B/C$$

$$F3 = AC/ + B/C + A/C$$

These functions have nine product terms and twenty one literals



Multiple functions in same set of variables (2)

Minor modifications to these expressions lead to

$$F1 = B/C/ + AC/ + AB/ + A/BC$$

$$F2 = BC/ + AC/ + AB + A/B/C$$

$$F3 = AC/ + AB/ + A/BC + A/B/C$$

This leads to seven product terms and sixteen literals

F1

		A	
		1	0
C	1	1	1
	0	1	1
		B	

F2

		A	
		1	0
C	1	1	1
	0	1	0
		B	

F3

		A	
		1	0
C	1	1	1
	0	1	0
		B	

Karnaugh-Map

The expressions for a logical function (right hand side of a function) can be very long and have many terms and each term many literals. Such logical expressions can be simplified using different properties of Boolean algebra. This method of minimization requires our ability to identify the patterns among the terms. These patterns should conform to one of the four laws of Boolean algebra. However, it is not always very convenient to identify such patterns in a given expression. If we can represent the same logic function in a graphic form that allows us to identify the inherent patterns, then the simplification can be performed more conveniently.

Karnaugh Map is one such graphic representation of a Boolean function in the form of a map. Karnaugh Map is due to M. Karnaugh, who introduced (1953) his version of the map in his paper "The Map Method for Synthesis of Combinational Logic Circuits". Karnaugh Map, abbreviated as K-map, is actually pictorial form of the truth-table. This Learning Unit is devoted to the Karnaugh map and its method of simplification of logic functions.

Karnaugh map of a Boolean function is graphical arrangement of minterms, for which the function is asserted.

We can begin by considering a two-variable logic function,

$$F = A'B + AB$$

Any two-variable function has $2^2 = 4$ minterms. The truth table of this function is

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

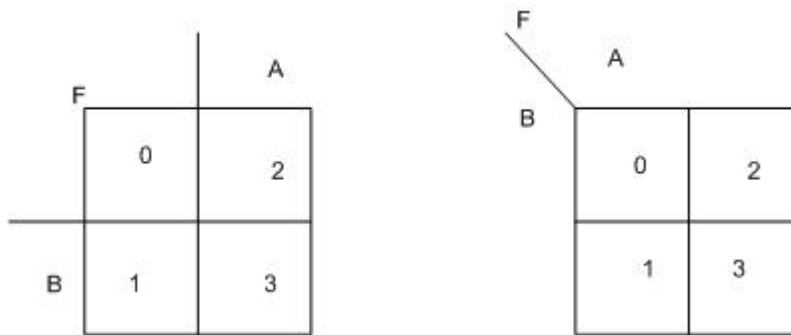
It can be seen that the values of the variables are arranged in the ascending order (in the numerical decimal sense).

We consider that any two terms are logically adjacent if they differ only with respect any one variable.

For example ABC is logically adjacent to $A'BC$, $AB'C$ and ABC' . But it is not logically adjacent to $A'B'C$, $A'BC'$, $A'B'C'$, $AB'C'$.

The entries in the truth-table that are positionally adjacent are not logically adjacent. For example $A'B$ (01) and AB' (10) are positionally adjacent but are not logically adjacent. The combination of 00 is logically adjacent to 01 and 10. Similarly 11 is adjacent to 10 and 01. Karnaugh map is a method of arranging the truth-table entries so that the logically adjacent terms are also physically adjacent.

The K-map of a two-variable function is shown in the figure. There are two popular ways of representing the map, both of which are shown in the figure. The representation, where the variable above the column or on the side of the row in which it is asserted, will be followed in this and the associated units.



- There are four cells (squares) in this map.
- The cells labelled as 0, 1, 2 and 3 represent the four minterms m_0 , m_1 , m_2 and m_3 .
- The numbering of the cells is chosen to ensure that the logically adjacent minterms are positionally adjacent.
- Cell 1 is adjacent to cell 0 and cell 3, indicating the minterm m_1 (01) is logically adjacent to the minterm m_0 (00) and the minterm m_3 (11).
- The second column, above which the variable A is indicated, has the cells 2 and 3 representing the minterms m_2 and m_3 . The variable A is asserted in these two minterms.

Let us define the concept of position adjacency. Position adjacency means two adjacent cells sharing one side. Such an adjacency is called simple adjacency. Cell 0 is positionally adjacent to cell 1 and cell 2, because cell 0 shares one side with each of them. Similarly, cell 1 is positionally adjacent to cell 0 and cell 3, as cell 2 is adjacent to cell 0 and cell 3, and cell 3 is adjacent to cell 1 and cell 2.

There are other kinds of positional adjacencies, which become relevant when the number of variables is more than 3. We will explore them at a later time.

The main feature of the K-map is that by merely looking at the position of a cell, it is possible to find immediately all the logically adjacent combinations in a function.

The function $F = (A'B + AB)$ can now be incorporated into the K-map by entering "1" in cells represented by the minterms for which the function is asserted. A "0" is entered in all other cells. K-map for the function F is

	F		A
		0	1
B		1	0

You will notice that the two cells in which "1" is entered are not positionally adjacent. Therefore, they are not logically adjacent.

Consider another function of two variables.

$$F = A'B + AB$$

The K-map for this function is

	F		A
		0	0
B		1	1

You will notice that the cells in which "1" is entered are positionally adjacent and hence are logically adjacent.

Three-Variable Karnaugh Map:

K-map for three variables will have $2^3 = 8$ cells as shown in the figure.

				A
	0	2	6	4
C	1	3	7	5
				B

The cells are labelled 0,1,...,7, which stand for combinations 000, 001,...,111 respectively. Notice that cells in two columns are associated with assertion of A, two columns with the assertion of B and one row with the assertion of C.

Let us consider the logic adjacency and position adjacency in the map.

- Cell 7 (111) is adjacent to the cells 3 (011), 5 (101) and 6 (110).
- Cell 2 (010) is adjacent to the cell 0 (000), cell 6 (110) and cell 3 (011).
- We know from logical adjacency the cell 0 (000) and the cell 4 (100) should also be adjacent. But we do not find them positionally adjacent. Therefore, a new adjacency called "cyclic adjacency" is defined to bring the boundaries of a row or a column adjacent to each other. In a three-variable map cells 4 (100) and 0 (000), and cells 1 (001) and 5 (101) are adjacent. The boundaries on the opposite sides of a K-map are considered to be one common side for the associated two cells.

Adjacency is not merely between two cells. Consider the following function:

$$\begin{aligned}
 F &= \Sigma (1, 3, 5, 7) \\
 &= m_1 + m_3 + m_5 + m_7 \\
 &= A'B'C + A'BC + AB'C + ABC \\
 &= A'C(B'+B) + AC(B'+B) \\
 &= A'C + AC \\
 &= (A'+A)C \\
 &= C
 \end{aligned}$$

The K-map of the function F is

	A			
	0	0	0	0
c	1	1	1	1
				B

It is shown clearly that although there is no logic adjacency between some pairs of the terms, we are able to simplify a group of terms. For example $A'B'C$, ABC , $A'BC$ and $AB'C$ are simplified to result in an expression "C". A cyclic relationship among the cells 1, 3, 5 and 7 can be observed on the map in the form $1 \rightarrow 3 \rightarrow 7 \rightarrow 5 \rightarrow 1$ (" \rightarrow " indicating "adjacent to"). When a group of cells, always 2^i ($i \leq n$) in number,

are adjacent to one another in a sequential manner those cells are considered be cyclically adjacent.

Other groups of cells with 'cyclic adjacency'

- 0, 1, 3 and 2
- 2, 3, 7 and 6
- 6, 7, 5 and 4
- 4, 5, 1 and 0
- 0, 2, 6 and 4

So far we noticed two kinds of positional adjacencies:

- Simple adjacency
- Cyclic adjacency (It has two cases, one is between two cells, and the other among a group of 2^i cells)

Four-variable Karnaugh Map: A four-variable (A, B, C and D) K-map will have $2^4 = 16$ cells.

		A		
	0	4	12	8
	1	5	13	9
C	3	7	15	11
	2	6	14	10
		B		
				D

These cells are labelled 0, 1, ..., 15, which stand for combinations 0000, 0001, ..., 1111 respectively. Notice that the two sets of columns are associated with assertion of A and B, and two sets of rows are associated with the assertion of C and D.

We will be able to observe both simple and cyclic adjacencies in a four-variable map also. 4, 8 and 16 cells can form groups with cyclic adjacency. Some examples of such groups are

- 0, 1, 5 and 4
- 0, 1, 3 and 2
- 10, 11, 9 and 8

- 14, 12,13 and15
- 14, 6, 7 and 15
- 3, 7, 15, 11, 10, 14, 6 and 2

Consider a function of four variables

$$F = \Sigma (2, 3, 8, 9, 11, 12)$$

The K-map of this function is

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

Five-variable Karnaugh Map: Karnaugh map for five variables

		A							
		B		B					
		0	4	12	8	16	20	28	24
		1	5	13	9	17	21	29	25
		3	7	15	11	19	23	31	27
		2	6	14	10	18	22	30	26
		C		C					
						D			
		E							

- It has $2^5 = 32$ cells labelled as 0,1, 2 ...,31, corresponding to the 32 combinations from 00000 to 11111.
- The map is divided vertically into two symmetrical parts. Variable A is not-asserted on the left side, and is asserted on the right side. The two parts of the map, except for the assertion or non-assertion of the variable A are identical with respect to the remaining four variables B, C, D and E.

- Simple and cyclic adjacencies are applicable to this map, but they need to be applied separately to the two sections of the map. For example cell 8 and cell 0 are adjacent. The largest number of cells coming under cyclic adjacency can go up to $2^5 = 32$.
- Another type of adjacency, called 'symmetric adjacency', exists because of the division of the map into two symmetrical sections. Taking the assertion and non-assertion of A into account, we find that cell 0 and cell 16 are adjacent. Similarly there are 15 more adjacent cell pairs (4-20, 12-28, 8-24, 1-17, 5-21, 13-29, 9-25, 3-19, 7-23, 15-31, 11-27, 2-18, 6-22, 14-30, and 10-26).

Consider a function of five-variable

$$F = A'BC'DE' + A'BCDE' + A'BC'DE + ABCDE + A'BC'D'E + ABC'DE' + ABCDE' + ABC'DE + ABC'D'E + ABC'D'E'$$

		B			A		B	
	0	0	0	0	0	0	0	1
	0	0	0	1	0	0	1	1
E	0	0	0	1	0	0	0	1
	0	0	0	1	0	0	0	1
		C			C			D

From the study of two-, three-, four- and five-variable Karnaugh maps, we can summarise the following properties:

1. Every Karnaugh map has 2^n cells corresponding to 2^n minterms.
2. The main feature of a Karnaugh Map is to convert logic adjacency into positional adjacency.
3. There are three kinds of positional adjacency, namely simple, cyclic and symmetric.

We have already seen how a K-map can be prepared provided the Boolean function is available in the canonical SOP form.

A "1" is entered in all those cells representing the minterms of the expression, and "0" in all the other cells.

However, the Boolean functions are not always available to us in the canonical form. One method is to convert the non-canonical form into canonical SOP form and prepare the K-map. The other method is to convert the function into the standard SOP form and directly prepare the K-map.

Consider the function

$$F = A'B + A'B'C' + ABC'D + ABCD'$$

We notice that there are four variables in the expression. The first term, $A'B$, containing two variables actually represents four minterms, and the term $A'B'C'$ represents two minterms. The K-map for this function is

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

Notice that the second column represents $A'B$, and similarly $A'B'C'$ represents the two top cells in the first column. With a little practice it is always possible to fill the K-map with 1s representing a function given in the standard SOP form.

Boolean functions in POS form

Boolean functions, sometimes, are also available in POS form. Let us assume that the function is available in the canonical POS form. Consider an example of such a function

$$F = \Pi (0, 4, 6, 7, 11, 12, 14, 15)$$

In preparing the K-map for the function given in POS form, 0s are filled in the cells represented by the maxterms. The K-map of the above function is

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

Sometimes the function may be given in the standard POS form. In such situations we can initially convert the standard POS form of the expression into its canonical form, and enter 0s in the cells representing the maxterms. Another procedure is to enter 0s directly into the map by observing the sum terms one after the other.

Consider an example of a Boolean function given in the POS form.

$$F = (A+B+D') \cdot (A'+B+C'+D) \cdot (B'+C)$$

This may be converted into its canonical form as

$$\begin{aligned} F &= (A+B+C+D') \cdot (A+B+C'+D') \cdot (A'+B+C'+D) \cdot (A+B'+C+D) \cdot (A'+B'+C+D) \cdot \\ &\quad (A+B'+C+D') \cdot (A'+B'+C+D') \\ &= M_1 \cdot M_3 \cdot M_{10} \cdot M_4 \cdot M_{12} \cdot M_5 \cdot M_{13} \end{aligned}$$

The cells 1, 3, 4, 5, 10, 12 and 13 can have 0s entered in them while the remaining cells are filled with 1s.

The second method is through direct observation. To determine the maxterms associated with a sum term we follow the procedure of associating a 0 with those variables which appear in their asserted form, and a 1 with the variables that appear in their non-asserted form. For example the first term $(A+B+D')$ has A and B asserted and D non-asserted. Therefore the two maxterms associated with this sum term are 0001 (M_1) and 0011 (M_3). The second term is in its canonical form and the maxterm associated with is 1010 (M_{10}). Similarly the maxterms associated with the third sum term are 0100 (M_4), 1100 (M_{12}), 0101 (M_5) and 1101 (M_{13}). The resultant K-map is

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

We learnt in this Learning Unit

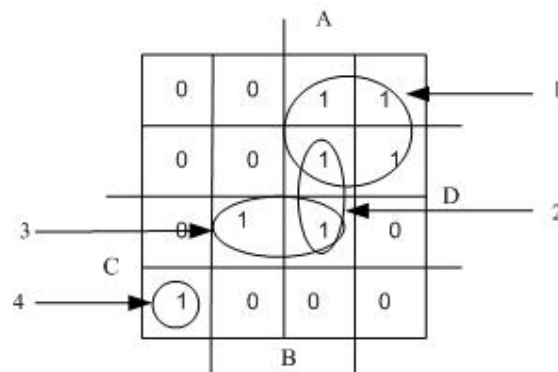
- The logic adjacency is captured as positional adjacency in a Karnaugh Map
- How to translate logic expressions given in SOP or POS forms into K-maps
- There are three types of logical adjacency, namely, simple, cyclic and symmetric adjacencies

Minimization with Karnaugh Map

Implicants: A Karnaugh map not only includes all the minterms that represent a Boolean function, but also arranges the logically adjacent terms in positionally adjacent cells. As the information is pictorial in nature, it becomes easier to identify any patterns (relations) that exist among the 1-entered cells (minterms). These patterns or relations are referred to as implicants.

Definition 1: An implicant is a group of 2^i ($i = 0, 1, \dots, n$) minterms (1-entered cells) that are logically (positionally) adjacent.

A study of implicants enables us to use the K-map effectively for simplifying a Boolean function. Consider the K-map



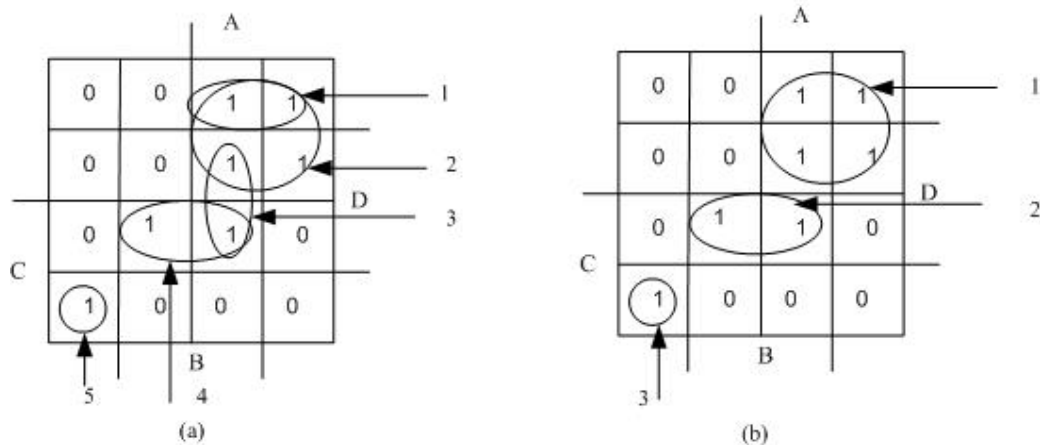
- There are four implicants: 1, 2, 3 and 4.
- The implicant 4 is a single cell implicant. A single cell implicant is a 1-entered cell that is not positionally adjacent to any of the other cells in map.
- The four implicants account for all groupings of 1-entered cells. This also means that the four implicants describe the Boolean function completely.

An implicant represents a product term, with the number of variables appearing in the term inversely proportional to the number of 1-entered cells it represents.

- Implicant 1 in the figure represents the product term AC'
- Implicant 2 represents ABD
- Implicant 3 represents BCD
- Implicant 4 represents $A'B'CD'$

The smaller the number of implicants, and the larger the number of cells that each implicant represents, the smaller the number of product terms in the simplified Boolean expression.

In this example we notice that there are different ways of identifying the implicants.



Five implicants are identified in the figure (a) and three implicants in the figure (b) for the same K-map (Boolean function). It is then necessary to have a procedure to identify the minimum number of implicants to represent a Boolean function.

We identify three types of implicants: "prime implicant", "essential implicant" and "redundant implicant".

A **prime implicant** is one that is not a subset of any one of the other implicant.

An **essential prime implicant** is a prime implicant which includes a 1-entered cell that is not included in any other prime implicant.

A **redundant implicant** is one in which all the 1-entered cells are covered by other implicants. A redundant implicant represents a redundant term in an expression.

Implicants 2, 3, 4 and 5 in the figure (a), and 1, 2 and 3 in the figure (b) are prime implicants.

Implicants 2, 4 and 5 in the figure (a), and 1, 2 and 3 in the figure (b) are essential prime implicants.

Implicants 1 and 3 in the figure (a) are redundant implicants.

Figure (b) does not have any redundant implicants.

Now the method of K-map minimisation can be stated as

"find the smallest set of prime implicants that includes all the essential prime implicants accounting for all the 1-entered cells of the K-map".

If there is a choice, the simpler prime implicant should be chosen. The minimisation procedure is best understood through examples.

Example 1: Find the minimised expression for the function given by the K-map in the figure.

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

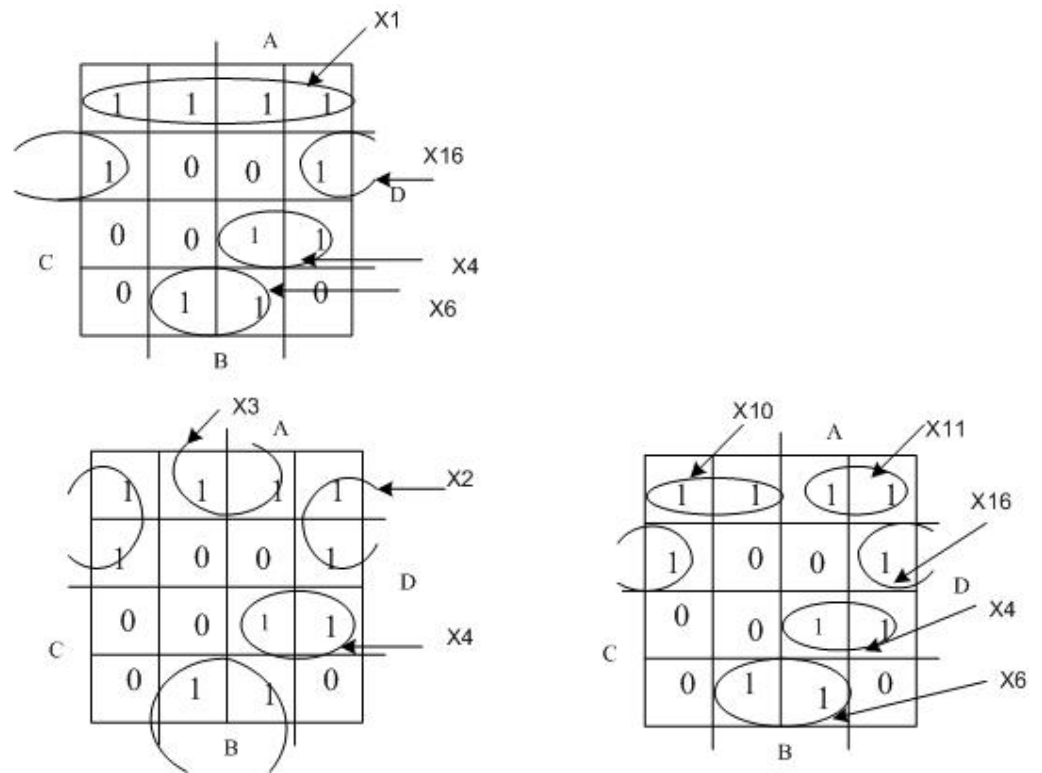
Fifteen implicants of the K-map are:

$$\begin{aligned}
 X1 &= C'D' & X2 &= B'C' & X3 &= BD' & X4 &= ACD \\
 X5 &= AB'C' & X6 &= BCD' & X7 &= A'B'C' & X8 &= BC'D' \\
 X9 &= B'C'D' & X10 &= A'C'D' & X11 &= AC'D' & X12 &= AB'D \\
 X13 &= ABC & X14 &= A'BD' & X15 &= ABD' & X16 &= B'C'D
 \end{aligned}$$

Obviously all these implicants are not prime implicants and there are several redundant implicants. Several combinations of prime implicants can be worked out to represent the function. Some of them are listed in the following.

$$\begin{aligned}
 F1 &= X1 + X4 + X6 + X16 \\
 &= X4 + X5 + X6 + X7 + X8 \\
 &= X2 + X3 + X4 \\
 &= X10 + X11 + X8 + X4 + X6
 \end{aligned}$$

The k-maps with these four combinations are



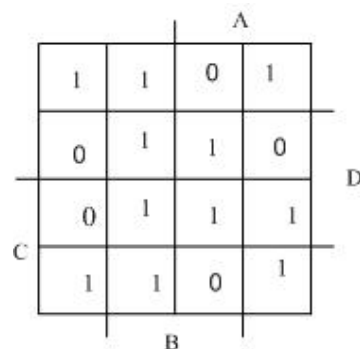
Among the prime implicants listed in the figure there are three implicants X1, X2 and X3 that group four 1-entered cells. Selecting the smallest number of implicants we obtain the simplified expression as:

$$F = X2 + X3 + X4$$

$$= B'C' + BD' + ACD$$

It may be noticed that X2, X3 and X4 are essential prime implicants.

Example 2: Minimise the Boolean function represented by the K-map shown in the figure.

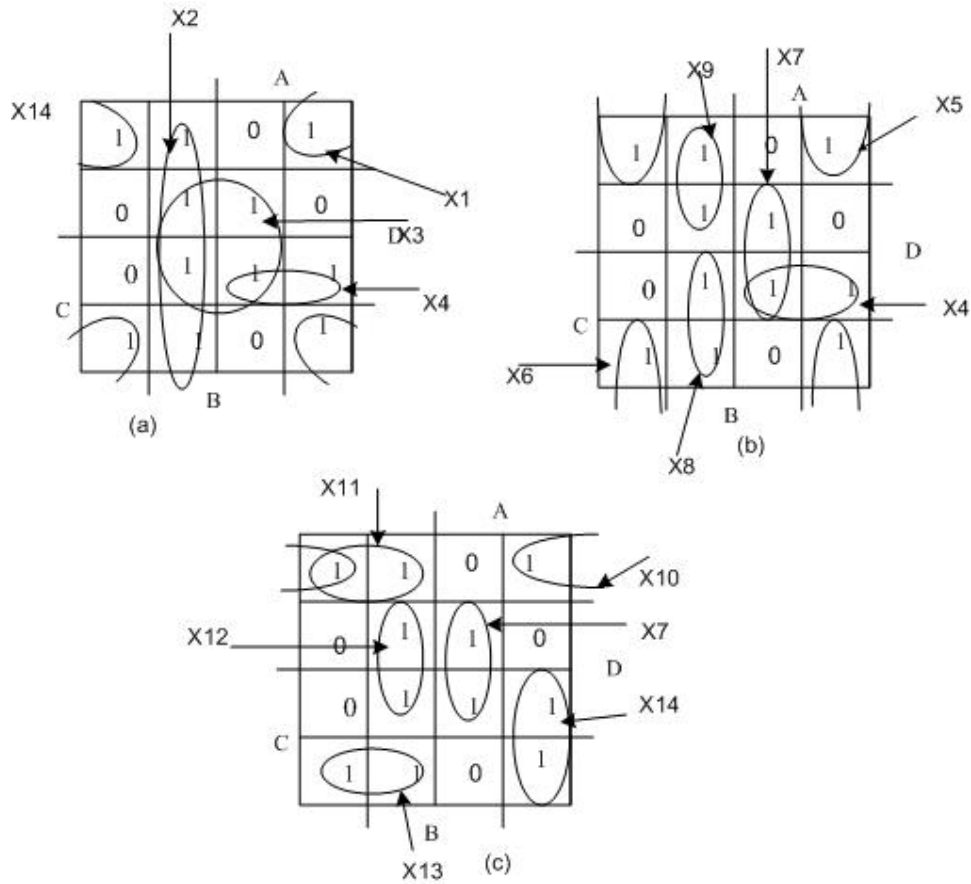


Three sets of prime implicants are:

- (a) $X1 = B'D'$ $X2 = A'B$ $X3 = BD$ $X4 = ACD$
- (b) $X4 = ACD$ $X5 = AB'D'$ $X6 = A'B'D'$ $X7 = ABD$
- $X8 = A'BC$ $X9 = A'BC'$

$$(c) \quad X7 = ABD \quad X10 = B'C'D' \quad X11 = A'C'D' \quad X12 = A'BD$$

$$X13 = A'C'D' \quad X14 = AB'C$$



Some of the simplified expressions are shown in the following:

$$F = X1 + X2 + X3 + X4$$

$$= X4 + X6 + X7 + X8 + X9$$

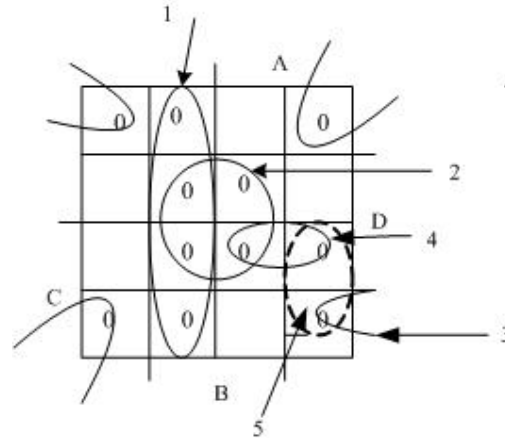
$$= X7 + X10 + X11 + X12 + X13 + X14$$

Standard POS form from Karnaugh Map

As mentioned earlier, POS form always follows some kind of duality, yet different from the principle of duality. The implicants are defined as groups of sums or maxterms which in the map representation are the positionally adjacent 0-entered cells rather than 1-entered cells as in the SOP case. When converting an implicant covering some 0-entered cells into a sum, a variable appears in complemented form in the sum if it is always 1 in value in the combinations corresponding to that implicant, a variable appears in uncomplemented form if it is always 0 in value, and the variable does not appear at all if it changes its values in the combinations corresponding to the implicant. We obtain a standard POS form of expression from the map representation by ANDing all the sums converted from implicants.

Example 3: Consider a Boolean function in the POS form represented in the K-map shown

in the figure



- Initially four implicants are identified (1, 2, 3 and 4).
- Implicant 1: B is asserted and A is not-asserted in all the cells of implicant 1, where as the variables C and D change their values from 0 to 1. It is represented by the sum term $(A + B')$.
- Implicant 2: It is represented by the sum term $(B' + D')$.
- Implicant 3: It is represented by $(B + D)$.
- Implicant 4: It is represented by $(A' + C' + D')$.

The simplified expression in the POS form is given by;

$$F = (A + B') \cdot (B' + D') \cdot (B + D) \cdot (A' + C' + D')$$

If we choose the implicant 5 (shown by the dotted line in the figure 19) instead of 4, the simplified expression gets modified as:

$$F = (A + B') \cdot (B' + D') \cdot (B + D) \cdot (A' + B + C')$$

We may summarise the procedure for minimization of a Boolean function through a K-map as follows:

1. Draw the K-map with 2^n cells, where n is the number of variables in a Boolean function.
2. Fill in the K-map with 1s and 0s as per the function given in the algebraic form (SOP or POS) or truth-table form.
3. Determine the set of prime implicants that consist of all the essential prime implicants as per the following criteria:
 - All the 1-entered or 0-entered cells are covered by the set of implicants, while making the number of cells covered by each implicant as large as possible.
 - Eliminate the redundant implicants.
 - Identify all the essential prime implicants.
 - Whenever there is a choice among the prime implicants select the prime

implicant with the smaller number of literals.

4. If the final expression is to be generated in SOP form, the prime implicants should be identified by suitably grouping the positionally adjacent 1-entered cells, and converting each of the prime implicant into a product term. The final SOP expression is the OR of the identified product terms.
5. If the final simplified expression is to be given in the POS form, the prime implicants should be identified by suitably grouping the positionally adjacent 0-entered cells, and converting each of the prime implicant into a sum term. The final POS expression is the AND of the identified sum terms.

Simplification of Incompletely Specified Functions

So far we assumed that the Boolean functions are always completely specified, which means a given function assumes strictly a specific value, 1 or 0, for each of its 2^n input combinations. This, however, is not always the case.

Consider the example is the BCD decoders

- The ten outputs are decoded from sixteen possible input combinations produced by four inputs representing BCD codes.
- An encoding scheme chooses ten valid codes.
- Irrespective of the encoding scheme there are always six combinations of the inputs that would be considered as invalid codes.
- If the input unit to the BCD decoder works in a functionally correct way, then the six invalid combinations of the inputs should never occur.

In such a case, it does not matter what the output of the decoder is for these six combinations. As we do not mind what the values of the outputs are in such situations, we call them "don't-care" situations. These don't-care situations can be used advantageously in generating a simpler Boolean expression than without taking that advantage.

Such don't-care combinations of the variables are represented by an "X" in the appropriate cell of the K-map.

Example: This example shows how an incompletely specified function can be represented in truth-table, Karnaugh map and canonical forms.

The decoder has three inputs A, B and C representing three bit codes and an output F. Out of the $2^3 = 8$ possible combinations of the inputs, only five are described and hence constitute the valid codes. F is not specified for the remaining three input codes, namely, 000, 110 and 111.

Functional description of a decoder

Mode No	Input Code	Output	Description
1	0 0 1	0	Input from keyboard
2	0 1 0	0	Input from mouse
3	0 1 1	0	Input from light-pen
4	1 0 0	1	Output to printer
5	1 0 1	1	Output to plotter

Treating these three combinations as the don't-care conditions, the truth-table may be written as:

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

The K-map for this function is

		A	
	X	0	X
C	0	0	X
		B	

The function in the SOP and POS forms may be written as

$$F = \Sigma(4, 5) + d(0, 6, 7)$$

$$F = \Pi(1, 2, 3) \cdot d(0, 6, 7)$$

The term $d(0, 6, 7)$ represents the collection of don't-care terms.

The don't-cares bring some advantages to the simplification of Boolean functions. The Xs can be treated either as 0s or as 1s depending on the convenience. For example the above map can be redrawn in two different ways as

		A	
	0	0	1
C	0	0	1
		B	

		A	
	0	0	0
C	0	0	0
		B	

The simplification can be done, therefore, in two different ways. The resulting expressions

for the function F are:

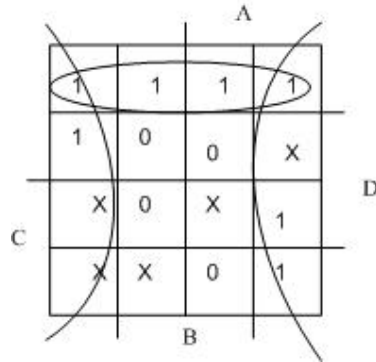
$$F = A$$

$$F = AB'$$

We can generate a simpler expression for a given function by utilising some of the don't-care conditions as 1s.

Example: Simplify $F = \Sigma (0,1,4,8,10,11,12) + d(2,3,6,9,15)$

The K-map of this function is



The simplified expression taking the full advantage of the don't cares is,

$$F = B' + C'D'$$

Simplification of several functions of the same set of variables

As there could be several product terms that could be made common to more than one function, special attention needs to be paid to the simplification process.

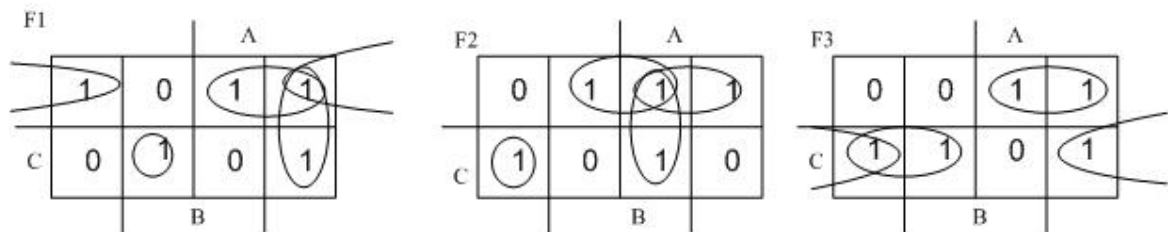
Example: Consider the following set of functions defined on the same set of variables:

$$F1 (A, B, C) = \Sigma (0, 3, 4, 5, 6)$$

$$F2 (A, B, C) = \Sigma (1, 2, 4, 6, 7)$$

$$F3 (A, B, C) = \Sigma (1, 3, 4, 5, 6)$$

Let us first consider the simplification process independently for each of the functions. The K-maps for the three functions and the groupings are



The resultant minimal expressions are:

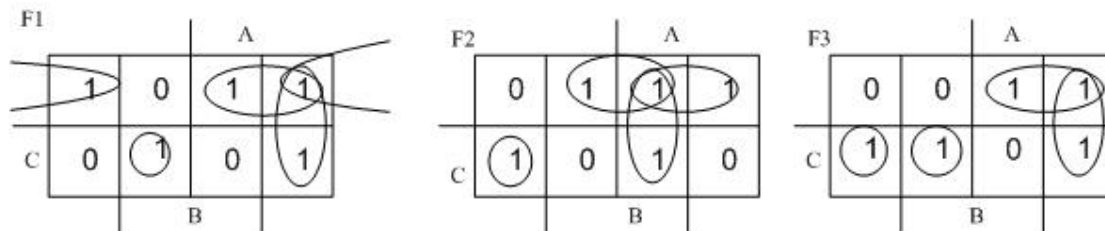
$$F1 = B'C' + AC' + AB' + A'BC$$

$$F2 = BC' + AC' + AB + A'B'C$$

$$F3 = AC' + B'C + A'C$$

These three functions have nine product terms and twenty one literals.

If the groupings can be done to increase the number of product terms that can be shared among the three functions, a more cost effective realisation of these functions can be achieved. One may consider, at least as a first approximation, cost of realising a function is proportional to the number of product terms and the total number of literals present in the expression. Consider the minimisation shown in the figure



The resultant minimal expressions are;

$$F1 = B'C' + AC' + AB' + A'BC$$

$$F2 = BC' + AC' + AB + A'B'C$$

$$F3 = AC' + AB' + A'BC + A'B'C$$

This simplification leads to seven product terms and sixteen literals.



Digital Electronics

Module 2: Quine-McCluskey Method

N.J. Rao

Indian Institute of Science



Motivation

- Map methods unsuitable if the number of variables is more than six
- Quine formulated the concept of tabular minimisation in 1952
- Improved by McClusky in 1956

Quine-McClusky method

- Can be performed by hand, but tedious, time-consuming and subject to error
- Better suited to implementation on a digital computer



Principle of Quine-McCusky Method

Quine-McClusky method is a two stage simplification process

Step 1: Prime implicants are generated by a special tabulation process

Step 2: A minimal set of implicants is determined



Tabulation

- List the specified minterms for the 1s of a function and don't-cares
- Generate all the prime implicants using logical adjacency ($AB' + AB = A$)

One can work with the equivalent binary number of the product terms.

Example: $A'BCD'$ and $A'BC'D'$ are entered as
0110 and 0100

Combined to form a term "01-0"



Creation of Prime Implicant Table

- Selected prime implicants are combined and arranged in a table



Example 1

$$F = S(1,2,5,6,7,9,10,11,14)$$

The minterms are tabulated as binary numbers in sectionalised format.

Section	Column 1		Decimal
	No.of 1s	Binary	
1	1	0001	1
		0010	2
2	2	0101	5
		0110	6
		1001	9
		1010	10
3	3	0111	7
		1011	11
		1110	14



Example 1 (2)

- Compare every binary number in each section with every binary number in the next section
- Identify the combinations where the two numbers differ from each other with respect to only one bit.
- Combinations cannot occur among the numbers belonging to the same section
- Example: 0001 (1) in section 1 can be combined with 0101 (5) in section 2 to result in 0-01 (1, 5).



Example 1 (3)

- The results of such combinations are entered into another column
- The paired entries are checked off
- The entries of one section in the second column can again be combined together with entries in the next section
- Continue this process



Example 1 (4)

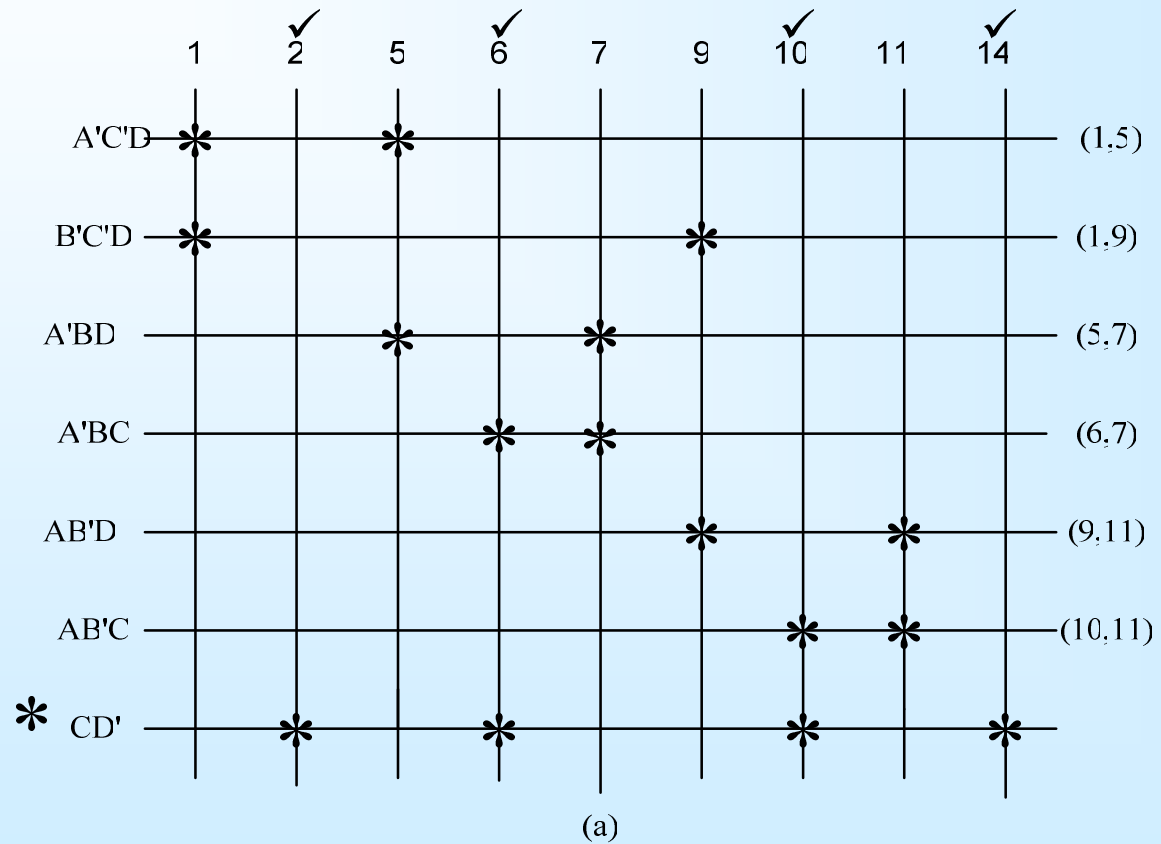
Section	Column 1		Column 2		Column 3	
	No. of 1s	Binary	Decimal			
1	1	0001 ✓	1	1-01	(1,5)	--10 (2,6,10,14) --10 (2,10,6,14)
		0010 ✓	2	-001	(1,9)	
				0-10	(2,6) ✓	
				-010	(2,10) ✓	
2	2	0101 ✓	5	01-1	(5,7)	
		0110 ✓	6	011-	(6,7)	
		1001 ✓	9	-110	(6,14) ✓	
		1010 ✓	10	10-1	(9,11)	
				101-	(10,11)	
			1-10	(10,14) ✓		
3	3	0111 ✓	7			
		1011 ✓	11			
		1110 ✓	14			

Note: Combination of entries in column 2 can only take place if the corresponding entries have the dashes at the same place.



Example 1 (5)

- All those terms which are not checked off constitute the set of prime implicants
- The repeated terms should be eliminated (--10 in the column 3)
- The seven prime implicants: (1,5), (1,9), (5,7), (6,7), (9,11), (10,11), (2,6,10,14)
- This is not a minimal set of prime implicants
- The next stage is to determine the minimal set of prime implicants



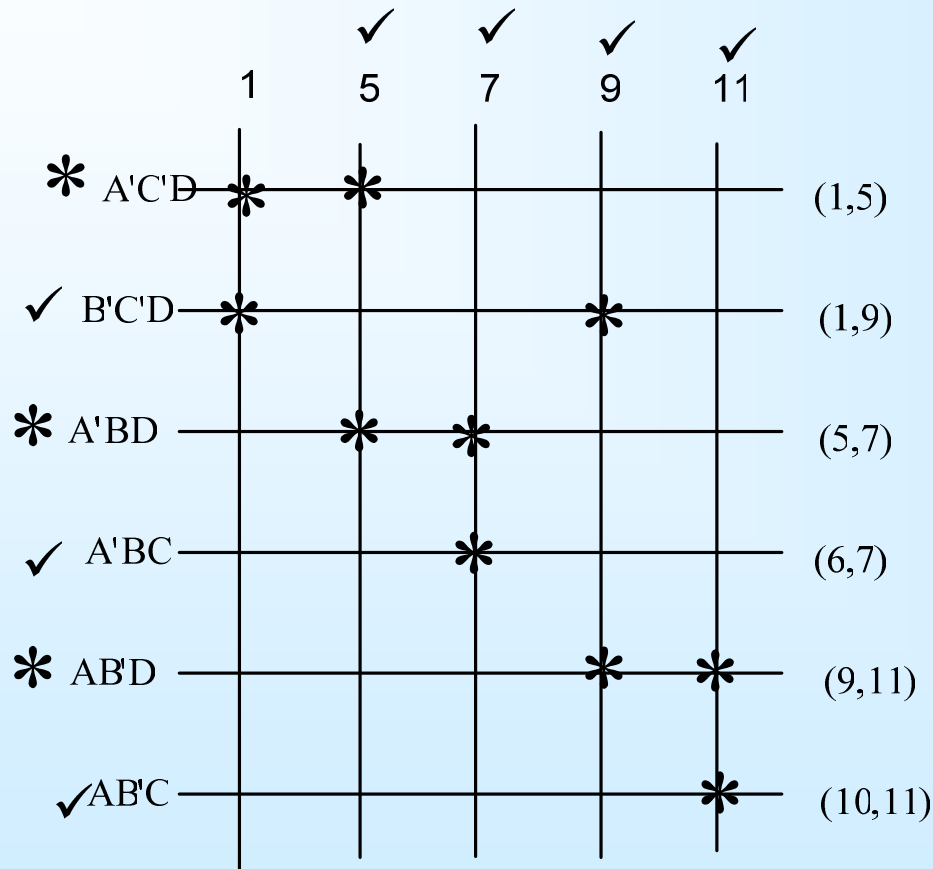


Selection of minimal set of implicants

- Determine essential prime implicants
 - These are the minterms not covered by any other prime implicant Identified by columns that have only one asterisk
 - Columns 2 and 14 have only one asterisk each
 - The associated row, CD' , is an essential prime implicant.
 - CD' is selected as a member of the minimal set (mark it by an asterisk)
 - Remove the corresponding columns, 2, 6, 10, 14, from the prime implicant table
- A new table is prepared.



Selection of minimal set of implicants (2)



(b)



Dominating Prime Implicants

- Identified by the rows that have more asterisks than others
- Choose Row A/BD
- Includes the minterm 7, which is the only one included in the row represented by A/BC
- A/BD is dominant implicant over A/BC
- A/BC can be eliminated
- Mark A/BD by an asterisk
- Check off the columns 5 and 7



Dominating Prime Implicants (2)

Choose $AB'D$

- Dominates over the row $AB'C$
- Mark the row $AB'D$ by an asterisk
- Eliminate the row $AB'C$
- Check off columns 9 and 11

Select $A'C'D$

- Dominates over $B'C'D$.
- $B'C'D$ also dominates over $A'C'D$
- Either $B'C'D$ or $A'C'D$ can be chosen as the dominant prime implicant



Minimal SOP expression

- If $A'C'D$ is retained as the dominant prime implicant
$$F = CD' + A'C'D + A'BD + AB'D$$
- If $B'C'D$ is chosen as the dominant prime implicant
$$F = CD' + B'C'D + A'BD + AB'D$$
- The minimal expression is not unique



Types of implicant tables

- Cyclic prime implicant table
- Semi-cyclic prime implicant table

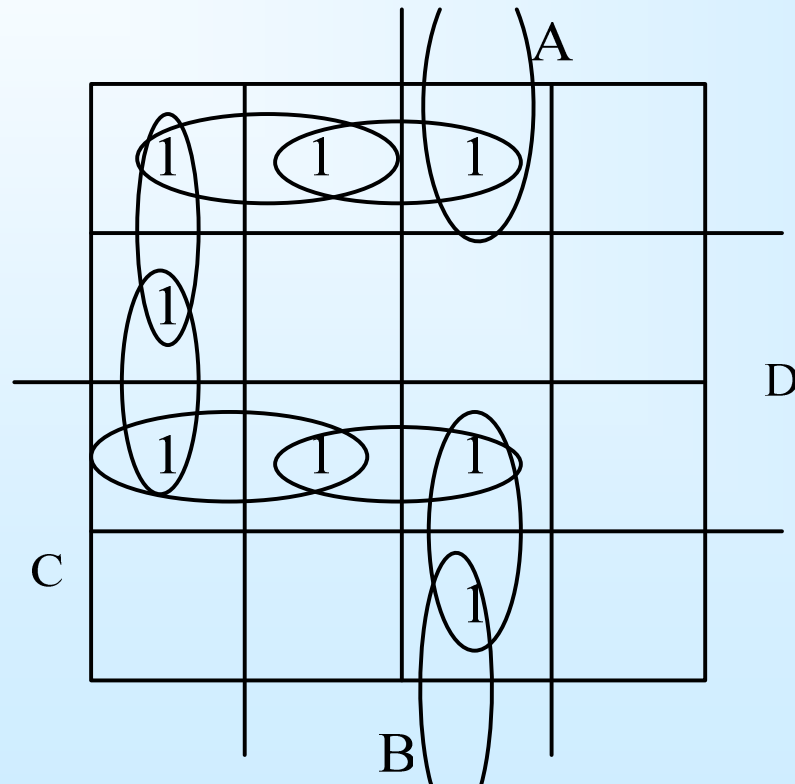
A prime implicant table is cyclic if

- it does not have any essential implicants which implies (at least two asterisks in every column)
- there are no dominating implicants (same number of asterisks in every row)



Example: Cyclic prime implicants

$$F = S(0,1,3,4,7,12,14,15)$$





Example: Possible Prime Implicants

$$a = A'B'C' \quad (0,1)$$

$$b = A'B'D \quad (1,3)$$

$$c = A'CD \quad (3,7)$$

$$d = BCD \quad (7,15)$$

$$e = ABC \quad (14,15)$$

$$f = ABD' \quad (12,14)$$

$$g = BC'D' \quad (4,12)$$

$$h = A'C'D' \quad (0,4)$$



Example: Prime implicant table

	✓ 0	✓ 1	✓ 3	4	✓ 7	12	✓ 14	✓ 15	
* a	✗	✗							(0,1)
b		✗	✗						(1,3)
* c			✗		✗				(3,7)
d					✗			✗	(7,15)
* e							✗	✗	(14,15)
f						✗	✗		(12,14)
* g				✗		✗			(4,12)
h	✗			✗					(0,4)



Process of simplification

- All columns have two asterisks
- There are no essential prime implicants.
- Choose any one of the prime implicants to start with
- Start with prime implicant a (mark with asterisk)
- Delete corresponding columns, 0 and 1
- Row c becomes dominant over row b, delete row b
- Delete columns 3 and 7
- Row e dominates row d, and row d can be eliminated
- Delete columns 14 and 15
- Choose row g it covers the remaining asterisks associated with rows h and f



Example: Reduced Prime Implicants Table

	✓ 3	4	✓ 7	12	14	15	
* c	x		x				(3,7)
d			x			x	(7,15)
e					x	x	(14,15)
f				x	x		(12,14)
g		x		x			(4,12)
h		x					(0,4)

(a)

	4	12	14	15	
* e			x	x	(14,15)
✓ f		x	x		(12,14)
* g	x	x			(4,12)
✓ h	x				(0,4)

(b)



Example: Simplified Expression

$$F = a + c + e + g$$
$$= A/B/C/ + A/CD + ABC + BC/D/$$

The K-map of the simplified function

		CD		A	D
		00	01			11	10
AB	00	1	1	1	
	01	1		1	
C	11	1		1	
	10			1	



Semi-cyclic prime implicant table

- The number of minterms covered by each prime implicant is identical in cyclic function
- Not necessarily true in a semi-cyclic function



Example: Semi-cyclic Prime Implicant Table (Function of 5 variables)

	0	2	8	9	10	11	15	16	17	18	19	23	25	31	
a	x	x	x		x										(0,2,8,10)
b	x	x						x		x					(0,2,16,18)
c			x	x	x	x									(8,9,10,11)
d								x	x	x	x				(16,17,18,19)
e						x	x								(11,15)
g							x							x	(15,31)
h												x		x	(23,31)
i											x	x			(19,23)
j									x				x		(17,25)
k				x									x		(25,9)



Example: Semi-cyclic Prime Implicant Table (Function of 5 variables) (2)

Minimised Function

$$F = a + c + d + e + h + j$$

$$\text{or } F = a + c + d + g + h + j$$

$$\text{or } F = a + c + d + g + j + i$$

$$\text{or } F = a + c + d + g + i + k$$



Simplification of Incompletely Specified Functions

- Do the initial tabulation including the don't-cares
- Construct the prime implicant table
- Columns associated with don't-cares need not be included
- Further simplification is similar to that for completely specified functions



Example

$$F(A,B,C,D,E) = \sum(1,4,6,10,20,22,24,26) + d(0,11,16,27)$$

- Pay attention to the don't-care terms
- Mark the combinations among themselves (d)



Primary Implicant Table

00000 (d)	0 ✓	0000- (0,1)	-0-00 (0,4,16,20)
-----	-----	00-00 (0,4) ✓	-0-00 (0,16,4,20)
00001	1 ✓	-0000 (0,16) (d)	-----
00100	4 ✓	-----	-01-0 (4,6,20,22)
10000 (d)	16 ✓	001-0 (4, 6) ✓	-01-0 (4,20,6,22)
-----	-----	-0100 (4,20) ✓	-----
00110	6 ✓	10-00 (16,20) ✓	-101- (10,26,11,27)
01010	10 ✓	1-000 (16,24) ✓	-101- (10,11,26,27)
10100	20 ✓	-----	
11000	24 ✓	-0110 (6,22) ✓	
-----	-----	-1010 (10,26) ✓	
10110	22 ✓	0101- (10,11) ✓	
11010	26 ✓	101-0 (20,22) ✓	
01011 (d)	11 ✓	110-0 (24,26)	
-----	-----	-----	
11011 (d)	27 ✓	1101- (26,27) ✓	
		-1011 (11,27) ✓	



Prime Implicant Table

Don't-cares are not included

	1	4	6	10	20	22	24	26	
a	*								(0,1)
b							*		(16,24)
c							*	*	(24,26)
d		*	*						(0,4,6,23)
e		*	*		*	*			(4,6,20,22)
g				*				*	(10,11,26,27)



Minimal expression

$$\begin{aligned} F(A,B,C,D,E) &= a + c + e + g \\ &= A/B/C/D' + ABC/E' + B/CE' + BC/D \end{aligned}$$

Quine-McCluskey Method of Minimization

Karnaugh Map provides a good method of minimizing a logic function. However, it depends on our ability to observe appropriate patterns and identify the necessary implicants. If the number of variables increases beyond five, K-map or its variant Variable Entered Map can become very messy and there is every possibility of committing a mistake. What we require is a method that is more suitable for implementation on a computer, even if it is inconvenient for paper-and-pencil procedures. The concept of tabular minimisation was originally formulated by Quine in 1952. This method was later improved upon by McClusky in 1956, hence the name Quine-McClusky.

This Learning Unit is concerned with the Quine-McClusky method of minimisation. This method is tedious, time-consuming and subject to error when performed by hand. But it is better suited to implementation on a digital computer.

Principle of Quine-McClusky Method

The Quine-McClusky method is a two stage simplification process.

- Generate prime implicants of the given Boolean function by a special tabulation process.
- Determine the minimal set of implicants is determined from the set of implicants generated in the first stage.

The tabulation process starts with a listing of the specified minterms for the 1s (or 0s) of a function and don't-cares (the unspecified minterms) in a particular format. All the prime implicants are generated from them using the simple logical adjacency theorem, namely, $AB' + AB = A$. The main feature of this stage is that we work with the equivalent binary number of the product terms. For example in a four variable case, the minterms $A'BCD'$ and $A'BC'D'$ are entered as 0110 and 0100. As the two logically adjacent minterms $A'BCD'$ and $A'BC'D'$ can be combined to form a product term $A'BD'$, the two binary terms 0110 and 0100 are combined to form a term represented as "01-0", where '-' (dash) indicates the position where the combination took place.

Stage two involves creating a prime implicant table. This table provides a means of identifying, by a special procedure, the smallest number of prime implicants that represents the original Boolean function. The selected prime implicants are combined to form the simplified expression in the SOP form. While we confine our discussion to the creation of minimal SOP expression of a Boolean function in the canonical form, it is easy to extend the procedure to functions that are given in the standard or any other forms.

Generation of Prime Implicants

The process of generating prime implicants is best presented through an example.

Example 1: $F = \Sigma (1,2,5,6,7,9,10,11,14)$

All the minterms are tabulated as binary numbers in sectionalised format, so that each section consists of the equivalent binary numbers containing the same number of 1s, and the number of 1s in the equivalent binary numbers of each section is always more than that in its previous section. This process is illustrated in the table as below.

Section	Column 1		Decimal
	No. of 1s	Binary	
1	1	0001	1
		0010	2
2	2	0101	5
		0110	6
		1001	9
		1010	10
3	3	0111	7
		1011	11
		1110	14

The next step is to look for all possible combinations between the equivalent binary numbers in the adjacent sections by comparing every binary number in each section with every binary number in the next section. The combination of two terms in the adjacent sections is possible only if the two numbers differ from each other with respect to only one bit. For example 0001 (1) in section 1 can be combined with 0101 (5) in section 2 to result in 0-01 (1, 5). Notice that combinations cannot occur among the numbers belonging to the same section. The results of such combinations are entered into another column, sequentially along with their decimal equivalents indicating the binary equivalents from which the result of combination came, like (1, 5) as mentioned above. The second column also will get sectionalised based on the number of 1s. The entries of one section in the second column can again be combined together with entries in the next section, in a similar manner. These combinations are illustrated in the Table below

Section	Column 1			Column 2		Column 3	
	No. of 1s	Binary	Decimal				
1	1	0001 ✓	1	1-01	(1,5)	--10	(2,6,10,14)
		0010 ✓	2	-001	(1,9)	--10	(2,10,6,14)
2	2	0101 ✓	5	0-10	(2,6) ✓		
		0110 ✓	6	-010	(2,10) ✓		
		1001 ✓	9				
		1010 ✓	10				
3	3	0111 ✓	7	01-1	(5,7)		
		1011 ✓	11	011-	(6,7)		
		1110 ✓	14	-110	(6,14) ✓		
				10-1	(9,11)		
			101-	(10,11)			
			1-10	(10,14) ✓			

All the entries in the column which are paired with entries in the next section are checked off. Column 2 is again sectionalised with respect to the number of 1s. Column 3

is generated by pairing off entries in the first section of the column 2 with those items in the second section. In principle this pairing could continue until no further combinations can take place. All those entries that are paired can be checked off. It may be noted that combination of entries in column 2 can only take place if the corresponding entries have the dashes at the same place. This rule is applicable for generating all other columns as well.

After the tabulation is completed, all those terms which are not checked off constitute the set of prime implicants of the given function. The repeated terms, like --10 in the column 3, should be eliminated. Therefore, from the above tabulation procedure, we obtain seven prime implicants (denoted by their decimal equivalents) as (1,5), (1,9), (5,7), (6,7), (9,11), (10,11), (2,6,10,14). The next stage is to determine the minimal set of prime implicants.

Determination of the Minimal Set of Prime Implicants

The prime implicants generated through the tabular method do not constitute the minimal set. The prime implicants are represented in so called "prime implicant table". Each column in the table represents a decimal equivalent of the minterm. A row is placed for each prime implicant with its corresponding product appearing to the left and the decimal group to the right side. Asterisks are entered at those intersections where the columns of binary equivalents intersect the row that covers them. The prime implicant table for the function under consideration is shown in the figure.

	1	2	5	6	7	9	10	11	14	
A'C'D	*		*							(1,5)
B'C'D	*					*				(1,9)
A'BD			*		*					(5,7)
A'BC				*	*					(6,7)
AB'D						*		*		(9,11)
ABC							*	*		(10,11)
* CD'		*		*			*		*	

(a)

In the selection of minimal set of implicants, similar to that in a K-map, essential implicants should be determined first. An essential prime implicant in a prime implicant table is one that covers (at least one) minterms which are not covered by any other prime implicant. This can be done by looking for that column that has only one asterisk. For example, the columns 2 and 14 have only one asterisk each. The associated row, indicated by the prime implicant CD' , is an essential prime implicant. CD' is selected as a

member of the minimal set (mark that row by an asterisk). The corresponding columns, namely 2, 6, 10, 14, are also removed from the prime implicant table, and a new table is construction as shown in the figure.

	1	5	7	9	11	
* A'C'D	*	*				(1,5)
✓ B'C'D	*			*		(1,9)
* A'BD		*	*			(5,7)
✓ A'BC			*			(6,7)
* AB'D				*	*	(9,11)
✓ ABC					*	(10,11)

(b)

We then select dominating prime implicants, which are the rows that have more asterisks than others. For example, the row A'BD includes the minterm 7, which is the only one included in the row represented by A'BC. A'BD is dominant implicant over A'BC, and hence A'BC can be eliminated. Mark A'BD by an asterisk and check off the column 5 and 7.

We then choose AB'D as the dominating row over the row represented by AB'C. Consequently, we mark the row AB'D by an asterisk, and eliminate the row AB'C and the columns 9 and 11 by checking them off.

Similarly, we select A'C'D as the dominating one over B'C'D. However, B'C'D can also be chosen as the dominating prime implicant and eliminate the implicant A'C'D.

Retaining A'C'D as the dominant prime implicant the minimal set of prime implicants is {CD', A'C'D, A'BD and AB'D}. The corresponding minimal SOP expression for the Boolean function is:

$$F = CD' + A'C'D + A'BD + AB'D$$

If we choose B'C'D instead of A'C'D, then the minimal SOP expression for the Boolean function is:

$$F = CD' + B'C'D + A'BD + AB'D$$

This indicates that if the selection of the minimal set of prime implicants is not unique, then the minimal expression is also not unique.

There are two types of implicant tables that have some special properties. One is referred to as cyclic prime implicant table, and the other as semi-cyclic prime implicant table. A prime implicant table is considered to be cyclic if

1. it does not have any essential implicants which implies that there are at least two asterisks in every column, and
2. There are no dominating implicants, which implies that there are same number of asterisks in every row.

Example 2: A Boolean function with a cyclic prime implicant table is shown in the figure 3.

The function is given by

$$F = \Sigma (0, 1, 3, 4, 7, 12, 14, 15)$$

All possible prime implicants of the function are:

$$a = A'B'C' \quad (0,1)$$

$$e = ABC \quad (14,15)$$

$$b = A'B'D \quad (1,3)$$

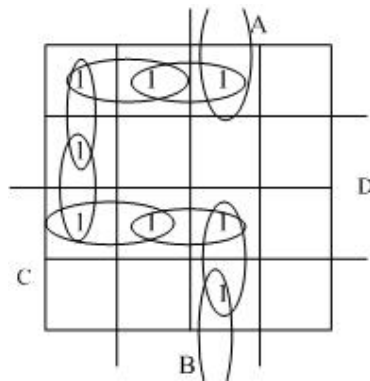
$$f = ABD' \quad (12,14)$$

$$c = A'CD \quad (3,7)$$

$$g = BC'D' \quad (4,12)$$

$$d = BCD \quad (7,15)$$

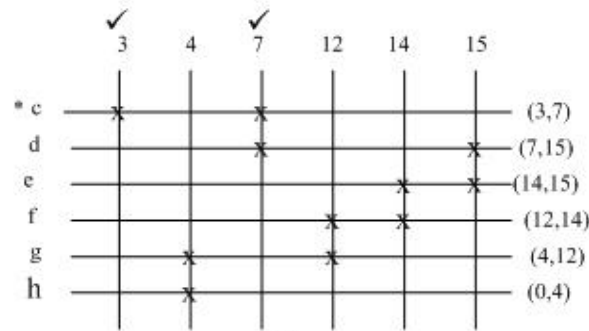
$$h = A'C'D' \quad (0,4)$$



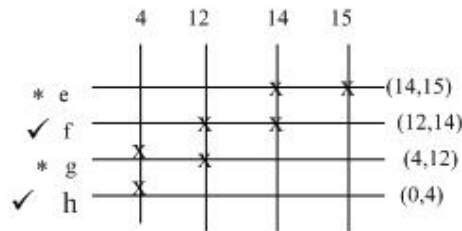
As it may be noticed from the prime implicant table in the figure that all columns have two asterisks and there are no essential prime implicants. In such a case we can choose any one of the prime implicants to start with. If we start with prime implicant a, it can be marked with asterisk and the corresponding columns, 0 and 1, can be deleted from the table. After their removal, row c becomes dominant over row b, so that row c is selected and hence row b is can be eliminated. The columns 3 and 7 can now be deleted. We observe then that the row e dominates row d, and row d can be eliminated. Selection of row e enables us to delete columns 14 and 15.

	✓ 0	✓ 1	✓ 3	4	7	12	✓ 14	✓ 15	
* a	x	x							(0,1)
b		x	x						(1,3)
* c			x		x				(3,7)
d					x			x	(7,15)
* e							x	x	(14,15)
f						x	x		(12,14)
* g				x		x			(4,12)
h	x			x					(0,4)

If, from the reduced prime implicant table shown in the figure, we choose row g it covers the remaining asterisks associated with rows h and f. That covers the entire prime implicant table. The minimal set for the Boolean function is given by:



(a)

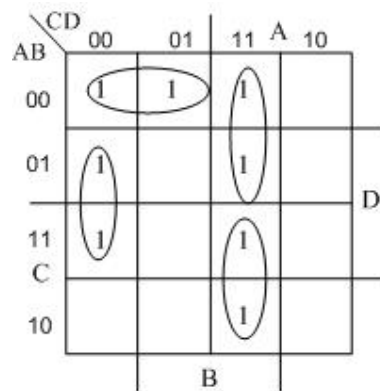


(b)

$$F = a + c + e + g$$

$$= A'B'C' + A'CD + ABC + BC'D'$$

The K-map of the simplified function is shown in the following figure



A semi-cyclic prime implicant table differs from a cyclic prime implicant table in one respect. In the cyclic case the number of minterms covered by each prime implicant is identical. In a semi-cyclic function this is not necessarily true.

Example 3: Consider a semi-cyclic prime implicant table of a five variable Boolean function shown in the figure.

	0	2	8	9	10	11	15	16	17	18	19	23	25	31	
a	*	*	*		*										(0,2,8,10)
b	*	*						*		*					(0,2,16,18)
c			*	*	*	*									(8,9,10,11)
d								*	*	*	*				(16,17,18,19)
e						*	*								(11,15)
g							*							*	(15,31)
h												*		*	(23,31)
i											*	*			(19,23)
j									*				*		(17,25)
k				*									*		(25,9)

Examination of the prime-implicant table reveals that rows a, b, c and d contain four minterms each. The remaining rows in the table contain two asterisks each. Several minimal sets of prime implicants can be selected. Based on the procedures presented through the earlier examples, we find the following candidates for the minimal set:

$$F = a + c + d + e + h + j$$

or

$$F = a + c + d + g + h + j$$

or

$$F = a + c + d + g + j + i$$

or

$$F = a + c + d + g + i + k$$

Based on the examples presented we may summarise the procedure for determination of the minimal set of implicants:

1. Find, if any, all the essential prime implicants, mark them with *, and remove the corresponding rows and columns covered by them from the prime implicant table.
2. Find, if any, all the dominating prime implicants, and remove all dominated prime implicants from the table marking the dominating implicants with *s. Remove the corresponding rows and columns covered by the dominating implicants.
3. For cyclic or semi-cyclic prime implicant table, select any one prime implicant as the dominating one, and follow the procedure until the table is no longer cyclic or semi-cyclic.
4. After covering all the columns, collect all the * marked prime implicants together to form the minimal set, and convert them to form the minimal expression for the function.

Simplification of Incompletely Specified functions

The simplification procedure for completely specified functions presented in the earlier sections can easily be extended to incompletely specified functions. The initial tabulation is drawn up including the dont-cares. However, when the prime implicant table is constructed, columns associated with dont-cares need not be included because they do not necessarily have to be covered. The remaining part of the simplification is similar to that for completely specified functions.

Example 4: Simplify the following function:

$$F(A,B,C,D,E) = \Sigma(1,4,6,10,20,22,24,26) + d(0,11,16,27)$$

Tabulation of the implicants

00000 (d)	0 ✓	0000- (0,1)	-0-00 (0,4,16,20)
		00-00 (0,4) ✓	-0-00 (0,16,4,20)
00001	1 ✓	-0000 (0,16) (d)	
00100	4 ✓		-01-0 (4,6,20,22)
10000 (d)	16 ✓	001-0 (4, 6) ✓	-01-0 (4,20,6,22)
		-0100 (4,20) ✓	
00110	6 ✓	10-00 (16,20) ✓	-101- (10,26,11,27)
01010	10 ✓	1-000 (16,24) ✓	-101- (10,11,26,27)
10100	20 ✓		
11000	24 ✓	-0110 (6,22) ✓	
		-1010 (10,26) ✓	
10110	22 ✓	0101- (10,11) ✓	
11010	26 ✓	101-0 (20,22) ✓	
01011 (d)	11 ✓	110-0 (24,26) ✓	
11011 (d)	27 ✓	1101- (26,27) ✓	
		-1011 (11,27) ✓	

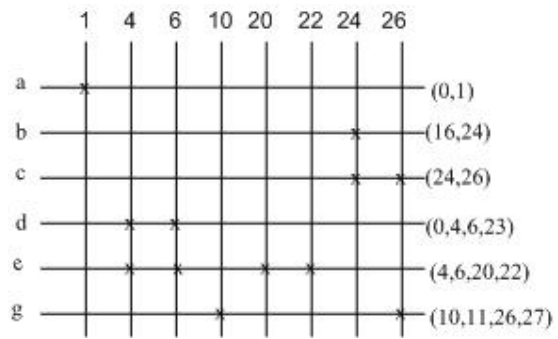
Pay attention to the don't-care terms as well as to the combinations among themselves, by marking them with (d).

Six binary equivalents are obtained from the procedure. These are 0000- (0,1), 1-000 (16,24), 110-0 (24,26), -0-00 (0,4,16,20), -01-0 (4,6,20,22) and -101- (10,11,26,27) and they correspond to the following prime implicants:

$$a = A'B'C'D' \quad b = AC'D'E' \quad c = ABC'E'$$

$$d = B'D'E' \quad e = B'CE' \quad g = BC'D$$

The prime implicant table is plotted as shown in the figure.



It may be noted that the don't-cares are not included.

The minimal expression is given by:

$$\begin{aligned}
 F(A,B,C,D,E) &= a + c + e + g \\
 &= A'B'C'D' + ABC'E' + B'CE' + BC'D
 \end{aligned}$$



Digital Electronics – Module 3

Logic Families: Introduction

N.J. Rao

Indian Institute of Science



Logic families

A logic family is characterized by

- Its circuit configuration
- Its technology
- Specific optimization of a set of desirable properties

Many logic families were introduced into the market since the introduction of integrated circuits in 1960s.

Some of the IC families had very short life spans.

- Standard TTL family which dominated the IC market got superseded by the Low Power Schottky family.
- Necessary to be aware of the evolving technologies



Features of a Logic Family

- Logic flexibility
- Availability of complex functions
- High noise immunity
- Wide operating temperature range
- Loading
- Speed
- Low power dissipation
- Lack of generated noise
- Input and output structures
- Packaging
- Low cost



Logic Flexibility

It is a measure of the capability and versatility or the amount of work or variety of uses that can be obtained from a logic family.

Factors that enhance the logic flexibility

- Wired-logic capability
- Asserted/ not-asserted outputs
- Driving capability
- I/O interfacing
- Driving other logic families
- Multiple gates



Complex Functions

- A complex function represents a grouping of basic gates requiring a relatively high level of integration.
- As complexity increases, the number of input/output pins also increases - but usually at a decreasing rate.
- High pin count gives the benefit of decreasing assembly costs per gate while increasing the reliability per gate.
- The complexity is also measured in terms of gates per chip.



Noise Immunity

High immunity to noise is desired to prevent the occurrence of false logic signals in a system.

Common sources of noise:

- Variations of the dc supply voltage,
- Ground noise
- Excessive coupling between signal leads
- Magnetically coupled voltages from adjacent lines,
- External sources (relays, circuit breakers, and power line transients)
- Radiated signals



Measures of Noise Immunity

- Voltage noise immunity (noise margin) is the amount of voltage that can be added algebraically to the worst-case output level before a worst-case gate tied to that output will begin to switch.
- Noise immunity is specified in terms of millivolts or volts



DC Noise Margin

It is a measure of its noise immunity, a gate's ability to withstand dc input signal variations.

- V_{IL} : Low level input voltage
- V_{IH} : High level input voltage
- V_{OL} : Low level output voltage
- V_{OH} : High level output voltage

Voltage levels associated with logic High and logic Low levels are not single values but a band of values.



DC Noise Margin (2)

A gate may accept an input signal in the range of 0.0 V to 0.8 V as logic Low while it produces at its output a Low voltage of 0.4 V under worst loading and voltage supply conditions.

DC margin is considered to be 0.4 V ($0.8 - 0.4 = 0.4$ V)

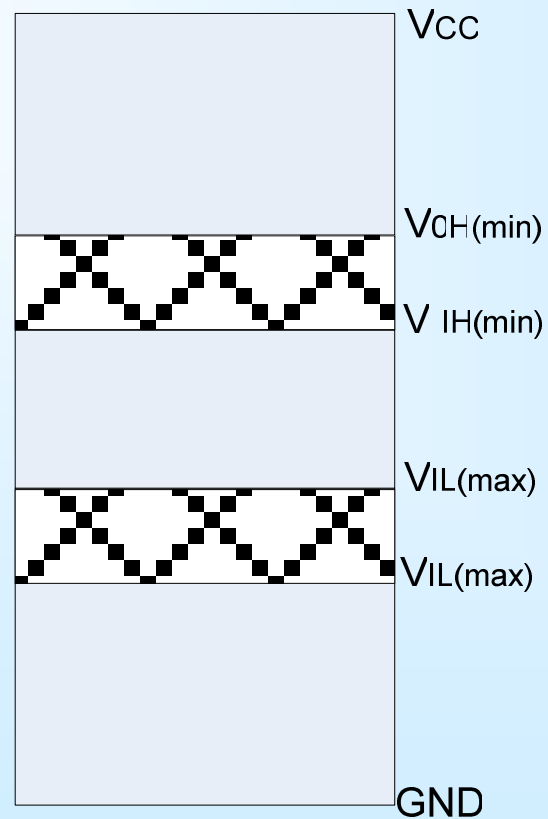
The dc noise margins are defined as

Low level dc noise margin: $V_{ILmax} - V_{OLmax}$

High level dc noise margin: $V_{OHmin} - V_{IHmin}$



DC Noise Margin (3)





AC Noise Margin

- It refers to the immunity of a gate to noise of very short durations.
- Amplitude and duration of the noise signals become important.
- The noise signal must contain enough energy to effect a change in the state of the circuit.
- AC noise margins are higher than dc noise margins.



AC Noise Margin (2)

The ability of a logic element to operate in a noisy environment depends on

- Built-in operating margins
- Time required for the device to react
- The ease with which a noise voltage is developed



Operating Temperature Range

- For commercial and industrial needs, temperatures usually range from 0° or -30° C to 55° , 70° or 85° C
- The military has an universal requirement for operability from -55° C to 125° C.
- Advantages of a wide temperature specification are offset by the increased cost



Loading

- The output of a logic gate may be connected to the inputs of several other similar gates
- The *fan out* of a gate is the maximum number of inputs of the same IC family that the gate can drive while maintaining its output levels within specified limits.



Loading

The input and output loading parameters are normalized, with regard to TTL devices

1 TTL Unit Load (U.L.) = $40 \mu\text{A}$ in the High state (Logic “1”)

1 TTL Unit Load (U.L.) = -1.6 mA in the Low state (Logic “0”)

The output of 74LS00 will sink 8.0 mA in Low state and source $400 \mu\text{A}$ in the High state.

- The normalized output Low drive factor is: $(8.0/1.6) = 5 \text{ U.L.}$
- Output High drive factor is: $(400 \mu\text{A}/40 \mu\text{A}) = 10 \text{ U.L.}$



Speed

- The shorter the propagation delay, the higher the speed of the circuit
- Propagation delay of a gate:
time interval between the application of an input pulse and the occurrence of the resulting output pulse.



Propagation Delays

Two propagation delays associated with a logic gate:

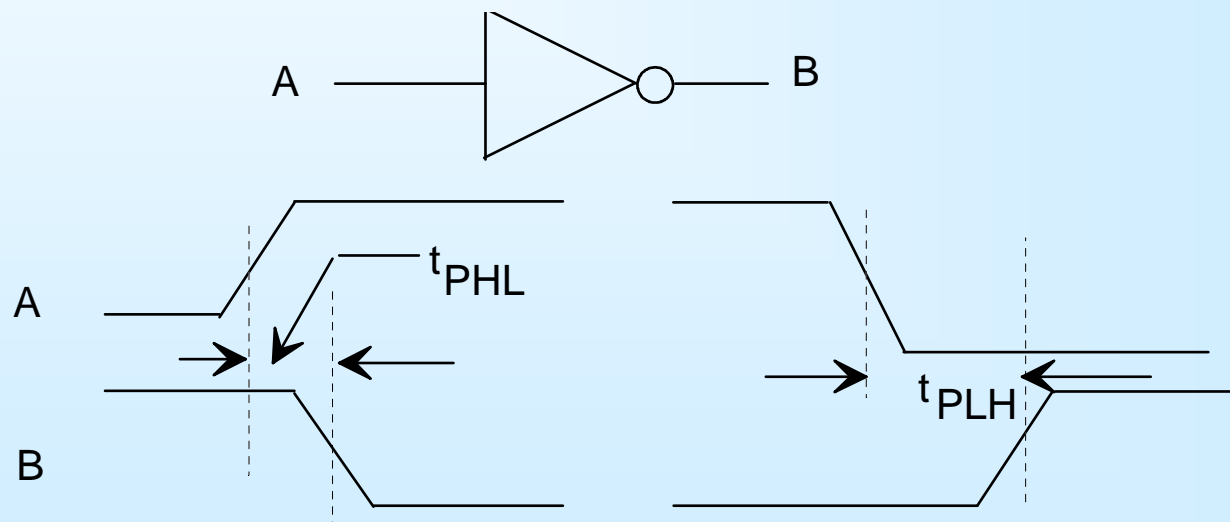
t_{PHL} : The time between a specified reference point on the input pulse and a corresponding reference point on the output pulse, with the output changing from the High level to the Low level.

t_{PLH} : The time between specified reference point on the input pulse and a corresponding reference point on the output pulse, with the output changing from the Low level to the High level.



Speed

The reference points are chosen as the 50% of the leading and trailing edges of the wave forms, or the threshold voltage (where the input and output voltages of the gate are equal) point.





Power Dissipation

Low power dissipation is desired in large systems as it leads to

- Lower cooling costs
- Lower power supply and distribution costs,
- Reduction in mechanical design problems
- Decrease in power dissipation on a per-gate basis with higher integration levels



Steady state dissipation

DC supply voltage V_{CC} x Average supply current I_{CC}

- Value of I_{CC} for a Low gate output is higher than for a High output
- Manufacturer's data sheet usually specifies both these values as I_{CCL} and I_{CCH} .
- The average I_{CC} is then determined based on a 50% duty cycle operation of the gate



Dissipation during transitions

- The supply current drawn is generally very different during the transition times
- More number of active devices come into operation, and parasitic capacitors will have to be charged and discharged.
- Power dissipation increases linearly as a function of the frequency of switching.



Dissipation during transitions (2)

Speed-power product (SPP) is specified by the manufacturer

SSP is specified in terms of pico Joules (symbolized by pJ)

SPP of a 74HC CMOS gate at 100 KHz is

$$\text{SPP} = (8\text{ns}) \times (0.17 \text{ mW}) = 1.36 \text{ pJ.}$$



Generated Noise

- Switching transients either on power line or signal line can be very serious sources of noise.
- Care has to be taken to design the power, ground and signal interconnections.
- All the power supply leads in a system must be bypassed.
- Supply distribution is less expensive if the circuits generate less noise.



Input and output structures

Effective interfacing both at the input and output are needed

Interfacing at the input requires facility

- To accept different voltage levels for the two logic states
- To accept signals with rise and fall times very different from those of the signals associated with that logic family

At the output we require

- Larger current driving capability
- Facility to increase the voltages associated with the two logic levels
- Ability to tie the outputs of gates to have wired logic operations



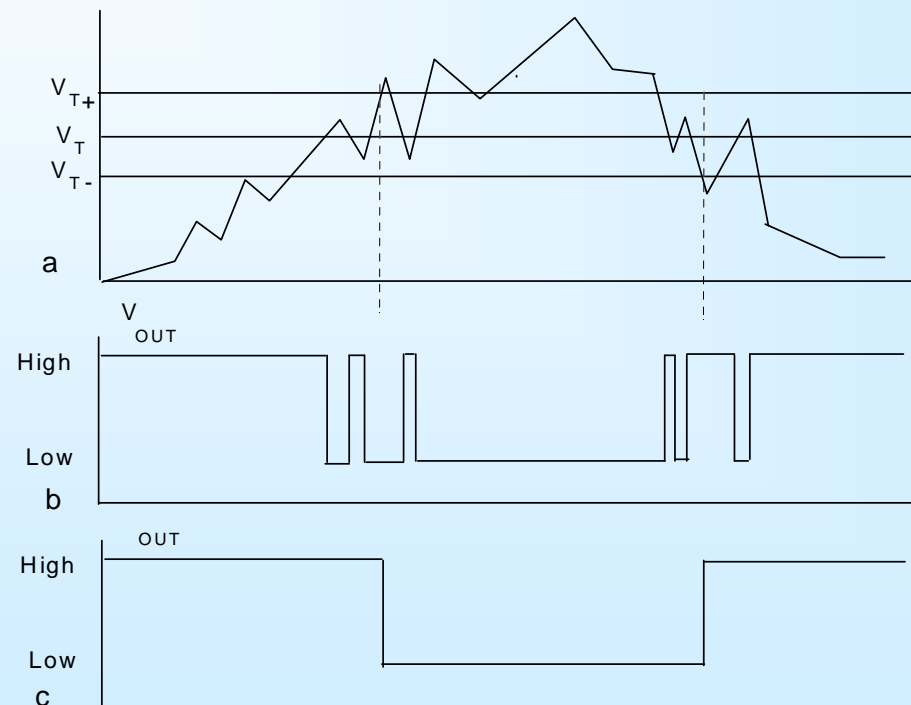
Interfacing at the inputs and outputs

- Interfacing the slow varying signals is achieved through Schmitt triggers.
- Voltage levels of the output signals can be increased by providing open-collector configurations. Open-collector configurations also permit us to achieve wired-logic operations
- The outputs of gates can be tied together by having tristate outputs.



Schmitt Trigger Inputs

When a slow changing signal superposed with noise is applied to gate





Three-State Outputs

- Logic outputs have two normal states; Low and High
- It is desirable to have another electrical state in which the output of the circuit offers very high impedance, *high-impedance*, *Hi-z* or *floating state*
- In this state, the circuit is effectively disconnected at its output, except for a small leakage current.
- Three states: logic 0, logic 1, and Hi-z.
- An output with three possible states is called *tri-state output*.



Three-State Outputs (2)

- Devices with three state outputs, should have an extra input, called as “output enable” (OE) for placing a device in low-impedance or high-impedance states.
- The outputs of devices which can have three states can be tied together, to create a three-state bus.
- The control circuitry must enable that at any given time only one output is enabled while all other outputs are kept in high-z state.



Open-Collector (or Drain) Outputs

- An IC device has a pull-up resistor at its output transistor
- Such circuits prevent us from tying the outputs of two such devices together.

If the internal pull-up elements are removed, then it allows one to

- tie up the outputs of more than one device together
- connect external pull-up resistor to increase the output voltage swing.

Devices with open-collector (open-drain) outputs are very useful for

- Creating wired logic operations, or
- Interfacing loads which are incompatible with the electrical characteristics of the logic family.



Packaging

- Initially most of the digital ICs were made available in *dual-in-line* packages (DIP).
- Commercial ICs come in plastic DIPs
- Ceramic DIPs are used for operation over a larger temperature range
- Increasing integrations lead to a wide range of chip level packages



Cost

Often the most important one, is the cost of a logic family. It is not sufficient to compare the cost of logic families at gate level.

The total system cost is decided by

- Cost of ICs
- Cost printed wiring board on which the ICs are mounted
- Assembly of circuit board
- Programming the programmable devices
- etc.
- Procurement
- Testing
- Power supply
- Documentation
- Storage

PROPERTIES OF A LOGIC FAMILY

Since the introduction of integrated circuits in 1960s, many logic families were introduced into the market. Each logic family is characterised by

- a circuit configuration
- a particular semiconductor technology
- a specific optimisation of a set of desirable properties

Some of the IC families had very short life spans. With continuously changing technologies, ICs that were quite popular suddenly become unattractive and uneconomical. For example Standard TTL family which dominated the IC market for a long period got superseded by the Low Power Schottky family. A digital designer should not only have a good knowledge of the existing digital families but should also be aware of the trends as well. The major requirements and the desirable features of a logic family are:

- Logic flexibility
- Availability of complex functions
- High noise immunity
- Wide operating temperature range
- Loading
- Speed
- Low power dissipation
- Lack of generated noise
- Input and output structures
- Packaging
- Low cost

Logic Flexibility

Logic flexibility is a measure of the capability and versatility or the amount of work or variety of uses that can be obtained from a logic family, in other words, it is a measure of the utility of a logic family in meeting various system needs. Factors that enhance the logic flexibility are *wired-logic capability, asserted/not-asserted outputs, line driving capability, indicator driving, I/O interfacing, driving other logic families and multiple gates.*

Wired logic refers to the capability of tying the outputs of gates together to perform additional logic without extra hardware and components. Frequently, asserted/not-

asserted versions of a variable are required in a logic system. If the logic family has gates with not-asserted outputs, use of inverters can be avoided. If the circuits can drive non-standard loads such as long signal lines, lamps and indicator tubes, additional discrete circuits can be avoided. The gate count can be minimised in a digital system if AND, NAND, OR, NOR and EX-OR gates are all available in the family. The logic families currently popular, namely TTL, CMOS and to a limited extent ECL, in the market have similar logic flexibility, and as such this factor does not constitute a deciding issue in selecting a logic family.

Complex Function

A complex function may be described as a grouping of basic gates requiring a relatively high level of integration. As complexity increases, the number of input/output pins also increases - but usually at a decreasing rate. Gate-to-pin ratios that normally increase with complexity give the benefit of decreasing assembly costs per gate while increasing the reliability per gate. The complexity is also measured, at present, by the number of gates that can be offered in a programmable logic device or programmable gate array.

Noise Immunity

In order to prevent the occurrence of false logic signals in a system, high immunity to noise is desired. Common sources of noise in digital circuits are

- Variations of the dc supply voltage
- Ground noise
- Excessive coupling between signal leads
- Magnetically coupled voltages from adjacent lines
- External sources such as relays, circuit breakers, and power line transients

If the noise immunity is higher, the number of precautions required to prevent the false logic signals will also be less. This becomes an important advantage in those areas, such as in industrial logic control systems that are subject to high noise levels. At present with increasing use of electronic control systems even in household appliances, the ambient noise levels at homes have significantly risen. Voltage noise immunity, or noise margin, is normally specified in terms of millivolts or volts. The noise immunity is specified as the amount of voltage that can be added algebraically to the worst-case output level before a worst-case gate tied to that output will begin to switch.

DC Noise Margin: The *dc noise margin* of a logic gate is a measure of its noise immunity, a gate's ability to withstand dc input signal variations. The term dc noise margin applies to noise voltages of relatively long duration compared to the gate's response times. The dc noise margin is defined in terms of the following voltage levels associated with a gate;

V_{IL} : Low level input voltage

V_{IH} : High level input voltage

V_{OL} : Low level output voltage

V_{OH} : High level output voltage

Voltage levels associated with logic High and logic Low levels are not single values but a band of values.

For example, a gate may accept an input signal in the range of 0.0 V to 0.8 V as logic Low while it produces at its output a Low voltage of 0.4 V under worst loading and voltage supply conditions.

In such a situation 0.4 V ($0.8 - 0.4 = 0.4$ V) is considered to be the dc noise margin.

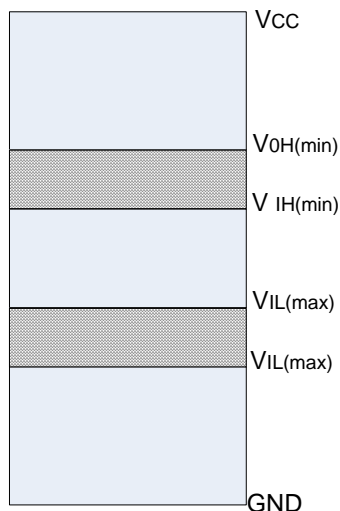
When the output of one gate is connected to the input of another gate, as the output is limited to 0.4 V even if a noise voltage up to 0.4 is superimposed on it, the second gate would accept it as logic Low signal.

The dc noise margins are defined as

Low level dc noise margin: $V_{ILmax} - V_{OLmax}$

High level dc noise margin: $V_{OHmin} - V_{IHmin}$

The noise margins and the voltage levels associated with the gates can be graphically shown as in the figure.



AC Noise Margin: The term *ac noise margin* refers to the noise immunity of a gate to noise of very short durations. In short duration noise, both the amplitude and duration of the noise signals become important. The noise signal must contain enough energy to effect a change in the state of the circuit. Therefore, the ac noise margins are considerably higher than dc noise margins.

The ability of a logic element to operate in a noisy environment involves more than the dc and ac noise margins. To be a problem, an externally generated noise pulse must be received into the system and cause malfunction. The noise voltage must be introduced into the circuit by radiated or coupled means. The amount of noise power required to develop a given voltage is strictly a function of the circuit impedances. Noise power must be transferred from the noise source with some arbitrary impedance, through a coupling to the impedance of the circuit under consideration. The ability to operate in a noisy environment is, then, an interaction of the built-in operating margins, the time required for the device to react, and the ease with which a noise voltage is developed. Therefore, the noise rejection capabilities of a logic family represent a combination of a number of circuit parameters.

Operating Temperature Range

A wide operating range is always desired and is often a design requirement.

For commercial and industrial needs, temperatures usually range from 0° C or -30° C to 55° C, 70° C or 85° C.

The military has a universal requirement for operability from -55° C to 125° C.

In most cases a logic line specified from -55° C to 125° C will exhibit better characteristics at room temperature conditions than a line specified by commercial requirements. It means performance of a logic circuit with regard to fan out, noise immunity and tolerance to power supply variations is usually better, since the circuits must still be within specifications even when the inherent degradation due to temperature extremes occurs. The advantages of a wide temperature specification are often offset by the increased cost.

Loading

In digital systems many digital ICs are interconnected to perform different functions. The output of a logic gate may be connected to the inputs of several other similar gates so the load on the driving gate becomes an important factor. The *fan-out* of a gate is the maximum number of inputs of ICs from the same IC family that the gate

can drive while maintaining its output levels within specified limits. In other words, the fan-out specifies the maximum loading that a given gate is capable of handling.

The input and output loading parameters are generally normalised, with regard to TTL devices, to the following values.

1 TTL Unit Load (U.L.) = 40 μ A in the High state (Logic "1")

1 TTL Unit Load (U.L.) = -1.6 mA in the Low state (Logic "0")

For example the output of 74LS00 will sink 8.0 mA in Low state and source 400 μ A in the High state.

The normalised output Low drive factor is:

$$(8.0/1.6) = 5 \text{ U.L.}$$

The output High drive factor is:

$$(400/40) = 10 \text{ U.L.}$$

Speed

Propagation delay is a very important characteristic of logic circuits because it limits the speed (frequency) at which they can operate. The shorter the propagation delay, the higher the speed of the circuit.

The propagation delay of a gate is basically the time interval between the application of an input pulse and the occurrence of the resulting output pulse.

There are two propagation delays associated with a logic gate:

1. t_{PHL} : The time between a specified reference point on the input pulse and a corresponding reference point on the output pulse, with the output changing from the High level to the Low level.
2. t_{PLH} : The time between specified reference point on the input pulse and a corresponding reference point on the output pulse, with the output changing from the Low level to the High level.

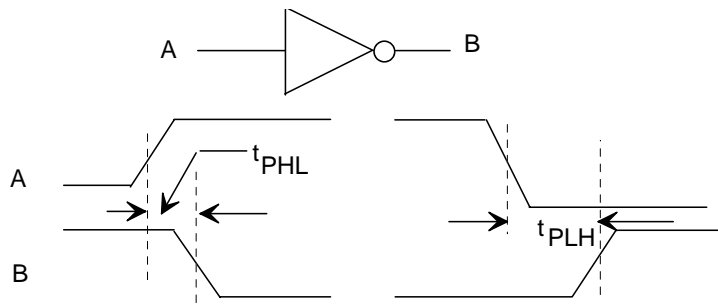
The reference points on the wave forms with respect to which the time delays are measured can be chosen as

The 50% of the leading and trailing edges of the wave forms

or

The threshold voltage (where the input and output voltages of the gate are equal) point.

These propagation delays are illustrated in the figure for both inverted and non-inverted outputs, with 50% point taken as the reference.



Power Dissipation

Logic with low power dissipation is desired in large systems because it lowers cooling costs, and power supply and distribution costs, thereby reducing mechanical design problems as well. In an air-borne or satellite application, power dissipation may be the most critical parameter because of power-source limitations. As chip complexity and packaging density continue to increase, power dissipation will decrease on a per-gate basis, but will increase per-chip basis. This is dictated by heat dissipation restriction arising from system design and maximum allowable semiconductor junction temperatures.

The power dissipation of a logic gate is

$$\text{dc supply voltage } V_{CC} \times \text{the average supply current } I_{CC}$$

Normally, the value of I_{CC} for a Low gate output is higher than for a High output. The manufacturer's data sheet usually specifies both these values as I_{CCL} and I_{CCH} . The average I_{CC} is then determined based on a 50% duty cycle operation of the gate.

The supply current drawn is generally very different during the transition time than during the steady state operation in logic High or Low states. During the transition times more number of active devices is likely to come into operation, and parasitic capacitors will have to be charged and discharged. Therefore, there is more dissipation every time a logic circuit switches its state. It also means that the power dissipation increases linearly as a function of the frequency of switching. A gate that operates at higher frequency will dissipate more power than the same gate operating at a lower frequency. This phenomenon will have a significant effect on the design of high frequency circuits.

In view of this another parameter known as *speed-power product* (SPP) is specified by the manufacturer as a measure of the performance of a logic circuit based on the product of the propagation delay time with the power dissipation at a specified frequency.

The speed-power product is specified in terms of pico Joules, symbolised by pJ.

For example, the SPP of a 74HC CMOS gate at 100 KHz is

$$\text{SPP} = (8\text{ns}) \times (0.17 \text{ mW}) = 1.36 \text{ pJ}.$$

Generated Noise

The switching transients either on power line or signal line can be very serious sources of noise. They can conduct and radiate through different channels and influence the functioning of the near by circuits or systems. Therefore, the lack of generated noise is an important requirement of a logic family. When the switching noise is significant, special care has to be taken to design the power, ground and signal interconnections.

- All the power supply leads in a system must be bypassed.
- Power supply and ground distribution has to be carefully designed.

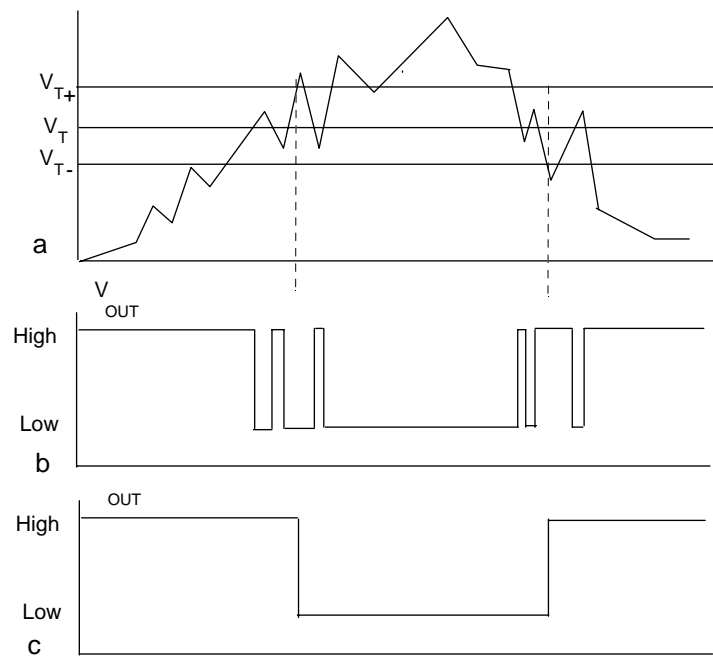
Supply distribution is less expensive if the logic family generates minimal noise. Also, the maximum line lengths in the back plane and wiring on the printed wiring board are functions of cross talk generated by the logic family. A logic family that draws constant current in both logic Low and High states, and does not change supply current when switching states will generate less noise.

Input and output Structures

A logic family should provide features for effective interfacing both at the input and output. Interfacing at the input requires facility to accept different voltage levels for the two logic states, and to accept signals with rise and fall times very different from those of the signals associated with that logic family. At the output we require larger current driving capability, facility to increase the voltages associated with the two logic levels, and the ability to tie the outputs of gates to have wired logic operations. Interfacing the slow varying signals (signals with rise and fall times greater than one microsecond) is achieved through Schmitt triggers. Voltage levels of the output signals can be increased by providing open-collector (or open-drain) configurations.

Such open-collector (open-drain) configurations also permit us to achieve wired-logic operations. The outputs of gates can be tied together by having tristate outputs.

Schmitt Trigger Inputs: When a slow changing signal superposed with noise is applied to a gate which has a single threshold V_T , there is a possibility of the output changing several times during signal transition period, as shown in the figure (b). Clearly, such a response is not acceptable. When the input signal to a gate has long transition times, the gate is likely to stay in the linear region of its operation for a long period. During this period the gate is likely to get into oscillations because of the parasitics associated with the circuit, which are not desirable. The problems associated with slow changing signals and the superposed noise can be solved if the gate has Schmitt trigger type of input.



A Schmitt trigger is a special circuit that uses feedback internally to shift the switching threshold depending on whether the input is changing from Low to High or from High to Low. For example, suppose the input of a Schmitt-trigger inverter is initially at 0 V (solid Low) and the output is High close to the V_{CC} (or V_{DD}). If the input voltage is increased, the output will not go Low until the input voltage reaches a threshold voltage, V_T . Any value of the input voltage above this threshold will make the output to remain Low. The output of a Schmitt gate for a slow changing noisy signal is shown in the figure (c). Every logic family should have a few gates which provide for Schmitt inputs to effectively interface with real world signals.

Three-State Outputs: Logic outputs have two normal states, Low and High, corresponding to logic values 0 and 1. It is desirable to have another electrical state, not a logic state at all, in which the output of the circuit offers very high impedance. In this state, it is equivalent to disconnecting the circuit at its output, except for a small leakage current. Such a state is called *high-impedance*, *Hi-z* or *floating state*. Thus we have an output that could go into one of the three states: logic 0, logic 1 and Hi-z. An output with three possible states is called *tri-state output*.

Devices that have three state outputs, should have an extra input signal, that can be called as “output enable” (OE) for placing the device either in low-impedance or high-impedance states. The outputs of devices which can have three states can be tied together, to create a three-state bus. The control circuitry must enable that at any given time only one output is enabled while all other outputs are kept in Hi-z state.

Open-Collector (or Drain) Outputs: The collector terminal of a transistor (or the drain terminal of a MOSFET) is normally connected in a logic device to a pull-up resistor or a special pull-up circuit. Such circuits prevent us from tying the outputs of two such devices together. If the internal pull-up elements are removed, then it gives freedom to the designer to tie up the outputs of more than one device together, or to connect external pull-up resistor to increase the output voltage swing. Devices with open-collector (open-drain) outputs are very useful for creating wired logic operations or for interfacing loads which are incompatible with the electrical characteristics of the logic family. It is, therefore, desirable for a logic family to have devices, at least some, which have open-collector (or open-drain) outputs.

Packaging

Until a few years ago most of the digital ICs were made available in *dual-in-line* packages (DIP). If the devices were to be operated in commercial temperature range, they come in plastic DIPs, and if they are to be used over a larger temperature range, they would be used in ceramic DIPs. With increasing miniaturisation at systems level and integration at the chip level the number of pins/IC have been steadily increasing. This increase in the pin count led to the introduction of different packages for the ICs. Selecting an appropriate package is one of the design decisions today's digital designer has to make.

Cost

The last consideration, and often the most important one, is the cost of a given logic family. The first approximate cost comparison can be obtained by pricing a common function such as a dual four-input or quad two-input gate. But the cost of a few types of gates alone can not indicate the cost of the total system. The total system cost is decided not only by the cost of ICs but also by the cost of

- printed wiring board on which the ICs are mounted
- assembly of circuit board
- testing
- programming the programmable devices
- power supply
- documentation
- procurement
- storage
- etc.

In many instances the cost of ICs could become a less important component of the total cost of the system.

Concluding Note

The question that arises after considering all the desirable features of a logic family is "why not design a family that best meets these needs and then mass produce it and drive the costs down?" Unfortunately, this can not be achieved as there is no universal logic family that does a good job of meeting all the previously stated needs. Silicon technology, though better understood and studied than any other solid-state technology, still has its own limitations. Besides, the demand for higher and higher performance specifications continues to grow.

Electrical Characteristics of Schottky TTL Family

Table gives the worst case values for the input and output voltage levels in both the logic states.

	TTL Families	Military(-55 to +125°C)				Commercial(0to 70°C)				
		V _I	V _{IH}	V _{OL}	V _{OH}	V _{IL}	V _{IH}	V _{OL}	V _{OH}	
TTL	Standard (54/74)	0.8	2	0.4	2.4	0.8	2	0.4	2.4	V
STTL	Schottky (54/74S)	0.8	2	0.5	2.5	0.8	2	0.5	2.7	V
LSTTL	Low-power Schottky (54/74LS)	0.8	2	0.5	2.5	0.8	2	0.5	2.7	V
ALSTTL	Advanced Low- power Schottky (54/74ALS)	0.8	2	0.4	2.5	0.8	2	0.5	2.7	V
ASTTL	Advanced Schottky (54/74AS)	0.8	2	0.5	2.5	0.8	2	0.5	2.7	V
FAST	Fairchild Advanced Schottky (54/74F)	0.8	2	0.5	2.5	0.8	2	0.5	2.5	V

The noise margins are:

$$\text{dc noise margin in High state} = V_{OHmin} - V_{IHmin} = 0.7 \text{ V}$$

$$\text{dc noise margin in Low state} = V_{ILmax} - V_{OLmax} = 0.3 \text{ V}$$

The noise margin levels are different in High and Low states and are shown in the following Table. These levels are lower in comparison to the noise levels of CMOS circuits.

	TTL Families	Military (-55 to 125°C)		Commercial (0 to 70°C)		
		Low NM	High NM	Low NM	High NM	
TTL	Standard (54/74)	400	400	300	400	mV
STTL	Schottky (54/74S)	300	500	300	700	mV
LSTTL	Low-power Schottky (54/74LS)	300	500	300	700	mV
ALSTTL	Advanced Low- power Schottky (54/74ALS)	400	500	300	500	mV
ASTTL	Advanced Schottky (54/74AS)	400	500	300	500	mV
FAST	Fairchild Advanced Schottky (54/74F)	300	500	300	500	mV

Loading: The load characteristics of Schottky TTL families are given in the following Table.

TTL Families	Input currents		Output currents		Units
	I_{IH}	I_{IL}	I_{OH}	I_{OL}	
TTL	0.04	-1.6	-0.4	16	mA
STTL	0.05	-2	-1	20	mA
LSTTL	0.02	-0.4	-0.4	8	mA
ALSTTL	0.02	-0.1	-0.4	8	mA
ASTTL	0.02	-0.5	-1	20	mA
FAST	0	0	-0.4	8	mA

Fan out is a measure of the number of gate inputs that are connected to (or driven by) a single output. The currents associated with LSTTL family are:

$I_{ILmax} = -0.4 \text{ mA}$ (This current flows out of a LSTTL input. This is sometimes called Low-state unit load for LSTTL)

$I_{IHmax} = 20 \text{ } \mu\text{A}$ (This current flows into the LSTTL input. This is called High-state Unit load for LSTTL)

$I_{OLmax} = 8 \text{ mA}$

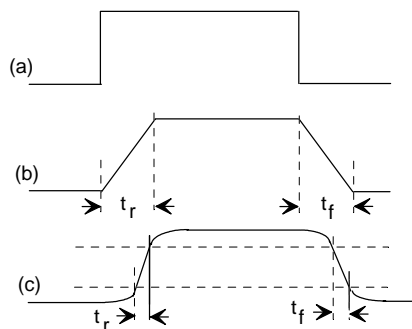
$I_{OHmax} = -400 \text{ } \mu\text{A}$

Fan out in both the High and Low states is 20

LSTTL Dynamic Electrical Behavior

Both the speed and the power consumption of LSTTL device depend on, to a large extent, AC or dynamic characteristics of the device and its load, that is, what happens when the output changes between states. The speed depends on two factors, transition times and propagation delay.

Transition Time: The amount of time that the output of a logic circuit takes to change from one state to another is called the transition time. The ideal situation we would like to have is shown in the figure (a).

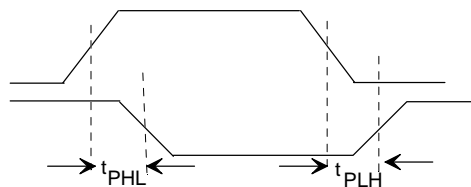


However, in view of the parasitic associated with circuits and boards, it is neither possible nor desirable to have such zero transition times. Realistically, an output takes

some finite time to transit from one state to the other. These transition times are also known as *rise time* and *fall time*. The semi-idealistic transitions are shown in the figure (b). But in actuality the transitions are never sharp in view of the parasitic elements, and edges are always rounded. We may identify the transition times as the times taken for the output to traverse the undefined voltage zones, as shown in the figure (c).

The rise and fall times of a LSTTL output depend mainly on two factors, the ON transistor resistance and the load capacitance. The load capacitance comes from three different sources: output circuits including a gate's output transistors, internal wiring and packaging, have capacitances associated with them (of the order of 2-10 pF); wiring that connects an output to other inputs (about 1pF per inch or more depending on the wiring technology); and input circuits including transistors, internal wiring and packaging (2-15 pF per input).

Propagation Delay: Several factors lead to nonzero propagation delays. In a LSTTL device, the rate at which transistors change state is influenced by the physics of the device, the circuit environment including input-signal transition rate, input capacitance, and output loading. To factor out the effect of rise and fall times, manufacturers usually specify propagation delays at the midpoints of input and output transitions, as shown in the figure.



Power Consumption: The currents drawn by the TTL circuits would be different in logic 0 and 1 states, as different sets of transistors get switched on in different states. Hence the designations of the supply current are I_{CCL} and I_{CCH} . For computing the power consumed by the gate an average (I_{CC}) of these two currents is taken. The power consumed is given by

$$P_D = I_{CC} \times V_{CC}$$

When a TTL circuit changes its state, the current drawn during the transition time would be larger than either of the steady states, as larger number of transistors would come into conducting state. The transition peak creates a large noise signal on the power supply line. If this is not properly filtered by using a bypass capacitance very close to the IC, it can constitute a major source of noise signals in TTL based digital systems. Therefore, there is a component of power dissipation that is proportional to frequency. However, this frequency dependent power dissipation becomes significant with regard to quiescent power dissipation only at very high frequencies.

Table gives the performance characteristics of TTL family, which also enables us to appreciate how the technology improvements lead to the performance improvements.

Family	Prop. Delay (ns)	PWR Dissp. (mW)	SPD.PWR Product (pJ)	Maximum Flip-Flop frequency (MHz)
TTL	10	10	100	35
HTTL	6	22	132	50
LTTL	33	1	33	3
LSTTL	9	2	18	45
STTL	3	19	57	125
ALS	4	1.2	4.8	70
AS	1.7	8	13.6	200
FAST	3.5	5.4	18.9	125



Digital Electronics

Module 3: TTL Family

N.J. Rao

Indian Institute of Science



TTL Family

It offered best performance-to-cost ratio at the time of its introduction

Its versatility lead to several subfamilies:

- Low Power TTL
- High Frequency TTL
- Schottky TTL

Several sub-families have evolved in the Schottky TTL family:

- Low-power Schottky TTL (LSTTL)
- Fairchild Advanced Schottky TTL (FAST)
- Advanced Low Power Schottky TTL (ALSTTL)
- Advanced Schottky TTL (ASTTL)



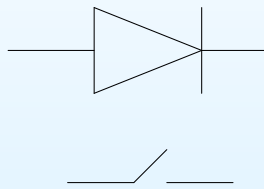
Bipolar logic families

- Use semiconductor diodes and bipolar junction transistor as the basic building blocks
- Simplest bipolar logic elements use *diodes* and *resistors* to perform logic operation (diode logic)
- Many TTL logic gates use diode logic internally, and boost their output drive capability using *transistor* circuits.
- Some TTL gates use parallel configurations of transistors to perform logic functions.

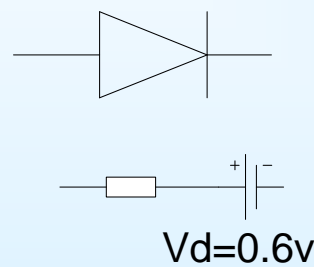


Diode

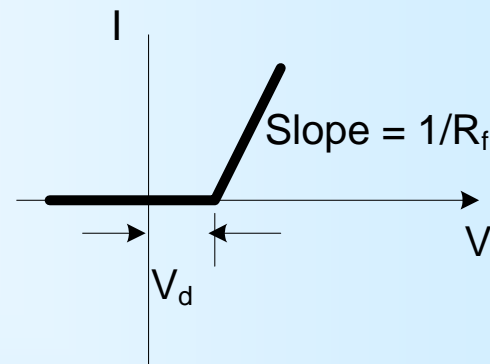
A diode can be modelled as



Reverse bias



Forward bias





Diode (2)

- It is an open circuit when it is reverse biased (we ignore its leakage current)
- It acts like a small resistance, R_f , in series with V_d , a small voltage source.
- R_f is the *forward resistance* of the diode, about 25Ω
- V_d is called *diode drop*, and is about 0.6 V

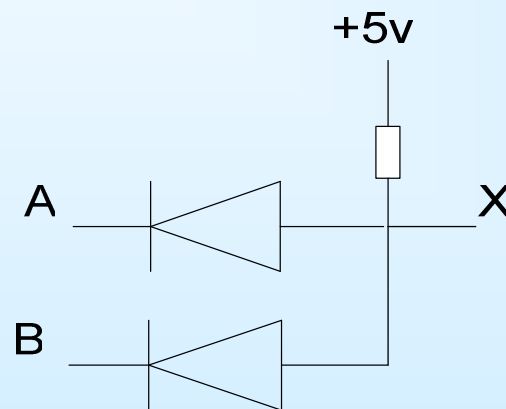


Logic operation with diodes

The circuit performs AND function

0-2 V (Low) input is considered logic 0

3-5 V (High) input is considered as logic 1.

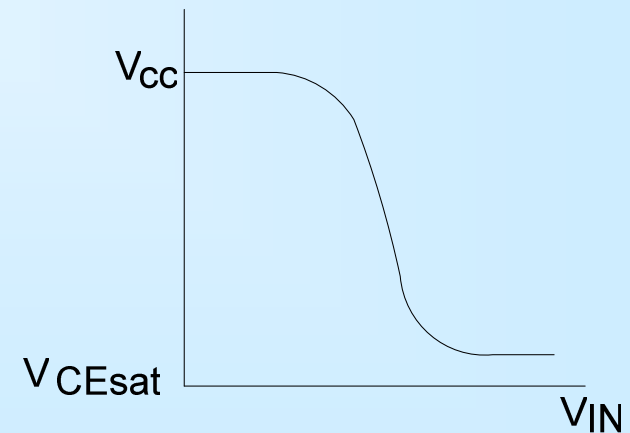
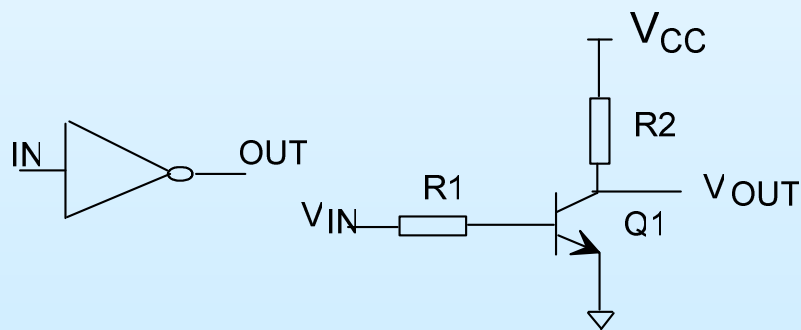
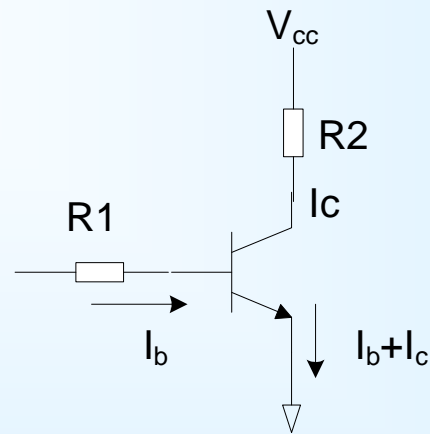


When both A and B inputs are High, the output X is High

When any one of the inputs is at Low level the output is Low



Bipolar Junction Transistor as a Switch





Transistor as a Switch

When the input of a saturated transistor is changed

- Output does not change immediately
- It takes extra time, called storage time, to come out of saturation

Storage time accounts for a significant portion of the propagation delay in the earlier TTL families.

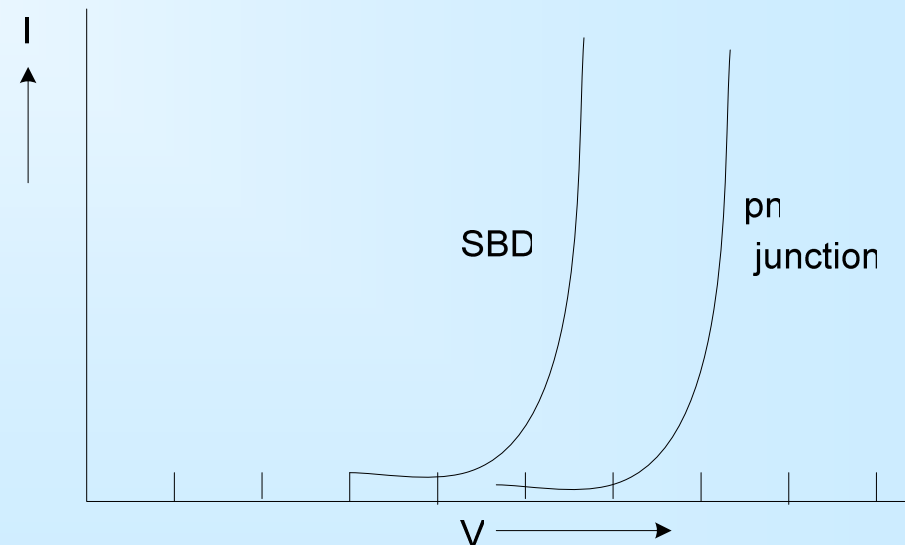
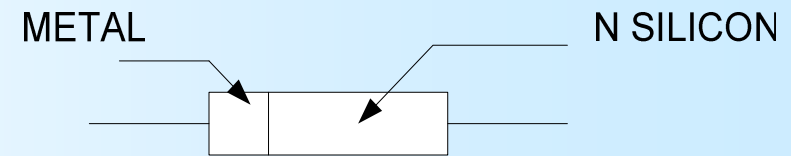
This storage time is reduced by placing a Schottky diode between the base and collector of each transistor that might saturate.



Schottky Barrier Diode

It is a rectifying metal-semiconductor contact formed between a metal and highly doped N semiconductor.

Forward current- voltage characteristics differences between the SBD and p-n junction

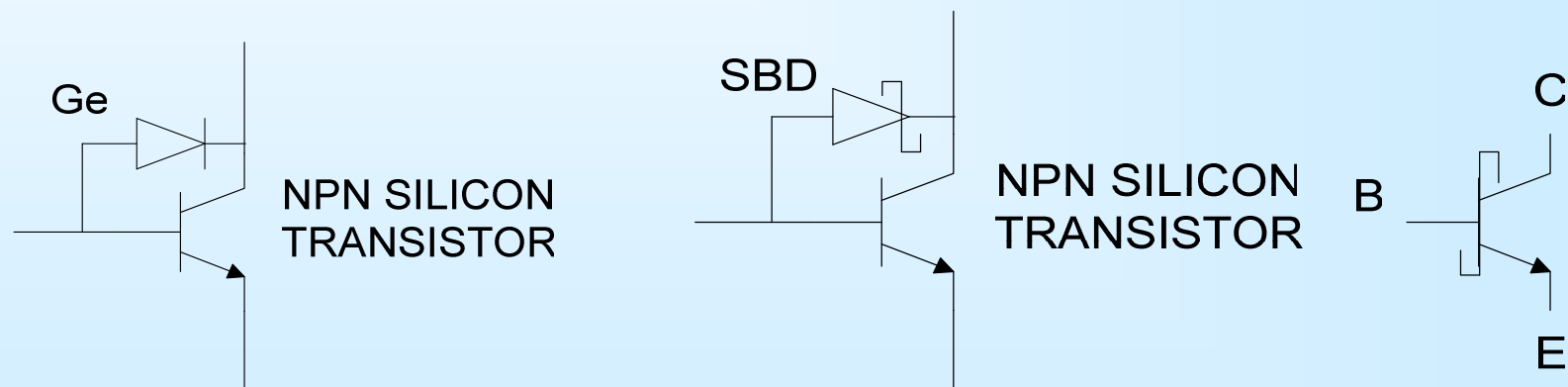




Schottky Transistor

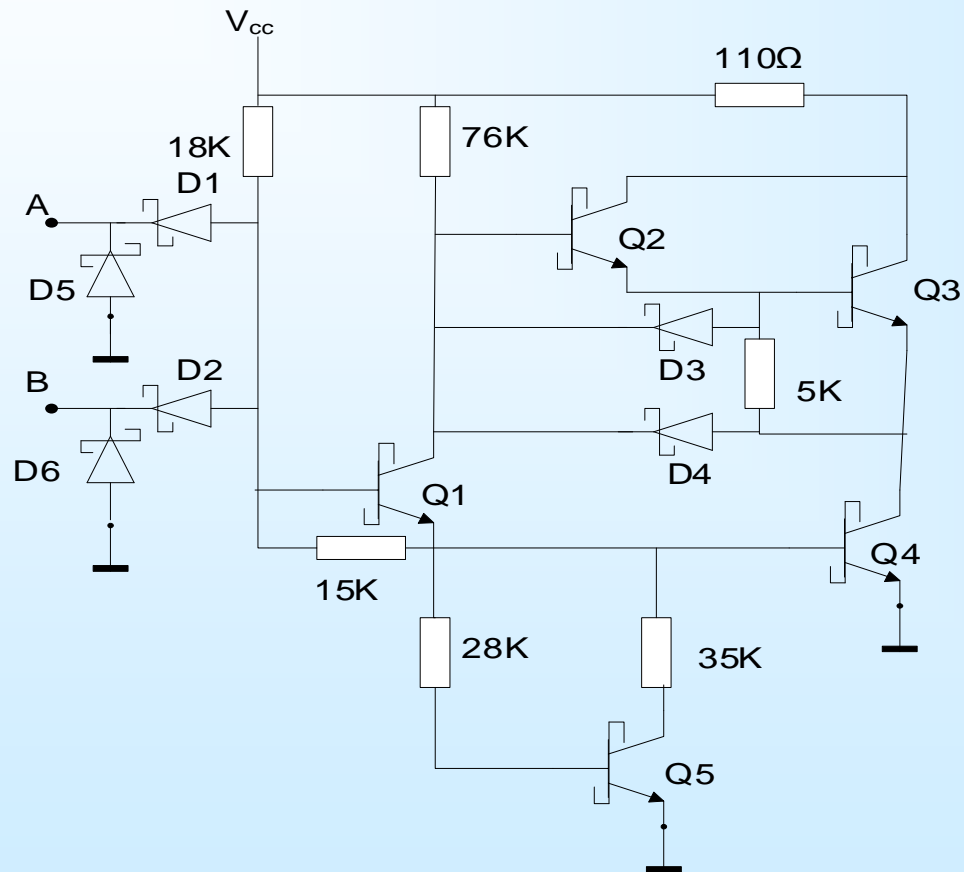
The Schottky transistor makes use of two earlier concepts:

- Baker clamp
- Schottky-Barrier-Diode (SBD)



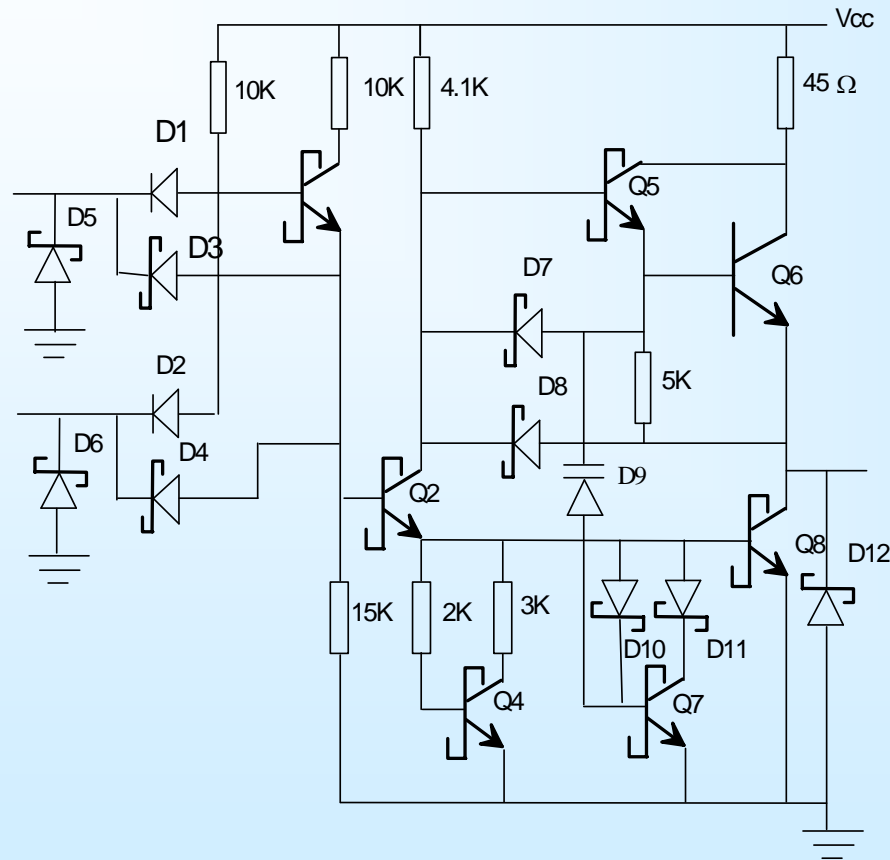


Basic NAND Gate





FAST Schottky TTL NAND



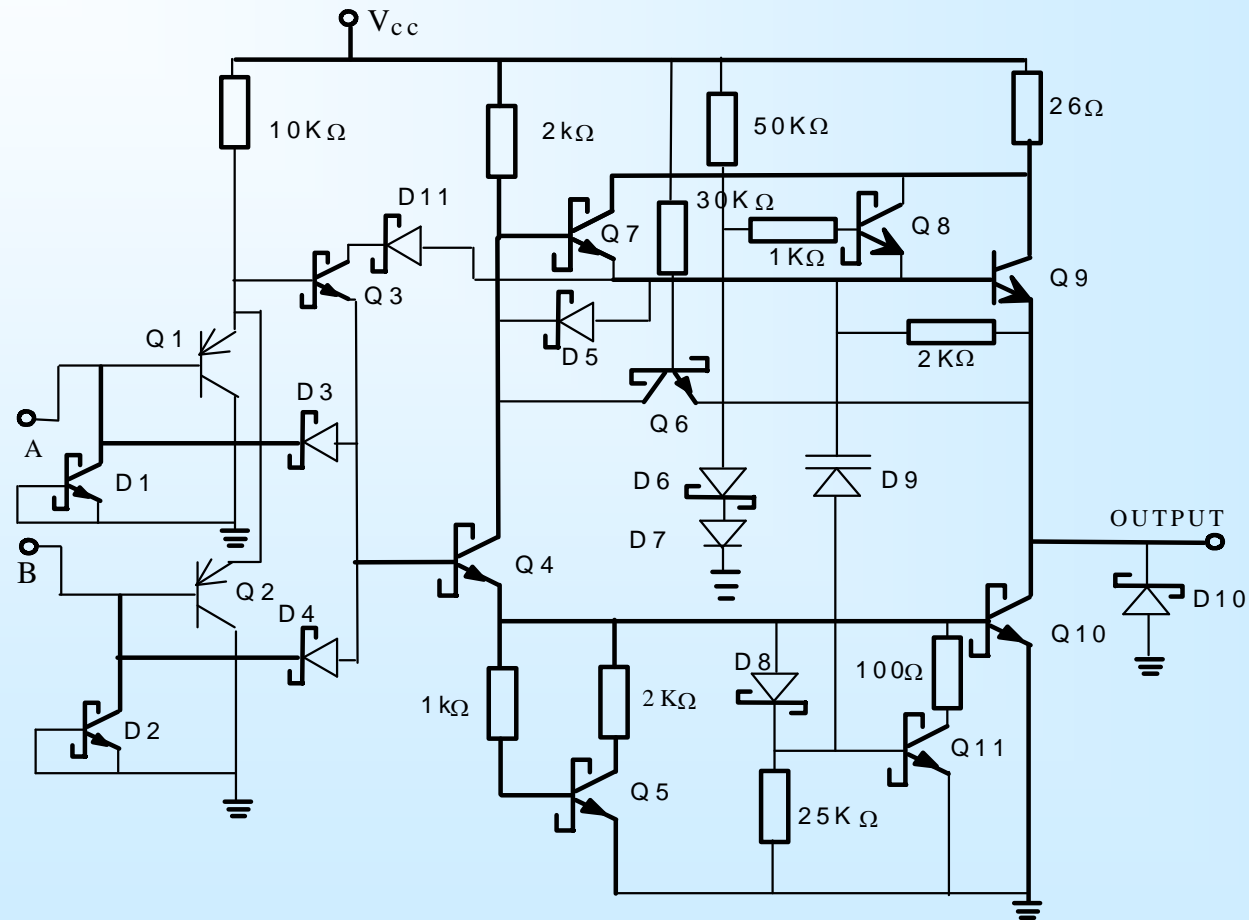


FAST devices provide

- 75-80% power reduction compared to standard Schottky TTL
- 20-40% improvement in the circuit performance using MOSAIC process
- A flatter power/frequency curve
- Higher fan out

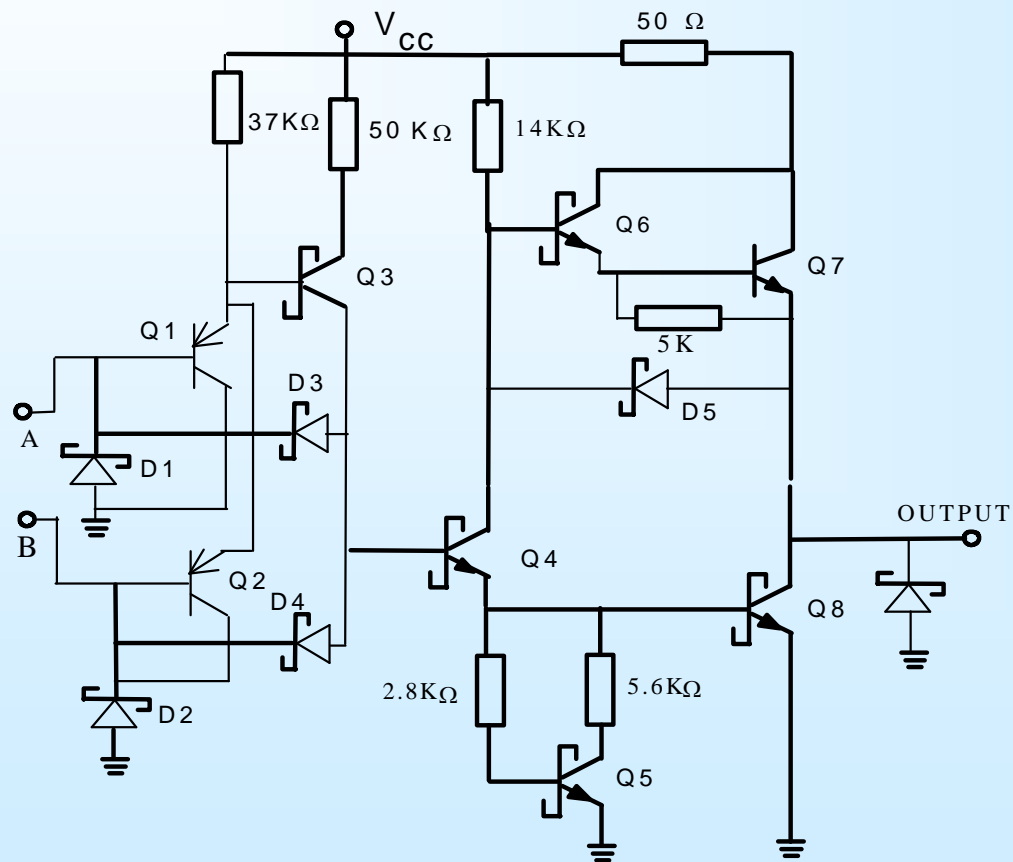


ALS NAND Gate





ASTTL NAND Gate





Electrical Characteristics of STTL family

	TTL Families	Military (-55 to +125°C)				Commercial (0 to 70°C)				
		V_I	V_{IH}	V_O	V_{OH}	V_{IL}	V_{IH}	V_{OL}	V_{OH}	
TTL	Standard (54/74)	0.8	2	0.4	2.4	0.8	2	0.4	2.4	V
STTL	Schottky (54/74S)	0.8	2	0.5	2.5	0.8	2	0.5	2.7	V
LSTTL	Low-power Schottky (54/74LS)	0.8	2	0.5	2.5	0.8	2	0.5	2.7	V
ALSTTL	Advanced Low- power Schottky (54/74ALS)	0.8	2	0.4	2.5	0.8	2	0.5	2.7	V
ASTTL	Advanced Schottky (54/74AS)	0.8	2	0.5	2.5	0.8	2	0.5	2.7	V
FAST	Fairchild Advanced Schottky (54/74F)	0.8	2	0.5	2.5	0.8	2	0.5	2.5	V



Noise Margins

dc noise margin in High state

$$= V_{OHmin} - V_{IHmin} = 0.7 \text{ V}$$

dc noise margin in Low state

$$= V_{ILmax} - V_{OLmax} = 0.3 \text{ V}$$



Noise Margins

	TTL Families	Military (-55 to +125°C)		Commercial (0 to 70°C)		
		Low NM	High NM	Low NM	High NM	
TTL	Standard (54/74)	400	400	300	400	mV
STTL	Schottky (54/74S)	300	500	300	700	mV
LSTTL	Low-power Schottky (54/74LS)	300	500	300	700	mV
ALSTTL	Advanced Low-power Schottky (54/74ALS)	400	500	300	500	mV
ASTTL	Advanced Schottky (54/74AS)	400	500	300	500	mV
FAST	Fairchild Advanced Schottky (54/74F)	300	500	300	500	mV



Loading

TTL Family	Input currents		Output currents		Units
	I_{IH}	I_{IL}	I_{OH}	I_{OL}	
TTL	0.04	-1.6	-0.4	16	mA
STTL	0.05	-2	-1	20	mA
LSTTL	0.02	-0.4	-0.4	8	mA
ALSTTL	0.02	-0.1	-0.4	8	mA
ASTTL	0.02	-0.5	-1	20	mA
FAST	0	0	-0.4	8	mA



Fan out

$I_{ILmax} = -0.4 \text{ mA}$ (This current flows out of a LSTTL input and this is called Low-state unit load for LSTTL)

$I_{IHmax} = 20 \text{ mA}$ (This current flows into the LSTTL input, and is called High-state Unit load for LSTTL)

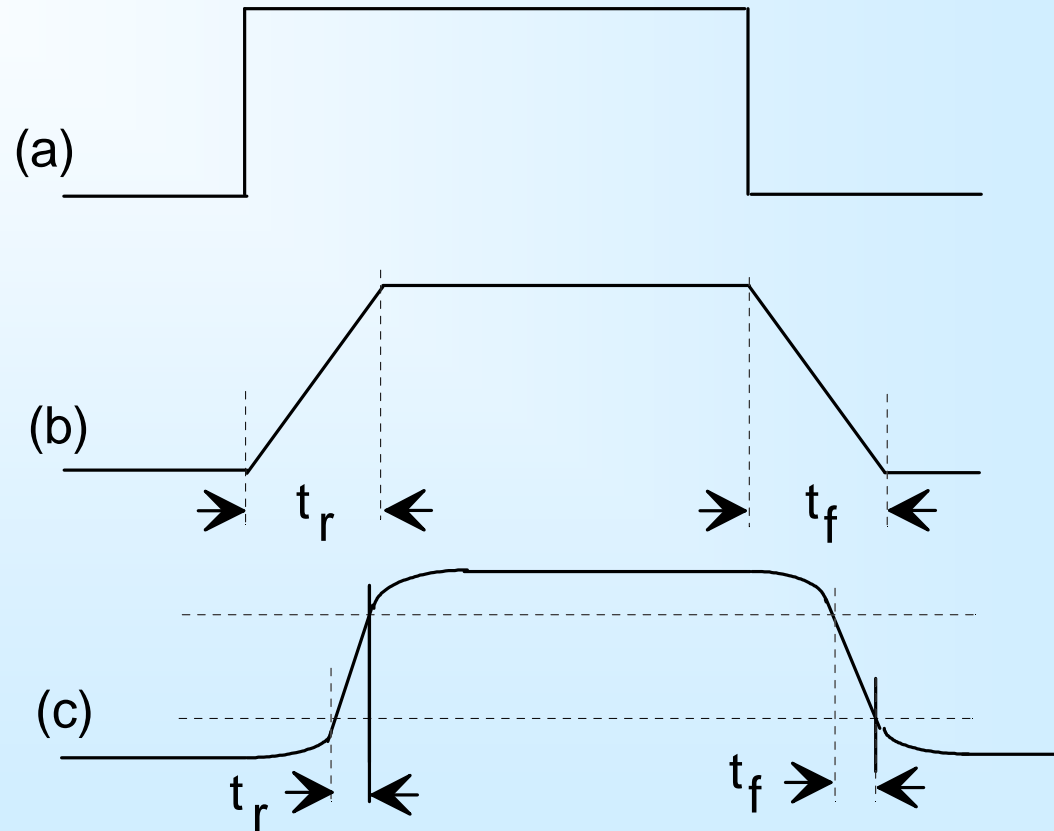
$I_{OLmax} = 8 \text{ mA}$

$I_{OHmax} = -400 \text{ }\mu\text{A}$

Fan out in both High and Low states is 20



Signal Representation





Transition Times

The rise and fall times depend on

- ON transistor resistance and
- Load capacitance

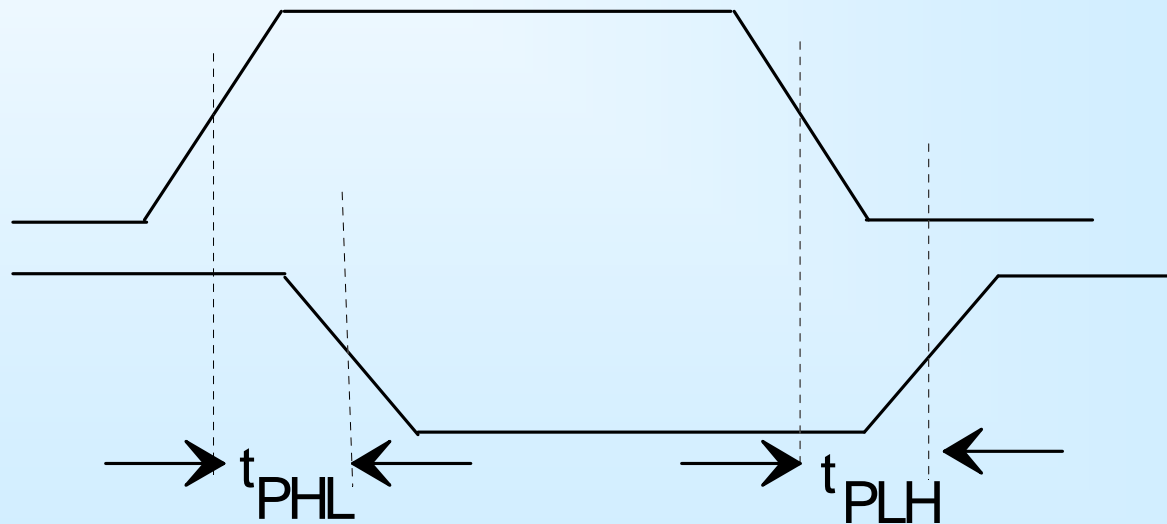
The load capacitance comes from

- Internal wiring and packaging have capacitances associated with them (about 2-10 pF)
- Wiring that connects an output to other inputs (about 1 pF per inch or more depending on the wiring technology)
- Input circuits including transistors, internal wiring and packaging (2-15 pF per input)



Propagation Delay

Manufacturers usually specify propagation delays at the midpoints of input and output transitions





Power Consumption

- The currents drawn would be different in logic 0 and 1 states
- I_{CC} is the average of I_{CCL} and I_{CCH}
- The power consumed is given by $P_D = I_{CC} \times V_{CC}$
- Current drawn during the transition time would be larger than either of the steady states
- Transition peaks create large noise signal on the power supply line.
- Needs filtering by using a bypass capacitance very close to the IC
- Transition component of power dissipation is proportional to frequency.
- This frequency dependent power dissipation becomes significant with regard to quiescent power dissipation only at very high frequencies.



Performance characteristics

Family	Prop. Delay (ns)	PWR Dissp. (mW)	SPD.PWR Product (pJ)	Maximum Flip-Flop frequency (MHz)
TTL	10	10	100	35
HTTL	6	22	132	50
LTTL	33	1	33	3
LSTTL	9	2	18	45
STTL	3	19	57	125
ALS	4	1.2	4.8	70
AS	1.7	8	13.6	200
FAST	3.5	5.4	18.9	125

TTL Family

Introduction

Transistor-Transistor Logic (TTL) and Emitter Coupled Logic (ECL) are the most commonly used bipolar logic families. Bipolar logic families use semiconductor diodes and bipolar junction transistors as the basic building blocks of logic circuits. Simplest bipolar logic elements use *diodes* and *resistors* to perform logic operation; this is called *diode logic*. Many TTL logic gates use diode logic internally, and boost their output drive capability using *transistor* circuits. Other TTL gates use parallel configurations of transistors to perform logic functions.

It turned out at the time of introducing TTL circuits that they were adaptable to virtually all forms of IC logic and produced the highest performance-to-cost ratio of all logic types. In view of its versatility a variety of subfamilies (Low Power, High Frequency, Schottky) representing a wide range of speed-power product have also been introduced. The Schottky family has been selected by the industry to further enhance the speed-power product. In Schottky family circuits, a Schottky diode is used as a clamp across the base-collector junction of a transistor to prevent it from going into saturation, thereby reducing the storage time. Several sub-families have evolved in the Schottky TTL family to offer several speed-power products to meet a wide variety of design requirements. These sub-families are:

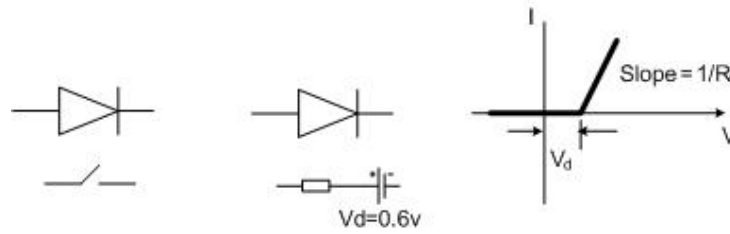
- Low-power Schottky TTL (LSTTL)
- Fairchild Advanced Schottky TTL (FAST)
- Advanced Low Power Schottky TTL (ALSTTL)
- Advanced Schottky TTL (ASTTL)

We will explore the characteristics of the TTL family in this Learning Unit.

Diodes

A semiconductor diode is fabricated from two types, p-type and n-type, of semiconductor material that are brought into contact with each other. The point of contact between the p and n materials is called p-n junction. Actually, a diode is fabricated from a single monolithic crystal of semiconductor material in which the two halves are doped with different impurities to give them p-type and n-type properties. A real diode can be modelled as shown in the figure 1.

- It is an open circuit when it is reverse biased (we ignore its leakage current)
- It acts like a small resistance, R_f , called the *forward resistance*, in series with V_d , called a *diode drop*, a small voltage source.
- The forward diode drop would be about 0.6 V and R_f is about 25 Ω .



Reverse bias Forward bias

FIG. 1: Model of a real diode

Diode action is exploited to perform logical operations. The circuit shown in the figure 2 performs AND function if 0-2 V (Low) input is considered logic 0 and 3-5 V (High) input is considered as logic 1. When both A and B inputs are High, the output X will be High. If any one of the inputs is at Low level, the output will also be at Low level.

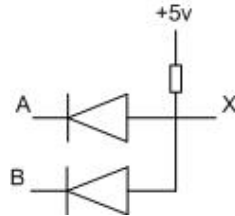


FIG.2: Diode AND gate

Bipolar Junction Transistor

A bipolar junction transistor is a three terminal device and acts like a current-controlled switch. If a small current is injected into the *base*, the switch is "on", that is, the current will flow between the other two terminals, namely, *collector* and *emitter*. If no current is put into the base, then the switch is "off" and no current flows between the emitter and the collector. A transistor will have two *p-n* junctions, and consequently it could be *pnp* transistor or *npn* transistor. An *npn* transistor, found more commonly in IC logic circuits, is shown in the figure 3 in its common-emitter configuration.

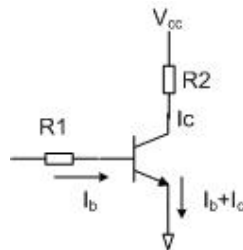


FIG. 3: Common emitter configuration of an *npn* transistor

The relations between different quantities are given as in the following:

$$I_b = (V_{IN} - 0.6)/R1$$

$$I_c = \beta \cdot I_b$$

$$V_{CE} = V_{CC} - I_c \cdot R2$$

$$= V_{CC} - \beta \cdot I_b \cdot R2$$

$$= V_{CC} - \beta(V_{IN} - 0.6) \cdot R2/R1$$

where β is called the gain of the transistor and is in the range of 10 to 100 for typical transistors. Figure 4 shows a logic inverter from an *npn* transistor in the common-emitter configuration. When the input voltage V_{IN} Low, the output voltage is High, and vice versa.

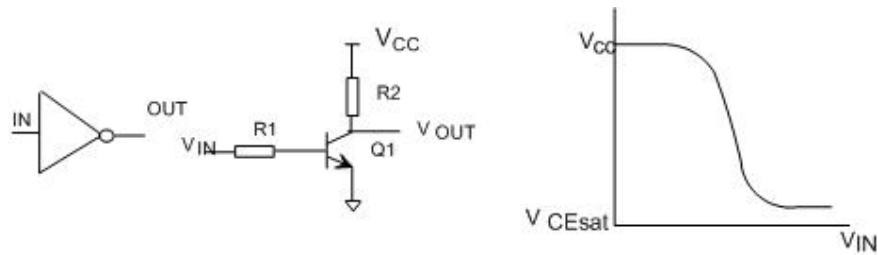


FIG. 4: Transistor inverter

When the input of a saturated transistor is changed, the output does not change immediately; it takes extra time, called storage time, to come out of saturation. In fact, storage time accounts for a significant portion of the propagation delay in the earlier TTL families. Present day TTL logic families reduce this storage time by placing a Schottky diode between the base and collector of each transistor that might saturate.

Schottky Barrier Diode

A Schottky Barrier Diode (SBD) is illustrated in figure 5. It is a rectifying metal-semiconductor contact formed between a metal and highly doped N semiconductor.

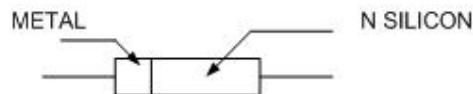


FIG. 5: Schottky Barrier -Diode

The valence and conduction bands in a metal overlap making available a large number of free-energy states. The free-energy states can be filled by any electrons which are injected into the conduction band. A finite number of electrons exist in the conduction band of a semiconductor. The number of electrons depends mainly upon the thermal energy and the level of impurity atoms in the material. When a metal-semiconductor junction is formed, free electrons flow across the junction from the semiconductor, via the conduction band, and fill the free-energy states in the metal. This flow of electrons builds a depletion potential across the barrier. This depletion potential opposes the electron flow and,

eventually, is sufficient to sustain a balance where there is no net electron flow across the barrier. Under the forward bias (metal positive), there are many electrons with enough thermal energy to cross the barrier potential into the metal. This forward bias is called "hot injection." Because the barrier width is decreased as forward bias V_F increases, forward current will increase rapidly with an increase in V_F .

When the SBD is reverse biased, electrons in the semiconductor require greater energy to cross the barrier. However, electrons in the metal see a barrier potential from the side essentially independent of the bias voltage and small net reverse current will flow. Since this current flow is relatively independent of the applied reverse bias, the reverse current flow will not increase significantly until avalanche breakdown occurs. A simple metal/n-semiconductor collector contact is an ohmic contact while the SBD contact is a rectifying contact. The difference is controlled by the level of doping in the semiconductor material.

Current in SBD is carried by majority carriers. Current in a p-n junction is carried by minority carriers and the resultant minority carrier storage causes the switching time of a p-n junction to be limited when switched from forward bias to reverse bias. A p-n junction is inherently slower than an SBD even when doped with gold. Another major difference between the SBD and p-n junction is forward voltage drop. For diodes of the same surface area, the SBD will have a larger forward current at the same forward bias regardless of the type of metal used. The SBD forward voltage drop is lower at a given current than a p-n junction. Figure 6 illustrates the forward current-voltage characteristic differences between the SBD and p-n junction.

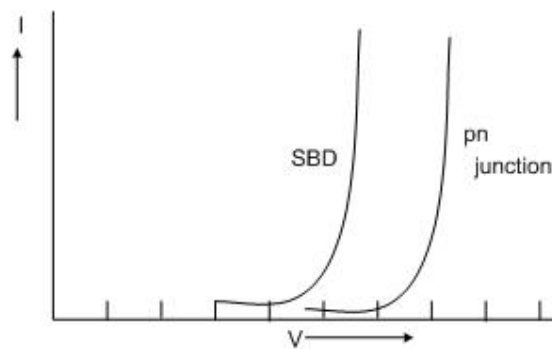


FIG. 6: Characteristics of SBD and *pn* junction diodes

Schottky Transistor

The Schottky transistor makes use of two earlier concepts: Baker clamp and the Schottky-Barrier-Diode (SBD). The Schottky clamped transistor is responsible for increasing the switching speed. The use of Baker Clamp, shown in the figure 7, is a method of avoiding saturation of a discrete transistor.

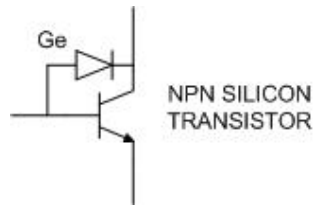


FIG. 7: Baker Clamp

The germanium diode forward voltage is 0.3 V to 0.4 V as compared to 0.7 V for the base-emitter junction silicon diode. When the transistor is turned on, base current drives the transistor toward saturation. The collector voltage drops, the germanium diode begins to conduct forward current, and excess base drive is diverted from the base-collector junction of the transistor. This causes the transistor to be held out of deep saturation, the excess base charge not stored, and the turn-off time to be dramatically reduced. However, a germanium diode cannot be incorporated into a monolithic silicon integrated circuit. Therefore, the germanium diode must be replaced with a silicon diode which has a lower forward voltage drop than the base-collector junction of the transistor. A normal p-n diode will not meet this requirement. An SBD can be used to meet the requirement as shown in the figure 8.

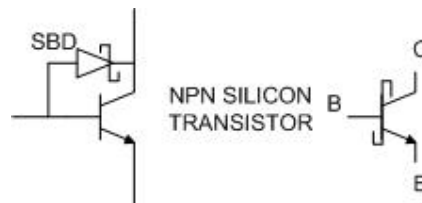


FIG.8: The Schottky-Clamped Transistor

The SBD meets the requirements of a silicon diode which will clamp a silicon *nnp* transistor out of saturation.

BASIC NAND GATE

The familiarization with a logic family is acquired, in general, through understanding the circuit features of a NAND gate. The circuit diagram of a two-input LSTTL NAND gate, 74LS00, is shown in the figure 9.

D1 and D2 along with 18 KΩ resistor perform the AND function. Diodes D3 and D4 do nothing in normal operation, but limit undesirable negative excursions on the inputs to a signal diode drop. Such negative excursions may occur on High-to-Low input transitions as a result of transmission-line effects. Transistor Q1 serves as an inverter, so the output at its collector represents the NAND function. It also, along with its resistors, forms a phase splitter that controls the output stage. The output state has two transistors, Q3 and Q4, only one of which is on at any time. The TTL output state is sometimes called a totem-pole output. Q2 and Q5 provide active pull-up and pull-down to the High and Low states,

respectively. Transistor Q5 regulates current flow into the base of Q4 and aids in turning Q4 off rapidly. Transistors Q3 and Q2 constitute a Darlington driver, with Q3 not being permitted to saturate. The network consisting of Schottky diodes D3 and D4 and a 5 K Ω resistor is connected to the output and aids in charging and discharging load capacitance when Q3 and Q4 are changing states. Transistor Q4 conducts when the output is in Low state.

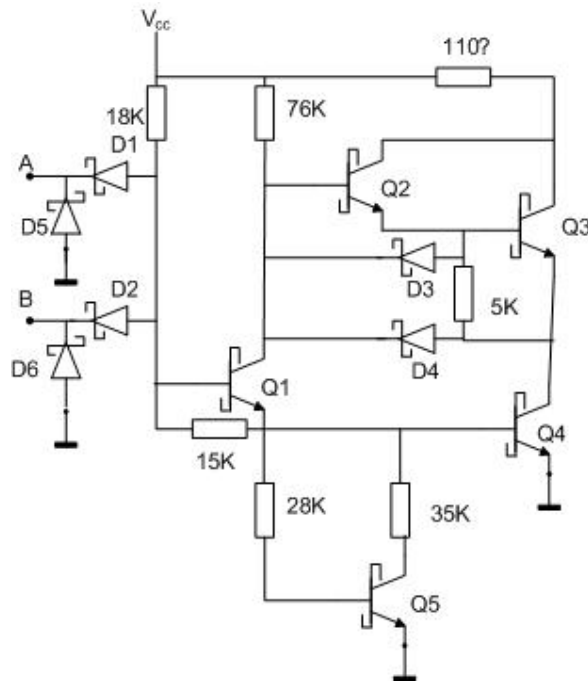


FIG. 9: Low Power Schottky NAND (74LS00)

The FAST Schottky TTL family provides a 75-80% power reduction compared to standard Schottky TTL and yet offers 20-40% improved circuit performance over the standard Schottky due to the MOSAIC process. Also, FAST circuits contain additional circuitry to provide a flatter power/frequency curve. The input configuration of FAST uses a lower input current which translates into higher fan-out. The NAND gate of FAST family is shown in the figure 10.

The F00 input configuration utilises a *p-n* diodes (D1 and D2) rather than *pnp*-transistor.

The *p-n* diode offers a much smaller capacitance and results in much better ac noise immunity at the expense of increased input

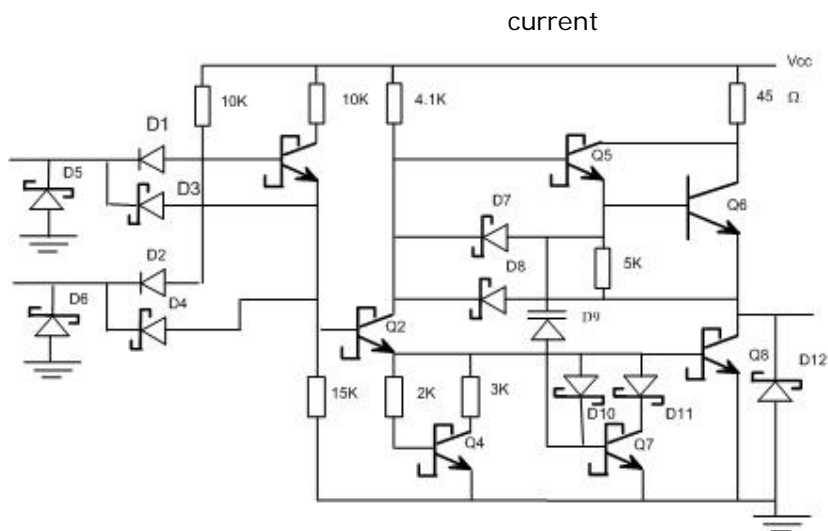


FIG. 10: FAST NAND (74F00)

Figure 11 shows one gate in 74ALS00A quad 2-input NAND gate parallel-connected *pnp* transistors Q1 and Q2 are used at the input. These transistors reduce the current flow, I_R , when the inputs are low and thus increase fan out. If inputs A, B, or both are low, then the respective *pnp* transistors turn on because their emitters are then more positive than their bases. If at least one of the inputs is low, the corresponding *pnp* transistor conducts, making the base of Q3 low and keeping Q3 off. If both the inputs A and B are high, both switches are open and Q3 turns on. Q3 drives Q4 (by emitter follower action), and Q4 drives the output totem pole. Schottky diodes D3, D4 and D5 are used to speed the switching and do not affect the logic. Note that the output and the inputs have Schottky protective diodes. Figure 12 shows one gate in 74AS00 gate.

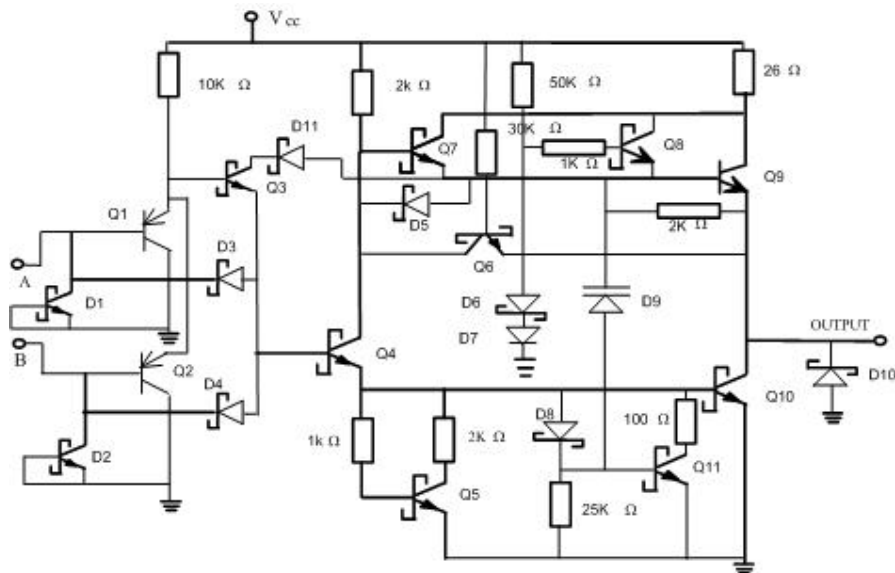


FIG. 11: ALS NAND gate (74ALS00A)

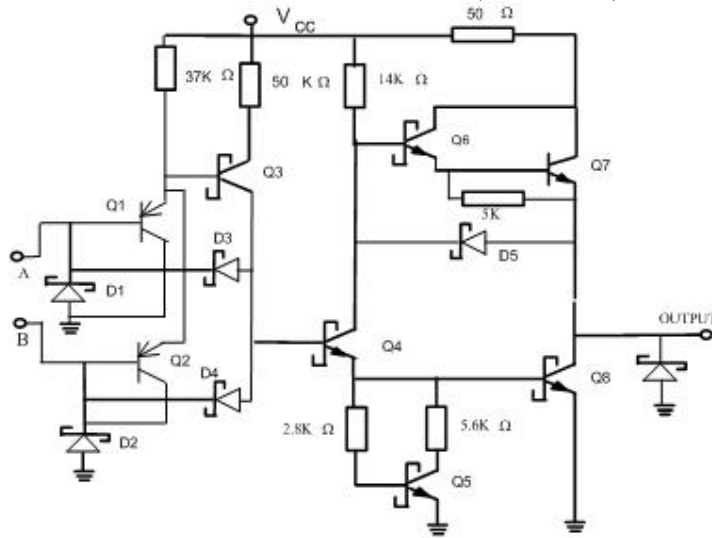


FIG. 12: ASTTL NAND gate (74AS00)

Note that the input logic circuitry is essentially the same as that in 74ALS00 gate, as is the output totem pole. The additional circuitry between input and output improves switching speeds using sophisticated drivers and feedback networks

The ALS and AS families incorporate the following features:

1. Full Schottky clamping of all saturating transistors virtually eliminating storing excessive base charge and significantly enhancing turn-off time of the transistors.
2. Elimination of transistor storage time provides stable switching times across the temperature range.
3. An active turn-off is added to square up the transfer characteristic and provide improved high-level noise immunity.
4. Input and output clamping is implemented with Schottky diodes to reduce negative-going excursions on the inputs and outputs. Because of its lower forward voltage drop and fast recovery time, the Schottky input diode provides improved clamping action over a conventional *p-n* junction diode.
5. The ion implantation process allows small geometries giving less parasitic capacitances so that switching times are decreased.
6. The reduction of the epi-substrate capacitance using oxide isolation also decreases switching times.



Digital Electronics

Module 3: CMOS Family

N.J. Rao

Indian Institute of Science



CMOS Family

CMOS has often been called the ideal technology.

It has

- Low power dissipation
- High noise immunity to power supply noise
- Symmetric switching characteristics
- Large supply voltage tolerance



CMOS Family

Reducing power requirements leads to

- Reduction in the cost of power supplies
- Simplifies power distribution
- Possible elimination of cooling fans
- A denser PCB
- Ultimately lower cost of the system



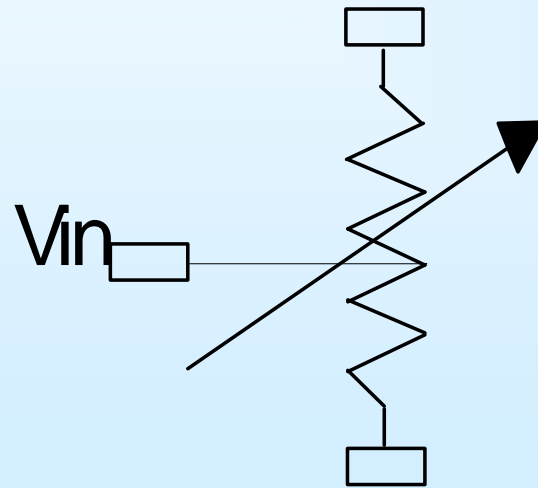
History of CMOS

- Operation of a MOS transistor was understood long before bipolar transistor was invented
- As its fabrication could not be monitored, development of MOS circuits lagged bipolar circuits considerably
- Initially they were attractive only in selected applications.
- At present CMOS circuits are used from SSI to VLSI



MOS transistor

- The basic building blocks in CMOS logic circuits are MOS transistors.
- A MOS transistor can be viewed as a 3-terminal device that acts like a voltage-controlled resistance





MOS transistor

- An input voltage, applied to one terminal, controls the resistance between the remaining two terminals.
- In digital applications, a MOS transistor is operated so that its resistance is always either very high (and the transistor “off”) or very low (and the transistor is always “on”).



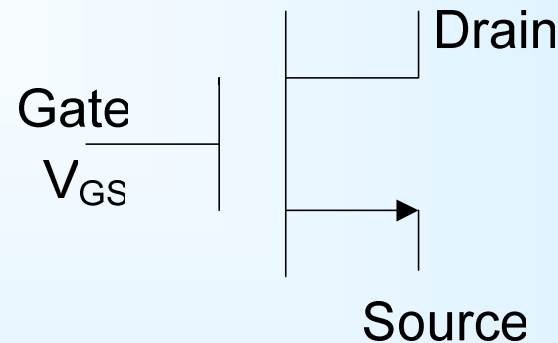
Types of MOS transistors

There are two types of transistors

- NMOS transistor that uses n-channel
- PMOS transistor that uses p-channel



NMOS Transistor



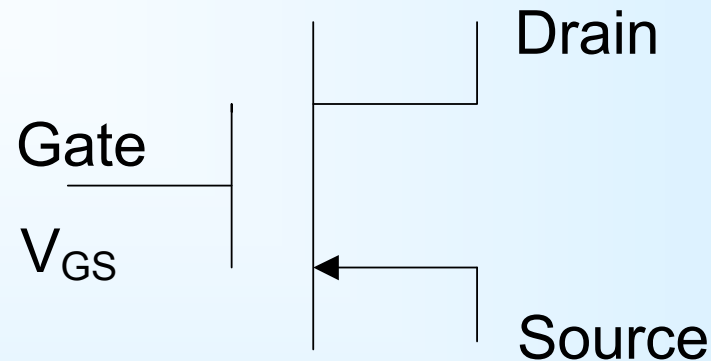
V_{GS} in NMOS device is normally zero or positive.

If $V_{GS} = 0$ then the resistance from drain to source (R_{DS}) is very high, of the order of mega ohm or more.

When V_{GS} is made positive R_{DS} can decrease to a very low value, of the order of 10 ohms.



PMOS Transistor



V_{GS} is normally zero or negative.

If V_{GS} is zero, then the resistance from source to drain (R_{DS}) is very large

When V_{GS} is negative R_{DS} can decrease to a very low value.



Gate of a MOS transistor

- It has very high impedance
- Gate is separated from the source and drain by an insulating material with a very high resistance.
- Gate voltage creates an electric field that enhances or retards the flow of current between source and drain. This is the “field effect” in a MOSFET.
- The high resistance between the gate and the other terminals keeps the gate current to values lower than a microampere irrespective of the gate voltage.



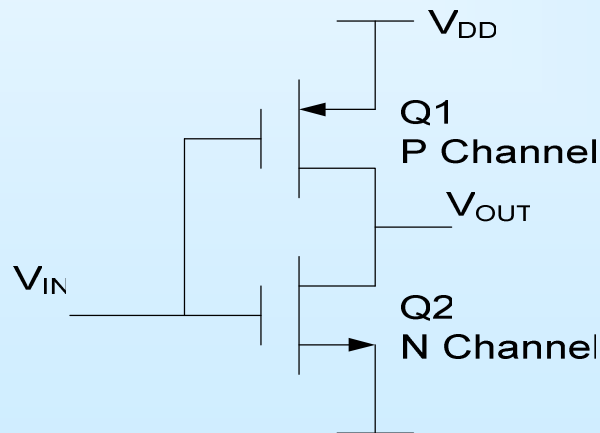
Gate of a MOS transistor (2)

- The gate current is called “leakage current”.
- The gate of a MOS transistor is capacitively coupled to the source and drain.
- In high speed circuits, the power needed to charge and discharge these capacitances on each input signal transition accounts for a non trivial portion of a circuit’s power consumption.



Basic CMOS Inverter circuit

- NMOS and PMOS transistors are used together in a complementary way to form CMOS logic
- The power supply voltage V_{DD} , typically is in the range of 2- 6 V, and is most often set at 5.0 V for compatibility with TTL circuits.





Basic CMOS Inverter circuit (2)

V_{IN}	Q1	Q2	V_{OUT}
0.0	On	Off	5V
5.0	Off	On	0V

When V_{IN} is at 0.0 V, the lower n-channel MOSFET Q1 is OFF since its V_{GS} is 0, but the upper p-channel MOSFET Q2 is ON since its V_{GS} would be -5.0 V

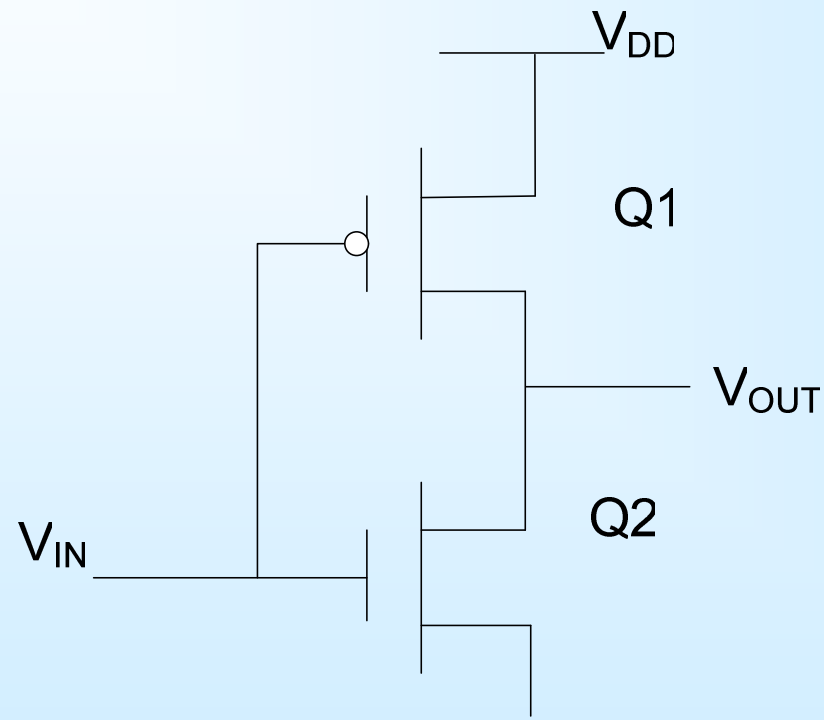
V_{OUT} at the output terminal would be +5.0 V.

Similarly when V_{IN} is at 5.0 Q1 will be ON presenting a small resistance, while Q2 will be OFF presenting a large resistance.

V_{OUT} would be 0 V

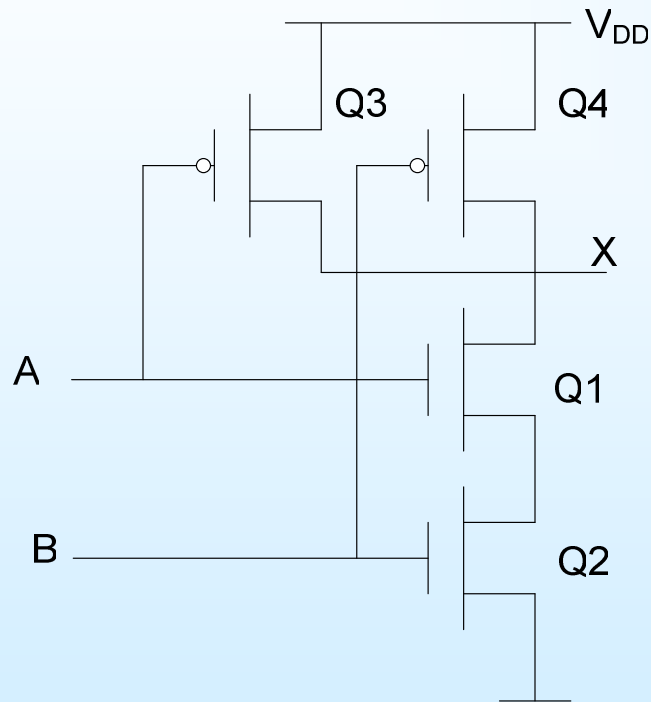


Inverter as per the bubble convention

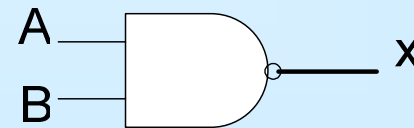




CMOS NAND Gate

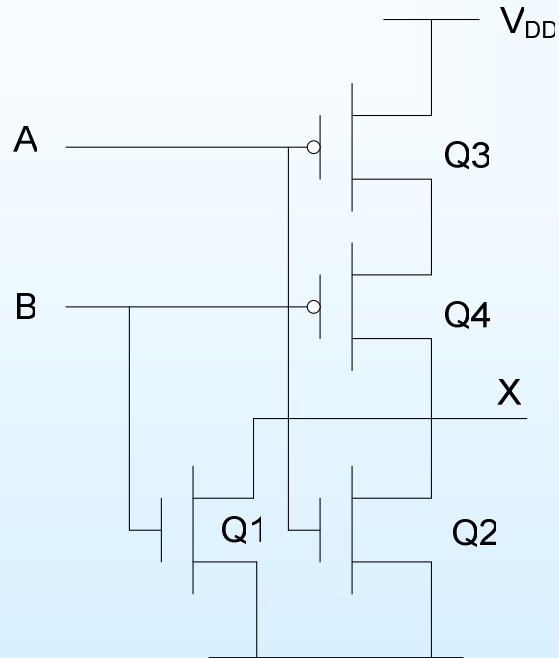


A	B	Q1	Q2	Q3	Q4	X
L	L	OFF	OFF	ON	ON	H
L	H	OFF	ON	ON	OFF	H
H	L	ON	OFF	OFF	ON	H
H	H	ON	ON	OFF	OFF	L

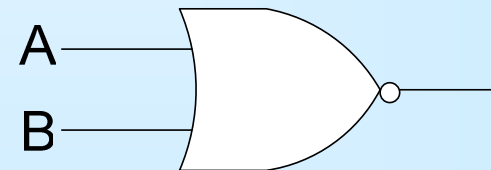




CMOS NOR Gate

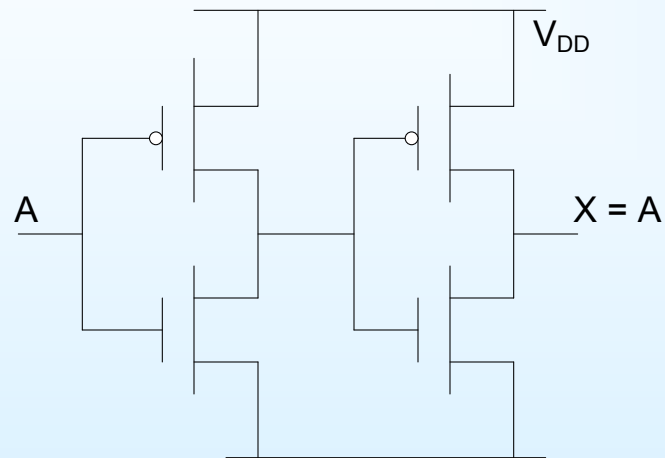


A	B	Q1	Q2	Q3	Q4	X
L	L	OFF	OFF	ON	ON	H
L	H	OFF	ON	ON	OFF	L
H	L	ON	OFF	OFF	ON	L
H	H	ON	ON	OFF	OFF	L

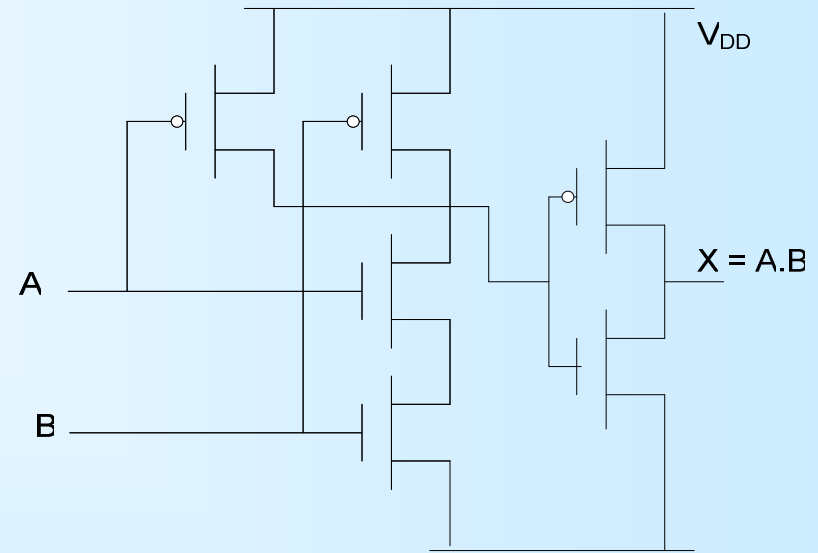




Non-inverting Gates



Buffer

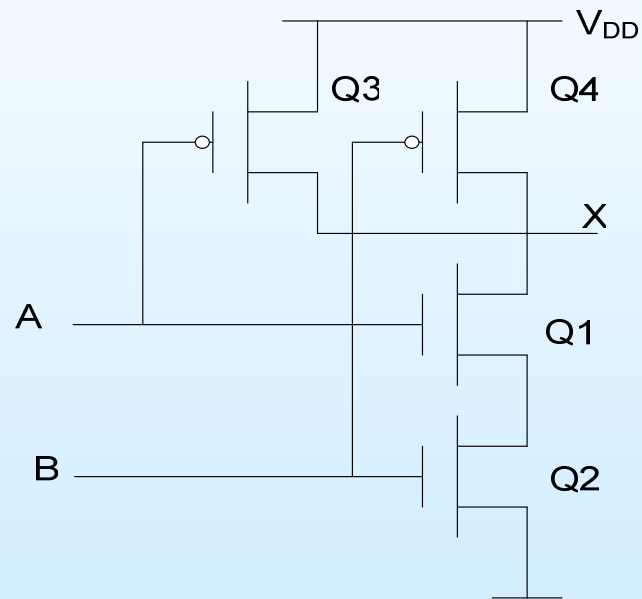


AND Gate

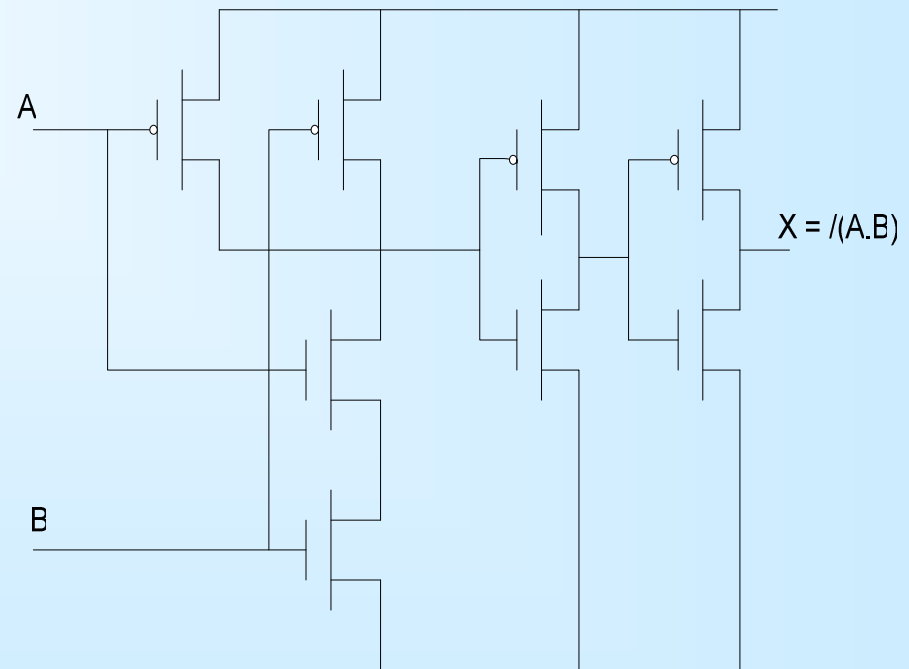


Buffering

Most of the CMOS families are buffered.



Unbuffered NAND



Buffered NAND



Advantages of buffering

- Output characteristics of all devices are more easily made identical.
- Multistage gates will have better noise immunity due to their higher gain caused by having several stages from input to output.
- Output impedance of buffered gates is unaffected by input conditions



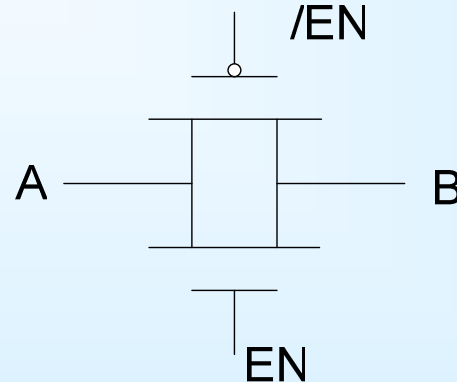
Advantages of buffering (2)

- Single stage gates implemented would require large transistors due to the large output drive requirements.
- Large devices would have a large input capacitance associated with them. This would affect the speed of circuits driving into an unbuffered gate, especially when driving large fan outs.
- Buffered gates have small input transistors and correspondingly small input capacitance.
- Internal stages are much faster than the output stage and speed lost by buffering is relatively small.



Transmission Gates

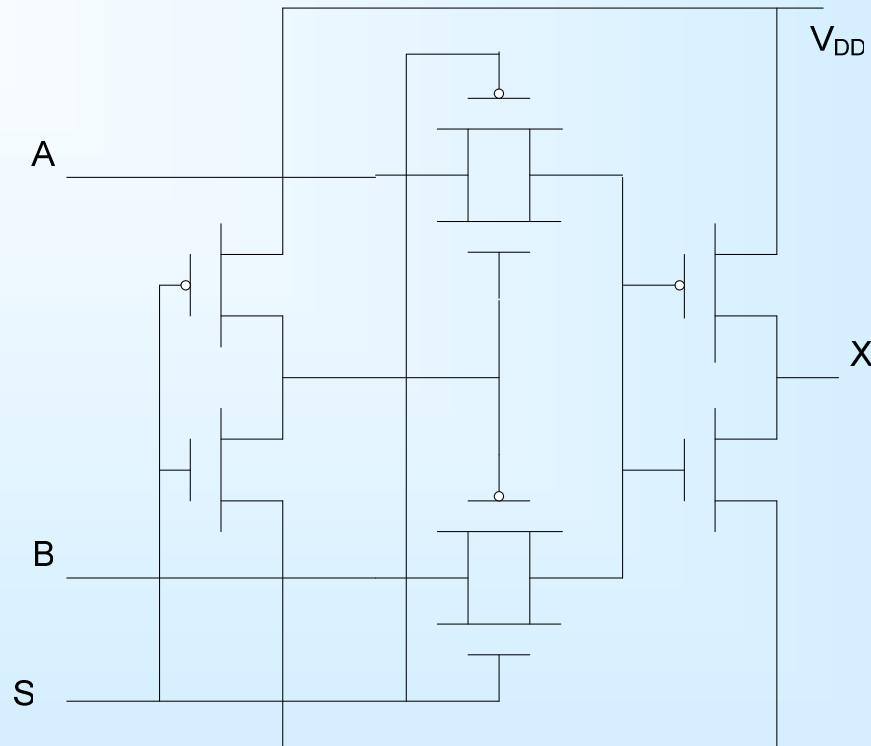
- A p-channel and n-channel transistor pair can be used as a logic-controlled switch.



- When EN is High there is a low impedance connection (as low as 5 W) between points A and B.
- When EN is Low, points A and B are disconnected.
- Propagation delay from A to B is very short.



2-input multiplexer with transmission gate



When S is Low, the B is connected to X, and when S is High, A is connected to X.

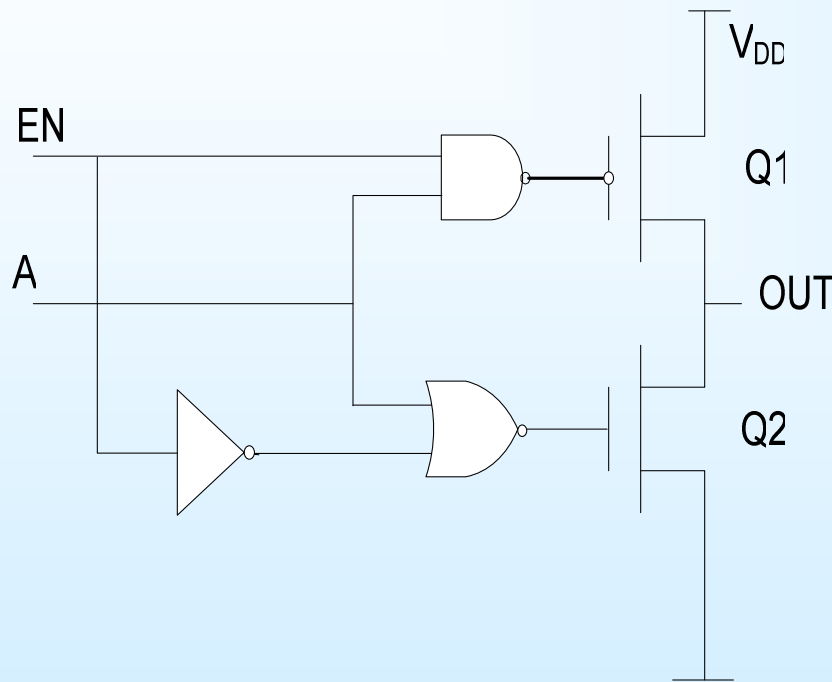


CMOS Input and Output Structures

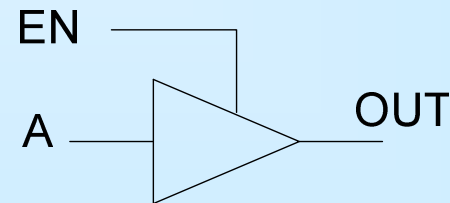
- CMOS family offers a Hex inverter with Schmitt inputs (74HC14).
- It offers a hysteresis of 1.5 V when operated at 5 V.



CMOS tri-state buffer

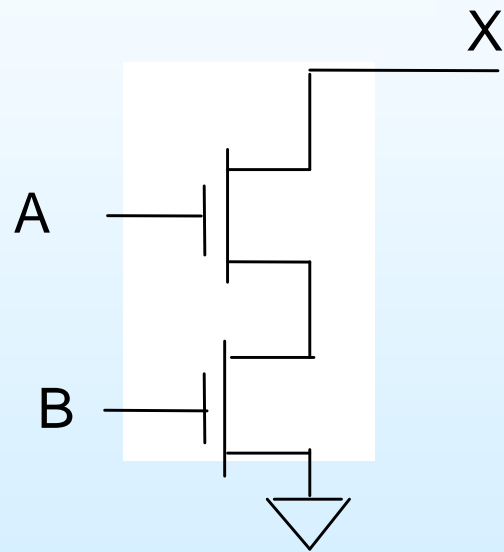


EN	A	Q1	Q2	OUT
L	L	OFF	OFF	Hi-Z
L	H	OFF	OFF	Hi-Z
H	L	ON	OFF	L
H	H	OFF	ON	H

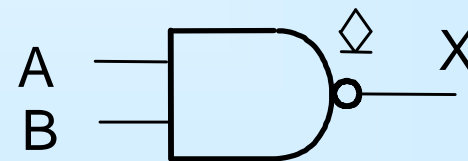




Open-drain CMOS NAND gate

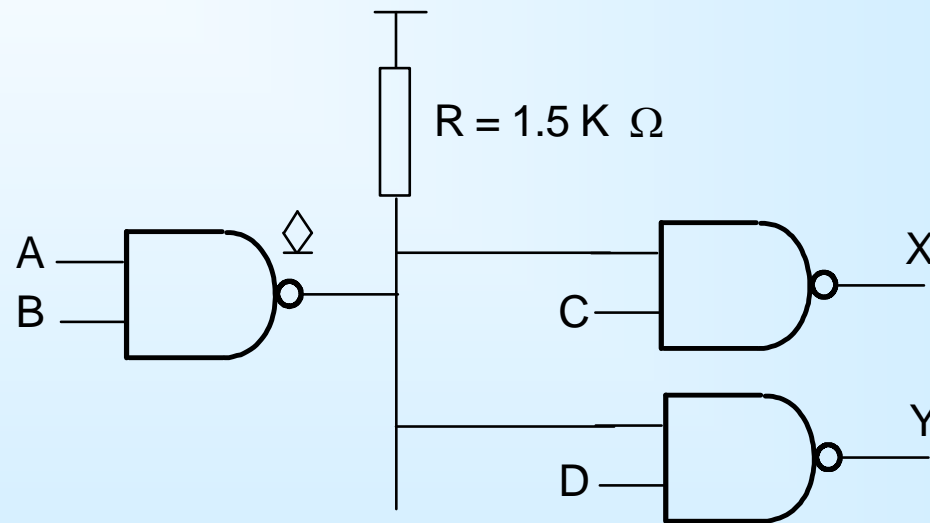


A	B	Q1	Q2	X
L	L	off	off	open
L	H	off	on	open
H	L	on	off	open
H	H	on	on	L





Open-drain CMOS NAND gate driving a load





CMOS Logic Families

- 4000-series
- High Speed CMOS (75HC CMOS)
- High Speed TTL compatible CMOS (75HCT CMOS)
- HC CMOS can use any power supply voltage between 2 and 6 V.
- Lowering the supply voltage is effective, since most CMOS power dissipation is CV^2f



CMOS Logic Families (2)

- AC (Advanced CMOS) ACT (Advanced CMOS, TTL compatible) were introduced in mid-1980s.
- FCT (Fast CMOS, TTL compatible) introduced in 1990s
- The family combines circuit innovations with smaller transistor geometries to produce devices that are even faster than AC and ACT while reducing power consumption and maintaining full compatibility with TTL.



Subfamilies of FCT CMOS

- FCT-T and FCT2-T
- These families represent a “technology crossover point” that occurred when the performance achieved using CMOS technology matched that of bipolar technology, and typically one third the power.
- Both the logic families are TTL compatible



Logical Levels

Family	V_{IHMIN}	V_{ILMAX}	V_{OHMIN}	V_{OLMAX}	NM LOW @ V_{CC} =5V	NM HIGH @ V_{CC} =5V	
4000B	$\frac{1}{3} V_C$	$\frac{2}{3} V_C$	$V_{CC}-0.1$	0.01	1.6	1.6	V
HCMOS	3.5	1.5	$V_{CC}-0.1$	0.1	1.4	1.4	V
HCTMOS	2	0.8	$V_{CC}-0.1$	0.1	0.7	2.4	V
ACMOS	3.5	1.5	$V_{CC}-0.1$	0.1	1.4	1.4	V
ACTMOS	2	0.8	$V_{CC}-0.1$	0.1	0.7	2.4	V
FCT	2	0.7	2.4	0.5	0.2	0.4	V



Noise Margins

Voltage levels associated with CMOS gates

$$V_{IL(max)} = 30\% VDD$$

$$V_{OH(min)} = VDD - 0.1 V$$

$$V_{IH(min)} = 70\% VDD$$



Input and Output Current Levels

CMOS Families	Input currents		Output currents		
	I_{IH}	I_{IL}	I_{OH}	I_{OL}	
4000b +5	<u>0.001</u>	0.001	-1.6 @2.5 V	0.4@0.4 V	mA
74HC	0.001	-0.001	-4 @ V_{CC} -0.8	4 @0.4	mA
74HCT	0.001	0.001	-4 @ V_{CC} -0.8	4 @ 0.4 V	mA
74AC	0.001	-0.001	-24@ V_{CC} -0.8	24 @0.4 V	mA
74ACT	0.001	-0.001	-24@ V_{CC} -0.8	24 @0.4 V	mA
74FCT	0.005	-0.005	-15 @ 2.4 V	48 @0.5 V	mA



Fan out

For HCMOS

- I_{ILmax} is $\pm 1 \mu A$ in any state
- $I_{OHmax} = -20 \mu A$ and $I_{OLmax} = 20 \mu A$
- Low-state fan out is 20
- High-state fan out is 20
- If we are willing to work with slightly degraded output voltages, which would reduce the available noise margins, we can go for a much larger fan out



Dynamic Electrical Behavior

Speed depends on transition times and propagation delay

The rise and fall times of an output of CMOS IC depend on

- ON transistor resistance
- Load capacitance



Dynamic Electrical Behavior (2)

Load capacitance comes from

- Output circuits including a gate's output transistors
- Internal wiring and packaging, have capacitances associated with them (of the order of 2-10 pF)
- Wiring that connects an output to other inputs (about 1pF per inch or more depending on the wiring technology)
- Input circuits including transistors, internal wiring and packaging (2-15 pF per input).



Dynamic Electrical Behavior (3)

- OFF transistor resistance would be about $1\text{ M}\Omega$,
- ON resistance of p-channel transistor would be of the order of $200\ \Omega$
- ON resistance of n-channel resistance would be about $100\ \Omega$
- We can compute the rise and fall times from the equivalent circuits.



Propagation Delay

In a CMOS device, the rate at which transistors change state is influenced by

- Physics of the device
- Circuit environment including input-signal transition rate, input capacitance, and output loading



Speed Characteristics

Family	Prop. Delay (ns)	Flip-Flop frequency (MHz)
4000B	160	5
HCMOS	22	25
HCTMOS	24	25
ACMOS	8.5	45
ACTMOS	8	45
FCTMOS	5.8 (≈ 138)	60

Device outputs in AC and ACT families have very fast rise and fall times. Input signals should have rise and fall times of 3.0 ns (400 ns for HC and HCT devices) and signal swing of 0V to 3.0V for ACT devices or 0V to V_{DD} for AC devices.



Power Consumption

- A CMOS circuit consumes significant power only during transition
- Sources of dynamic power dissipation
- Partial short-circuiting of the CMOS output structure
- Capacitive load (C_L) on the output



Partial short-circuiting

The amount of power consumed during transition depends on

- the value of V_{DD}
- the frequency of output transitions

Equivalent dissipation capacitance C_{PD} as given by the manufacturer

$$PT = C_{PD} \cdot V_{DD}^2 \cdot f$$

C_{PD} for a gate of HCMOS is about 24 pF



Dissipation due to capacitive loading

- During Low-to-High transition, current passes through the p -channel transistor to charge the load capacitance.
- During High-to-Low transition, current flows through the n -channel transistor to discharge the load capacitor.
- During the transitions the voltage across the capacitor changes by V_{DD} .
- For each pulse there would be two transitions.



Dissipation due to capacitive loading (2)

As the currents are passing through the transistors, and capacitor itself would not be dissipating any power, the power dissipated due to the capacitive load is

$$P_L = C_L \cdot V_{DD}^2 \cdot f$$



Total dynamic power dissipation

$$\begin{aligned} P_D &= P_T + P_L \\ &= C_{PD} \cdot V_{DD}^2 \cdot f + C_L \cdot V_{DD}^2 \cdot f \\ &= (C_{PD} + C_L) \cdot V_{DD}^2 \cdot f \end{aligned}$$

FCT does not have a C_{PD} specification

I_{CCD} specification gives the same information in a different way.

The internal power dissipation due to transition at a given frequency f can be calculated by the formula

$$P_T = V_{CC} \cdot I_{CCD} \cdot f$$



Power Dissipation Characteristics

Parameter	HC	HCT	AC	ACT	FCT	Units
Quiescent power dissipation						
'00	0.0025	0.0025	0.005	0.005		mW
'138	0.04	0.04	0.04	0.04	7.5	mW
Power dissipation (capacitance)						
'00	24	24	30	30		pF
'138	85	85	60	60		pF



Power Dissipation Characteristics (2)

Parameter	HC	HCT	AC	ACT	FCT	Units
Dynamic power dissipation						
'00 at 1 MHz	0.6	0.6	0.75	0.75		mW
'138 at 1 MHz	2.1	2.1	1.5	1.5	1.5	mW
Total power dissipation						
'00 at 100KHz	0.0625	0.0625	0.08	0.08		mW
'00 at 1 MHz	0.6025	0.6025	0.755	0.755		mW
'00 at 10 MHz	6.0025	6.0025	7.505	7.505		mW
'138 at 100KHz	0.25	0.25	0.19	0.19	7.5	mW
'138 at 1 MHz	2.14	2.14	1.54	1.54	9	mW
'138 at 10 MHz	21.04	21.04	21.04	21.04	30	mW

CMOS FAMILY

CMOS has often been called the ideal technology. It has low power dissipation, high noise immunity to power supply noise, symmetric switching characteristics and large supply voltage tolerance. Reducing power requirements leads to reduction in the cost of power supplies, simplifies power distribution, possible elimination of cooling fans and a denser PCB, ultimately leading to lower cost of the system. Though the operation of a MOS transistor was understood long before bipolar transistor was invented, its fabrication could not be monitored. Consequently development of MOS circuits lagged bipolar circuits considerably, and initially they were attractive only in selected applications. In recent years, advances in the design of MOS circuits have vastly increased their performance and popularity. By far majority of the large scale integrated circuits such as microprocessors and memories use CMOS. The usage of CMOS logic is increasing in applications that use small and medium scale integrated circuits as CMOS circuits, while offering functionality and speed similar to bipolar logic circuits, consume very much less power.

CMOS LOGIC CIRCUITS

The basic building blocks in CMOS logic circuits are MOS transistors. A MOS transistor can be received as a 3-terminal device that acts like a voltage-controlled resistance, as shown in the figure 1.

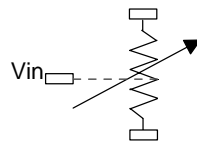
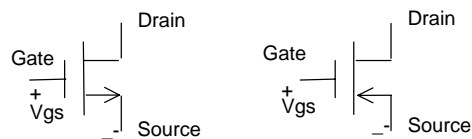


FIG. 1: MOS transistor as a voltage controlled resistance

An input voltage applied to one terminal controls the resistance between the remaining two terminals. In digital applications, a MOS transistor is operated so its resistance is always either very high (and the transistor "off") or very low (and the transistor is always "on"). There are two types of MOS transistors n-channel and p-channel. The circuit symbols for NMOS and PMOS transistors are shown in the figure 2.



NMOS transistor PMOS transistor

FIG. 2: Circuit symbols of MOSFETs

The terminals are called gate, source and drain. The voltage from gate to source (V_{GS}) in NMOS device is normally zero or positive. If $V_{GS} = 0$ then the resistance from drain to source (R_{DS}) is very high, of the order of mega ohm or more. When V_{GS} is made positive R_{DS} can decrease to a very low value, of the order of 10 ohms. In the PMOS transistor V_{GS} is normally zero or negative. If V_{GS} is zero, then the resistance from source to drain (R_{DS}) is very large, and when V_{GS} is negative R_{DS} can decrease to a very low value. The gate of a MOS transistor has very high impedance, as it is separated from the source and drain by an insulating material with a very high resistance. However, the gate voltage creates an electric field that enhances or retards the flow of current between source and drain. This is the “field effect” in a MOSFET. The high resistance between the gate and the other terminals keeps the gate current to values lower than a microampere irrespective of the gate voltage. This current is called “leakage current”. The gate of a MOS transistor is capacitively coupled to the source and drain. In high speed circuits, the power needed to charge and discharge these capacitances on each input signal transition accounts for a non trivial portion of a circuit’s power consumption.

Basic CMOS Inverter circuit: NMOS and PMOS transistors are used together in a complementary way to form CMOS logic, as shown in the figure 3. The power supply voltage V_{DD} , typically is in the range of 2- 6 V, and is most often set at 5.0 V for compatibility with TTL circuits.

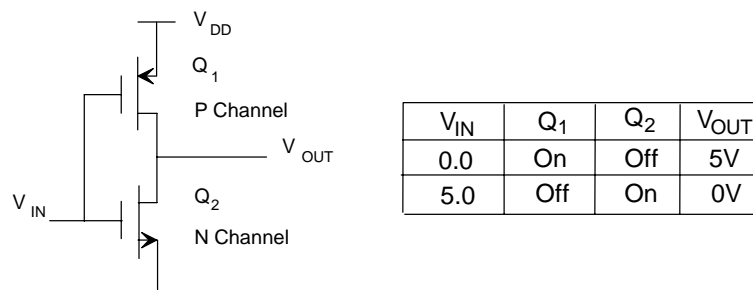


FIG. 3: CMOS Inverter

When V_{IN} is at 0.0 V, the lower n-channel MOSFET Q_1 is OFF since its V_{GS} is 0, but the upper p-channel MOSFET Q_2 is ON since its V_{GS} would be -5.0 V. Consequently Q_2 presents a small resistance while Q_1 presents a large resistance. V_{OUT} at the output terminal would be +5.0 V. Similarly when V_{IN} is at 5.0 Q_1 will be ON presenting a small resistance to ground while Q_2 will be OFF presenting a large resistance. The output terminal voltage (V_{OUT}) would be 0 V. Obviously this circuit behaves as an inverter.

As we associated a logic state 0 or 1 with a voltage, we can say when the input signal is asserted Q_1 is ON and Q_2 is OFF, and when the input signal is not asserted Q_1 is OFF and Q_2 is ON. We make use of this interpretation to further

simplify the circuit representation of MOSFETs, as shown in the figure 4. The bubble convention goes along with the convention followed in drawing logic diagrams.

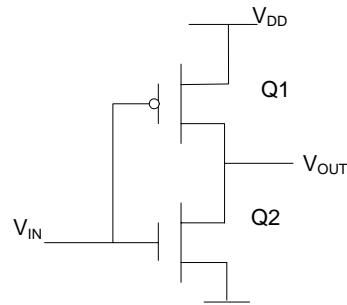
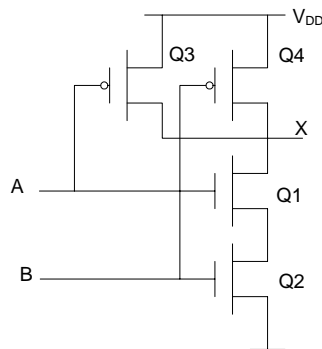


FIG. 4 CMOS inverter drawn as per logic convention

CMOS NAND and NOR gates: Logic gates can be realised using CMOS circuits. A k-input gate uses k p-channel MOSFETs and k n-channel MOSFETs. Figure 5 shows a 2-input NAND gate. If either input is Low, the output X is High with low impedance connection to V_{DD} through the corresponding p-channel transistor, and the path to the ground is blocked by the corresponding OFF n-channel MOSFET. If both inputs are High, the two n-channel MOSFETs are ON and the two p-channel MOSFETs are OFF. This is the operation required for the circuit to function as a NAND gate.



A	B	Q1	Q2	Q3	Q4	X
L	L	OFF	OFF	ON	ON	H
L	H	OFF	ON	ON	OFF	H
H	L	ON	OFF	OFF	ON	H
H	H	ON	ON	OFF	OFF	L

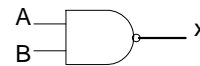
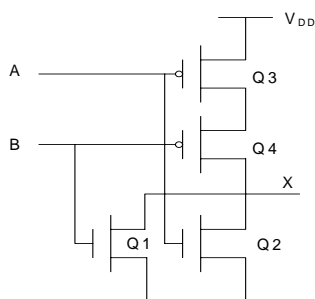


FIG. 5: 2-input CMOS NAND gate

A 2-input NOR gate is shown in figure 6. Only when A and B are Low the output X is High and for all other combination of input levels the output is Low.



A	B	Q1	Q2	Q3	Q4	X
L	L	OFF	OFF	ON	ON	H
L	H	OFF	ON	ON	OFF	L
H	L	ON	OFF	OFF	ON	L
H	H	ON	ON	OFF	OFF	L

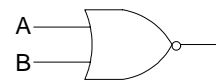


FIG. 6: 2-input CMOS NOR gate

Non Inverting Gates: In all logic families, the simplest gates are inverters, and the next simplest are NAND and NOR gates. It is typically not possible to design a non-inverting gate with a smaller number of transistors than an inverting one. CMOS non-inverting buffers and AND and OR gates are obtained by connecting an inverter to the output of the corresponding inverting gate. Figure 7 shows a non inverting buffer and an AND gate

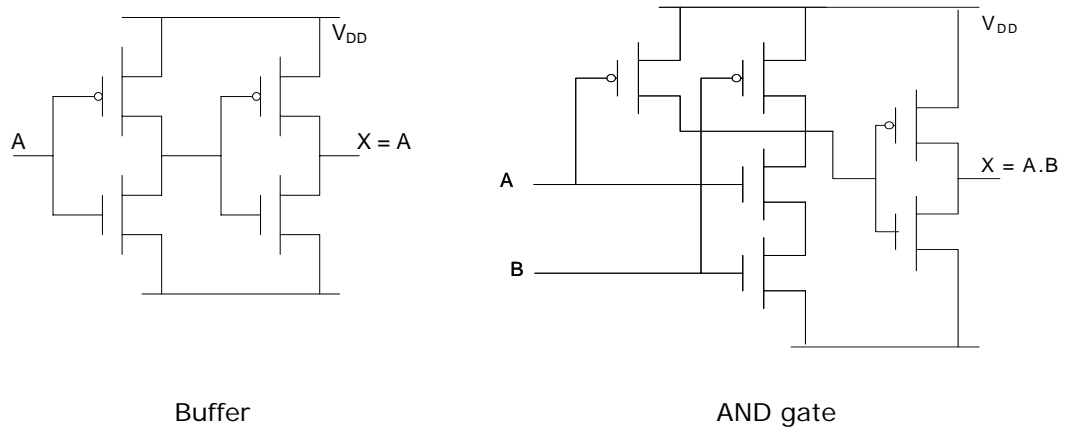


FIG. 7: Non inverting Buffer and AND gate

Buffering: Most of the CMOS families are buffered. Buffering CMOS logic merely denotes designing the IC so that the output is taken from an inverting buffer stage. An unbuffered and buffered NAND gates are illustrated in the figure 8.

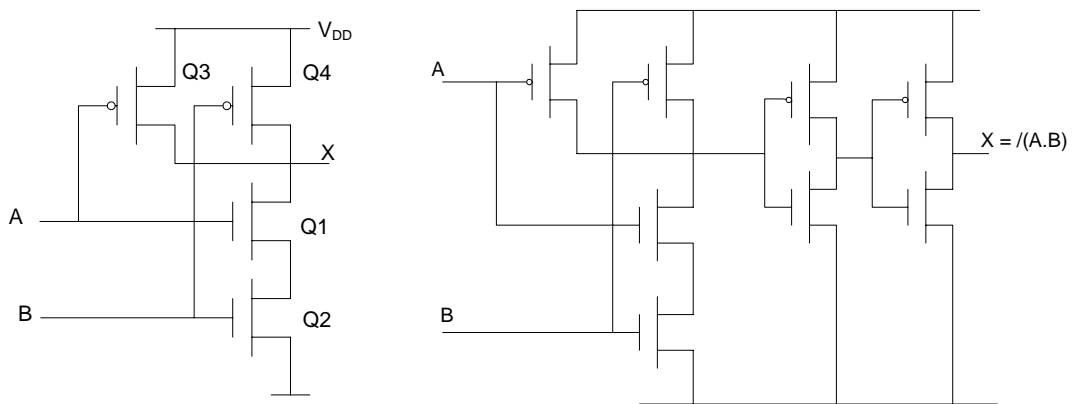


FIG. 8: Unbuffered and buffered NAND gates

There are several advantages to buffering. By using the standardised buffer, the output characteristics of all devices are more easily made identical. Multistage gates will have better noise immunity due to their higher gain caused by having several stages from input to output. Also, the output impedance of an unbuffered gate may change with input logic level voltage and input logic combination, whereas buffered output are unaffected by input conditions. Single stage gates implemented would require large transistors due to the large output drive requirements. These large devices would have a large input capacitance associated

with them. This would affect the speed of circuits driving into an unbuffered gate, especially when driving large fan outs. Buffered gates have small input transistors and correspondingly small input capacitances. One may think that a major disadvantage of buffered circuits would be speed loss. It would seem that a two or three stage gate would be two to three times slower than a buffered one. However, internal stages are much faster than the output stage and speed lost by buffering is relatively small.

Transmission Gates: A p-channel and n-channel transistor pair can be used as a logic-controlled switch. This circuit, shown in the figure 9, is called a CMOS transmission gate.

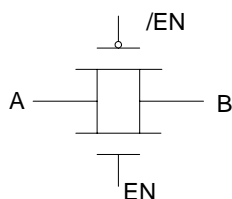


FIG. 9: CMOS transmission gate

A transmission gate is operated so that its input signals EN and /EN are always at opposite levels. When EN is High and /EN is Low, there is a low impedance connection (as low as 5Ω) between points A and B. When EN is Low and /EN is High, points A and B are disconnected. Once transmission gate is enabled, the propagation delay from A to B (or vice versa) is very short. Because of their short delays and conceptual simplicity, transmission gates are often used internally in larger-scale CMOS devices such as multiplexers and flip-flops. For example, figure 10 shows how transmission gates can be used to create a 2-input multiplexer

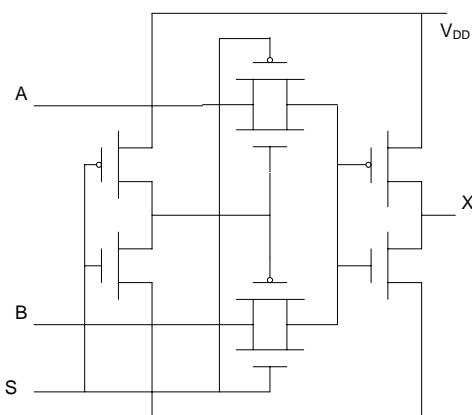


FIG. 10: Two-input multiplexer using CMOS transmission gates

When S is Low, the B is connected to X, and when S is High, A is connected to X. While it may take some nanoseconds for the transmission gate to change its state, the propagation delay from input to output of the gate would be very small.

CMOS Input and Output Structures: CMOS family like other logic families has provision for accepting slow changing inputs, offering three-state outputs, and for wired logic connection. CMOS family offers a Hex inverter with Schmitt inputs (74HC14). It offers a hysteresis of 1.5 V when operated at 5 V. It can transform slowly changing input signals into sharply defined, jitter-free output signals. In addition, they have a greater noise margin than conventional inverters.

A circuit diagram (including schematics for gates) for a CMOS three-state buffer is shown in the figure 11. When enable (EN) is Low, both output transistors are off, and the output is in the Hi-Z state. Otherwise, the output is High or Low as controlled by the "data" input A. The figure also shows logic symbol for a three-state buffer. There is a leakage current of up to 10 μA associated with a CMOS three-state output in its Hi-Z state. This current, as well as the input currents of receiving gates, must be taken into account when calculating the maximum number of devices that can be placed on a three-state bus. That is, in the Low or High state, an enabled three-state output must be capable of sinking or sourcing 10 μA of leakage current for every other three-state output on the bus, as well as sinking the current required by every input on the bus.

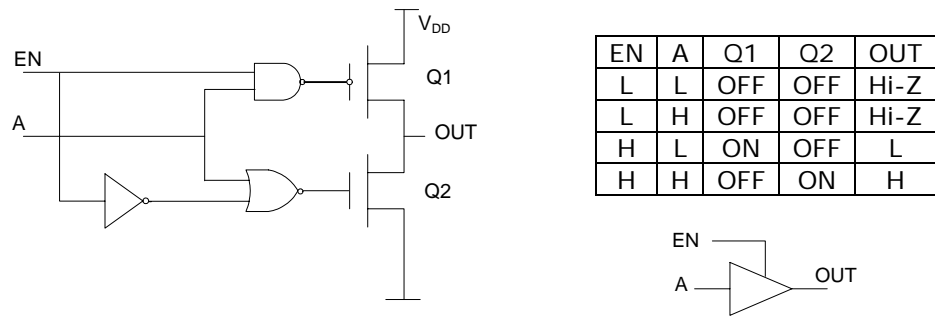


FIG. 11: CMOS three-state buffer

The p-channel transistors in CMOS output structures provide active pull-up. These transistors are omitted in gates with open-drain outputs, such as the NAND gate in figure 12.

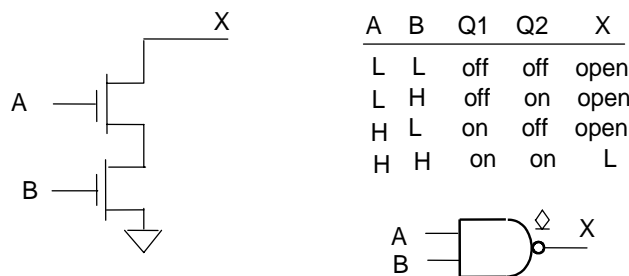


FIG.12: Open-drain CMOS NAND gate

The drain of the topmost n-channel transistor is left unconnected internally, so if the output is not Low it is “open”, as indicated in the figure 13. The underscored diamond in the symbol is sometimes used to indicate an open-drain output. This is similar to the “open-collector” output in TTL logic families. An open-drain output requires an external pull-up resistor to provide passive pull-up to the High level. For example, figure 13 shows an open drain CMOS NAND gate, with its pull-up resistor, driving a load.

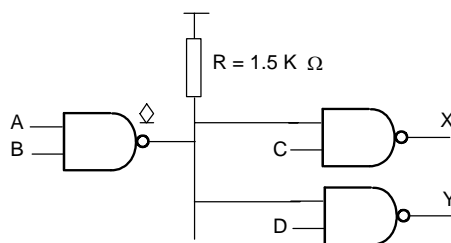


FIG. 13: Open-drain CMOS NAND gate driving a load

CMOS LOGIC FAMILIES

The first commercially successful CMOS family was 4000-series CMOS. Although 4000-series circuits offered the benefit of low power dissipation, they were fairly slow and were not easy to interface with the most popular logic family of the time, bipolar TTL. Thus, the 4000 series was supplanted in most of applications by CMOS families that had better performance characteristics. The first two 74-series CMOS families are HC (High-speed CMOS) and HCT (High-speed CMOS, TTL compatible). HC and HCT both have higher speed and better current sinking and sourcing capability. The HCT family uses a power supply voltage V_{DD} of 5 V and can be intermixed with TTL device, which also use a 5-V supply.

The HC is mainly optimised for use in systems that use CMOS logic exclusively, and can use any power supply voltage between 2 and 6 V. A higher voltage is used for higher speed, and lower voltage for lower power dissipation. Lowering the supply voltage is especially effective, since most CMOS power dissipation is proportional to the square of the voltage (CV^2f). Even when used with a 5 V power supply, HC devices are not quite compatible with TTL. In particular, HC circuits are designed to recognise CMOS input levels. The output levels produced by TTL devices do not quite match this range, so HCT devices use the different input levels. These levels are established in the fabrication process by making transistors with different switching threshold, producing the different transfer characteristics.

Two more CMOS families, known as AC (Advanced CMOS) and ACT (Advanced CMOS, TTL compatible) were introduced in mid-1980s. These families are fast, comparable to ALSTTL, and they can source or sink more current than most of the TTL circuits can. Like HC and HCT, the AC and ACT families differ only in the input levels that they recognise; their output characteristics are the same. Also like HC/HCT, AC/ACT outputs have symmetric output drive.

In the early 1990s, yet another CMOS family was launched. The FCT (Fast CMOS, TTL compatible) family combines circuit innovations with smaller transistor geometries to produce devices that are even faster than AC and ACT while reducing power consumption and maintaining full compatibility with TTL. There are two subfamilies, FCT-T and FCT2-T. These families represent a “technology crossover point” that occurred when the performance achieved using CMOS technology matched that of bipolar technology, and typically one third the power. Both the logic families are TTL compatible, which means that they conform to the industry-standard TTL voltage levels and threshold point (1.5 V), and operate from a 5 Volt V_{CC} power source. All inputs are designed to have a hysteresis of 200 mV (low-to-high threshold of 1.6 V and high-to-low threshold of 1.4V). This hysteresis increases both the static and dynamic noise immunity, as well as reducing the sensitivity to noise superimposed on slowly rising or falling inputs. Individual logic gates are not manufactured in the FCT families. Just about the simplest FCT logic element is a 74FCT138/74FCT138T decoder, which has six inputs, eight outputs and contains the equivalent of about twelve 4-input gates internally

ELECTRICAL BEHAVIOUR OF CMOS CIRCUITS

This section presents the electrical characteristics of CMOS families. The electrical characteristics refer to DC noise margins, fan out, speed, power consumption, noise, electrical discharge, open drain outputs and three state outputs.

Logical Levels and Noise Margins: The generated voltage levels given by the manufacturing data sheet for HCMOS circuits operating at $V_{DD} = 5\text{ V}$, are given in the Table 1. The input parameters are mainly determined by the switching threshold of the two transistors, while the output parameters are determined by the ON resistance of the transistors. These parameters apply when the device inputs and outputs are connected only to other CMOS devices. The dc voltage levels and noise margins of CMOS families are given in the Table 1.

TABLE 1: DC Characteristics of CMOS Families

Family	V_{IHMIN}	V_{ILMAX}	V_{OHMIN}	V_{OLMAX}	NM LOW @ $V_{CC} = 5V$	NM HIGH @ $V_{CC} = 5V$	Units
4000B	$\frac{2}{3}V_D$	$\frac{1}{3}V_D$	$V_{CC}-0.1$	0.01	1.6	1.6	V
HCMOS	3.5	1.5	$V_{CC}-0.1$	0.1	1.4	1.4	V
HCTMOS	2	0.8	$V_{CC}-0.1$	0.1	0.7	2.4	V
ACMOS	3.5	1.5	$V_{CC}-0.1$	0.1	1.4	1.4	V
ACTMOS	2	0.8	$V_{CC}-0.1$	0.1	0.7	2.4	V
FCT	2	0.7	2.4	0.5	0.2	0.4	V

These dc noise margins are significantly better than those associated with TTL families. As CMOS circuits can be operated with $V_{DD} = 2 V$ to $V_{DD} = 6 V$ the voltage levels associated with CMOS gates may be expressed as

$$V_{IL(max)} = 30\% V_{DD}$$

$$V_{OH(min)} = V_{DD} - 0.1 V$$

$$V_{IH(min)} = 70\% V_{DD}$$

Regardless of the voltage applied to the input of a CMOS inverter, the input currents are very small. The maximum leakage current that can flow, designated as $I_{I_{max}}$, is $\pm 1\mu A$ for HCMOS with 5 V power supply. As the load on a CMOS gate could vary, the output voltage would also vary. Instead of specifying the output impedance under all conditions of loading the manufacturers specify a maximum load for the output in each state, and guarantee a worst-case output voltage for that load. The load is specified in terms of currents. The input and output currents are given in the Table 2.

TABLE 2: Input and Output Current Levels of CMOS Families

CMOS Families	Input currents		Output currents		Units
	I_{IH}	I_{IL}	I_{OH}	I_{OL}	
4000b +5	0.001	0.001	-1.6@2.5 V	0.4@0.4 V	mA
74HC	0.001	-0.001	-4 @ $V_{CC}-0.8$	4@0.4	mA
74HCT	0.001	0.001	-4@ $V_{CC}-0.8$	4@ 0.4 V	mA
74AC	0.001	-0.001	-24 @ $V_{CC}-0.8$	24@0.4 V	mA
74ACT	0.001	-0.001	-24 @ $V_{CC}-0.8$	24 @0.4 V	mA
74FCT	0.005	-0.005	-15@ 2.4 V	48@0.5 V	mA

These specifications are given at voltages which are normally associated with TTL gates. If the current drawn by the load is smaller, the voltage levels would improve significantly. This happens when CMOS gates are connected to CMOS loads.

It is important to note that in a CMOS circuit the output structure by itself consumes very little current in either state, High or Low. In either state, one of the transistors is in the high impedance OFF state. When no load is connected the only current that flows through the transistors is their leakage current. With a load, however, current flows through both the load and the ON transistor, and power is consumed in both.

Fan out: The fan out of a logic gate is the number of inputs that the gate can drive without exceeding its worst-case loading specifications. The fan out depends not only on the characteristics of the output, but also on the inputs that it is driving. When a HCMOS gate is driving HCMOS gates, we note that I_{ILmax} is $\pm 1 \mu A$ in any state, and $I_{OHmax} = -20 \mu A$ and $I_{OLmax} = 20 \mu A$. Therefore, the Low-state fan out is 20 and High-state fan out is 20 for HCMOS gates. However, if we are willing to work with slightly degraded output voltages, which would reduce the available noise margins, we can go for I_{OHmax} and I_{OLmax} of 4.0 mA. This would mean that an HCMOS gate can drive as many as 4000 HCMOS gates. But in actuality this would not be true, as the currents we are considering are only the steady state currents and not the transition currents. The actual fan out under degraded load conditions would be far less than 4000. During the transitions, the CMOS output must charge or discharge the capacitance associated with the inputs that it drives. If this capacitance is too large, the transition from Low to High (or vice versa) may be too slow causing improper system operation.

CMOS DYNAMIC ELECTRICAL BEHAVIOUR

Both the speed and the power consumption of CMOS devices depend on to a large extent on AC or dynamic characteristics of the device and its load, that is, what happens when the output changes between states. The speed depends on two factors, transition times and propagation delay.

The rise and fall times of an output of CMOS IC depend mainly on two factors, the ON transistor resistance and the load capacitance. The load capacitance comes from three different sources: output circuits including a gate's output transistors, internal wiring and packaging, have capacitances associated with them (of the order of 2-10 pF); wiring that connects an output to other inputs (about 1pF per inch or more depending on the wiring technology); and input circuits including transistors, internal wiring and packaging (2-15 pF per input). The OFF transistor resistance would be about 1 M Ω , the ON resistance of p-channel transistor would be of the order of 200 Ω , and the ON resistance of n-channel resistance would be about 100 Ω . We can compute the rise and fall times from the equivalent circuits.

Several factors lead to nonzero propagation delays. In a CMOS device, the rate at which transistors change state is influenced both by the semiconductor physics of

the device and by the circuit environment including input-signal transition rate, input capacitance, and output loading. The speed characteristics of CMOS families are given in the Table 3.

TABLE 3: Speed Characteristics of CMOS families

Family	Prop. Delay (ns)	Flip-Flop frequency (MHz)
4000B	160	5
HCMOS	22	25
HCTMOS	24	25
ACMOS	8.5	45
ACTMOS	8	45
FCTMOS	5.8('138)	60

Device outputs in AC and ACT families have very fast rise and fall times. Input signals should have rise and fall times of 3.0 ns (400 ns for HC and HCT devices) and signal swing of 0V to 3.0V for ACT devices or 0V to V_{DD} for AC devices. Obviously such signal transition times are a major source of analog problems, including switching noise and "ground bounce".

Power Consumption: A CMOS circuit consumes significant power only during transition, that is dynamic power dissipation is more. One source of dynamic power dissipation is the partial short-circuiting of the CMOS output structure. When the input voltage is changing from one state to the other, both the p -channel and n -channel output transistors may be partially ON, creating a series resistance of 600 Ω or less. During this transition period, current flows through the transistors from V_{DD} to ground. The amount of power consumed in this way depends on the value of V_{DD} , the frequency of output transitions, and an equivalent dissipation capacitance C_{PD} as given by the manufacturer.

$$P_T = C_{PD} \cdot V_{DD}^2 \cdot f$$

P_T is the internal power dissipation given in watts, V_{DD} is the supply voltage in volts, f is frequency of output transitions in Hz, and C_{PD} is the power dissipation capacitance in farads. C_{PD} for a gate of HCMOS is about 24 pF. This relationship is valid only if the rise and fall times of the input signal are within the recommended maximum values.

Second source of dynamic power dissipation is the CMOS power consumption due to the capacitive load (C_L) on the output. During the Low-to-High transition, current passes through the p -channel transistor to charge the load capacitance. Likewise, during the High-to-Low transition current flows through the n -channel transistor to discharge the load capacitor. During these transitions the voltage

across the capacitor changes by $\pm V_{DD}$. For each pulse there would be two transitions. As the currents are passing through the transistors, and capacitor itself would not be dissipating any power, the power dissipated due to the capacitive load is

$$P_L = C_L \cdot \frac{V_{DD}^2}{2} \cdot 2f$$

$$P_L = C_L \cdot V_{DD}^2 \cdot f$$

The total dynamic power dissipation of a CMOS circuit is the sum of P_T and P_L :

$$\begin{aligned} P_D &= P_T + P_L \\ &= C_{PD} \cdot V_{DD}^2 \cdot f + C_L \cdot V_{DD}^2 \cdot f \\ &= (C_{PD} + C_L) \cdot V_{DD}^2 \cdot f \end{aligned}$$

In most applications of CMOS circuits, CV^2f power is the main type of power dissipation. While CV^2f type of power dissipation is also consumed by the bipolar circuits like TTL, but at low to moderate frequencies it is insignificant compared to the static power dissipation of bipolar circuits.

Unlike other CMOS families, FCT does not have a C_{PD} specification. However, I_{CCD} specification gives the same information in a different way. The internal power dissipation due to transition at a given frequency f can be calculated by the formula

$$P_T = V_{CC} \cdot I_{CCD} \cdot f$$

This family also makes different speed grades of the same function available. Power dissipation characteristics of CMOS families operated at 5V are given in the Table 4.

TABLE 4: Power Dissipation Characteristics of CMOS Families

Parameter	HC	HCT	AC	ACT	FCT	Units
Quiescent power dissipation						
'00	0.0025	0.0025	0.005	0.005		mW
'138	0.04	0.04	0.04	0.04	7.5	mW
Power dissipation capacitance						
'00	24	24	30	30		pF
'138	85	85	60	60		pF
Dynamic power dissipation						
'00 at 1 MHz	0.6	0.6	0.75	0.75		mW
'138 at 1 MHz	2.1	2.1	1.5	1.5	1.5	mW
Total power dissipation						
'00 at 100KHz	0.0625	0.0625	0.08	0.08		mW
'00 at 1 MHz	0.6025	0.6025	0.755	0.755		mW
'00 at 10 MHz	6.0025	6.0025	7.505	7.505		mW
'138 at 100KHz	0.25	0.25	0.19	0.19	7.5	mW
'138 at 1 MHz	2.14	2.14	1.54	1.54	9	mW
'138 at 10 MHz	21.04	21.04	21.04	21.04	30	mW



Digital Electronics

Module 3: ECL Family

N.J. Rao

Indian Institute of Science



ECL Family

- Bipolar families prevent saturating transistors using Schottky diodes across the base-collector junctions
- Current Mode Logic (CML) structure can be used to prevent saturation
- CML produces a small voltage swing, less than a volt, between low and high levels
- CML switches current between two possible paths depending on the output state
- Introduced by General Electric in 1961
- The concept was refined by Motorola and others to produce present day's 10K, 100K (ECL) families

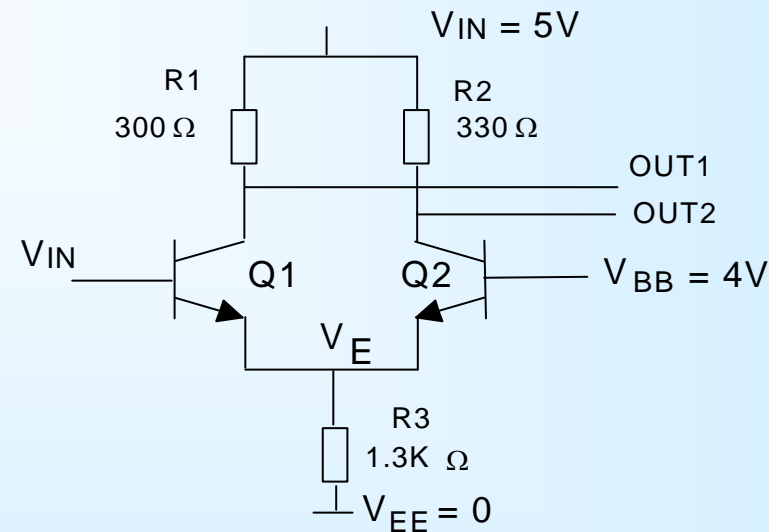


ECL Family (2)

- They offer propagation delays as short as 1 ns
- They are not as popular as TTL and CMOS mainly because they consume too much power
- High power consumption has made the design of ECL super computers, such as CRAY as a challenge in cooling technology
- ECL has poor power-speed product, does not provide a high level of integration
- ECL signals have fast edge rates requiring design for special transmission line effects
- ECL circuits are not directly compatible with TTL and CMOS



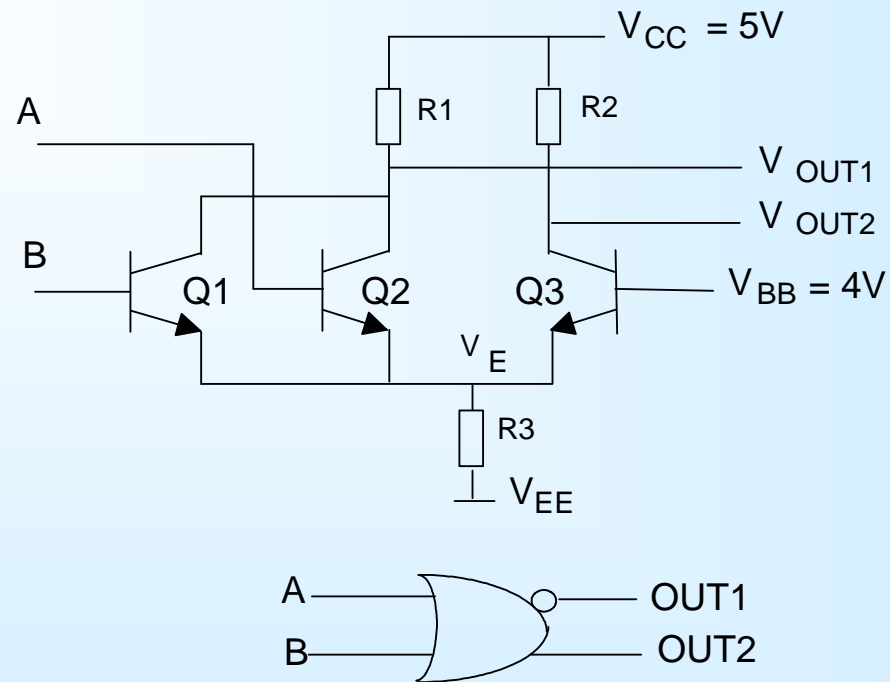
Basic CML Circuit



- Two transistors are connected as a differential amplifier with a common emitter resistor R3.
- Input Low and High levels, are defined to be 3.6 and 4.4 V.
- It produces output Low and High levels 0.6 V higher (4.2 and 5.0 V)



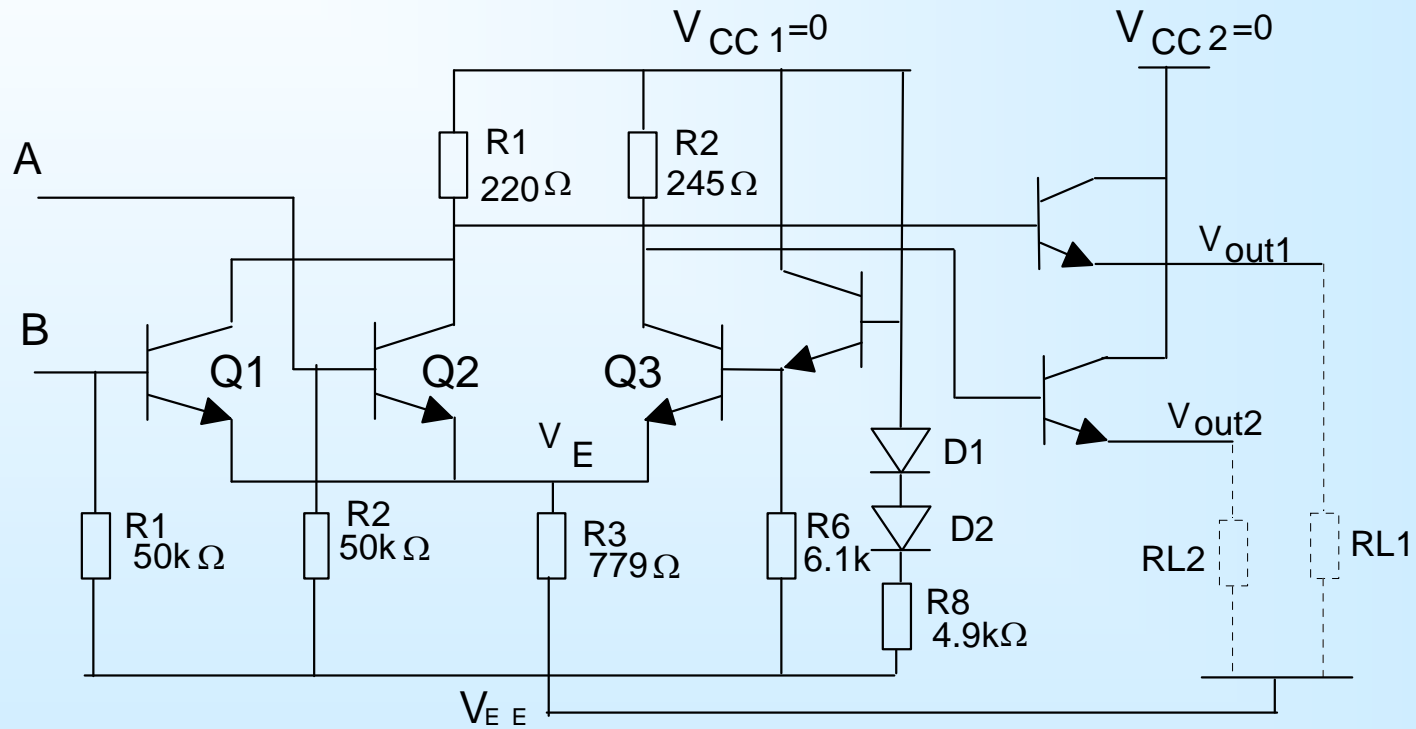
2-input OR/NOR gate



This circuit shown cannot meet the input/ output loading requirements effectively



ECL 10K OR/NOR gate (ECL10102)





ECL Families (Motorola)

MECL I in 1962

- It offered 8 ns gate propagation delay and 30 MHz toggle rates

MECL II in 1966

- This family offered 4 ns propagation delay for the basic gate, and 70 MHz toggle rates

MECL III in 1968

- It offered 1 ns gate propagation delays and flip-flop toggle rates higher than 500 MHz



ECL Families (Motorola)

MECL 10K series in 1971

- It offered circuits with 2 ns propagation delays. Edge speed was slowed down to 3.5 ns.

MECL 10KH in 1981

- It provides a propagation delay of 1 ns with edge speed at 1.8 ns and used process called MOSAIC.

MECL 100K

- This family offers functions different from those offered by 10K series. This family operates with a reduced power supply voltage -4.5 V, has shorter propagation delay of 0.75 ns, and transition time of 0.7 ns. The power consumption per gate is about 40 mW.



Subfamilies of MECL 10K

- 10100 and 10500 series (propagation delay of 2 ns, edge speed of 3.5 ns and flip-flop toggle rate of 160 MHz)
- 10200 and 10600 series (propagation delay of 1.5 ns, edge speed of 2.5 ns and flip-flop toggle rate of 250 MHz)
- 10800 series (propagation delay of 1 - 2.5 ns and edge speed of 3.5 ns)



Electrical Characteristics

Values are specified at $T_A = 25^\circ\text{C}$ and the nominal power supply voltage of $V_{EE} = -5.2\text{ V}$.

Its common-mode-rejection feature offers immunity against power-supply noise injection.

Family	V_{IHmin} V	V_{ILmax} V	V_{OHmax} V	V_{OLmax} V	NM Low mV	NM High mV
MECL III	-1.105	-1.475	-1.63	-0.98	155	125
ECL 10K	-1.105	-1.475	-1.63	-0.98	155	125
ECL 10KH	-1.13	-1.48	-1.63	-0.98	150	150
ECL 100K	-1.16	-1.47	-1.62	-1.03	150	130



Loading Characteristics

Family	I_{ILmax} mA	I_{IHmax} mA	I_{OLmax} mA	I_{OHmax} mA
MECL III	0.5	350	25	25
ECL 10K	0.5	265	22	22
ECL 10KH	0.5	265	22	22
ECL 100K	0.5	265	55	55



Transition Times/ Propagation Delays

Family	Prop. delay ns	Edge speed ns	Flip-flop toggle rate MHz
MECL III	1	1	500
ECL 10K (10100&10500)	2	3.5	160
ECL 10K (10200&10600)	1.5	2.5	250
ECL 10K (10800)	1 - 2.5	3.5	NA
ECL 10KH	1	1.8	250
ECL 100K	0.75	0.75	300



Power Consumption

Family	Power dissipation per gate mW	Power-speed product μJ
MECL III	60	60
ECL 10K (10100&10500)	25	50
ECL 10K (10200&10600)	25	37
ECL 10K (10800)	2.3	4.6
ECL 10KH	25	25
ECL 100K	40	30



Key aspects of ECL

- Fast and balanced output edges
- Low output impedance
- High drive capability
- Differential or single-ended operation

Limiting factors of ECL

- Negative rails
- incompatibility with other devices
- Need for the terminating rail (V_{TT})
- Higher power dissipation

ECL Family

The key to propagation delay in bipolar logic family is to prevent the transistors in a gate from saturating. Schottky families prevent the saturating using Schottky diodes across the base-collector junctions of transistors. It is also possible to prevent saturating by using a structure called Current Mode Logic (CML). Unlike other logic families considered so far, CML does not produce a large voltage swing between low and high levels. Instead, it has a small voltage swing, less than a volt, and it internal switches current between two possible paths depending on the output state.

The first CML logic family was introduced by General Electric in 1961. The concept was refined by Motorola and others to produce today's 10K, 100K Emitter Coupled Logic (ECL) families. These ECL families are fast and offer propagation delays as short as 1 ns. In fact, through out the evolution of digital circuit technology, some type of CML has always been the fastest commercial logic family. However commercial ECL families are not nearly as popular as TTL and CMOS mainly because they consume too much power. In fact, high power consumption has made the design of ECL super computers, such as CRAY as much of a challenge in cooling technology as in digital design. In addition, ECL has poor power-speed product, does not provide a high level of integration, has fast edge rates requiring design for special transmission line effect, and is not directly compatible with TTL and CMOS. But ECL family continues to survive and in applications which require maximum speed regardless of cost.

ECL Circuits

Basic CML Circuit: The basic idea of current mode logic is illustrated by the inverter/buffer circuit in the figure 1. This circuit has both inverting (OUT1) and non-inverting output (OUT2). Two transistors are connected as a differential amplifier with a common emitter resistor R3. Let the supply $V_{CC} = 5\text{ V}$, $V_{BB} = 4\text{ V}$ and $V_{EE} = 0\text{ V}$. Input Low and High levels are defined to be 3.6 and 4.4 V. This circuit produces output Low and High levels 0.6 V higher (4.2 and 5.0 V). When V_{IN} is high transistor Q1 is ON, but not saturated, and transistor Q2 is OFF. When Q1 is ON V_E is one diode drop lower than V_{IN} , or 3.8 V. Therefore, current through R3 is $(3.8/1.3\text{ K}\Omega) 2.92\text{ mA}$. If Q1 has a β of 10, then 2.65 mA of this current comes through the collector and R1, so V_{OUT1} is 4.2V (Low) since the voltage across Q1 ($= 4.2 - 3.8 = 0.4\text{ V}$) is greater than V_{CEsat} , Q1 is not saturated Q2 is off because of its base to emitter voltage ($4.0 - 3.8 = 0.2\text{ V}$) is less than 0.6 V. Thus V_{OUT2} is at 5.0 V (High) as no current passes through R2.

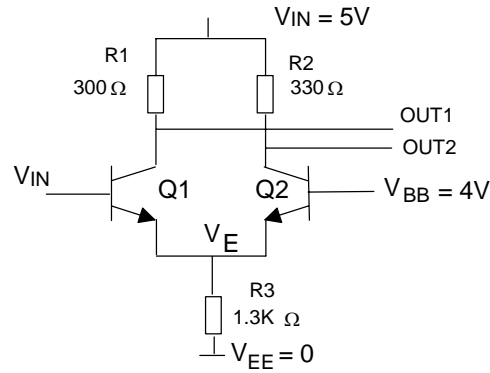


FIG. 1: Basic CML inverter/buffer circuit

When V_{IN} is Low, transistor Q1 is OFF, and Q2 is ON but not saturated. V_E will be one diode drop below V_{BB} ($4.0 - 0.6 = 3.4$ V). The current through R3 is ($3.4/1.3$ K $\Omega =$) 2.6 mA. The collector current of Q2 is 2.38 mA for a β of 10. The voltage drop across R2 is ($2.38 \times 0.33 =$) 0.5 V, and V_{OUT2} is about 4.2 V. Since the collector-emitter voltage of Q2 is ($4.2 - 3.4 =$) 0.8V, it is not saturated. Q1 is off because its base-emitter voltage is ($3.6 - 3.4 =$) 0.2 and is less than 0.6 V. Thus V_{OUT1} is pulled up to 5.0 V through R1.

To perform logic with the basic unit of figure 1, we simply place additional transistors in parallel with Q1. Figure 2 shows a 2-input OR/NOR gate. If any input is High, the corresponding input transistor is active, and V_{OUT1} is Low (NOR output). At the same time, Q3 is off, and V_{OUT2} is High (OR output). However, the circuit shown in figure 2 cannot meet the input/output loading requirements effectively.

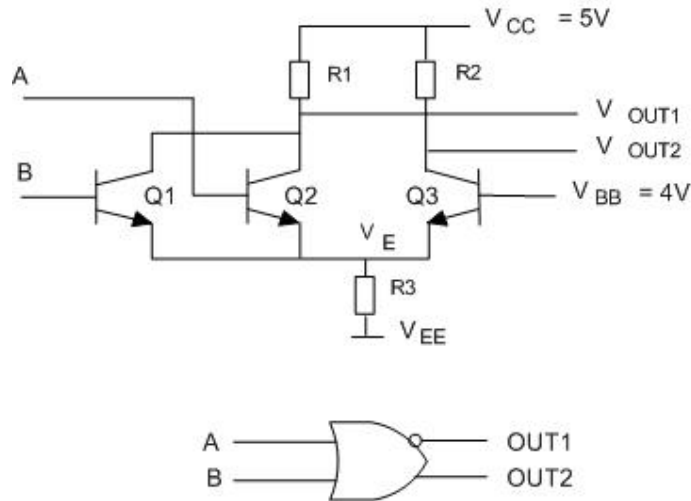


FIG. 2: CML 2-input OR/NOR gate

ECL 10K Family: The most popular ECL family is designated as the ECL10K as it has 5-digit designations to its ICs. The ECL 10K OR/NOR gate is shown in the figure 3

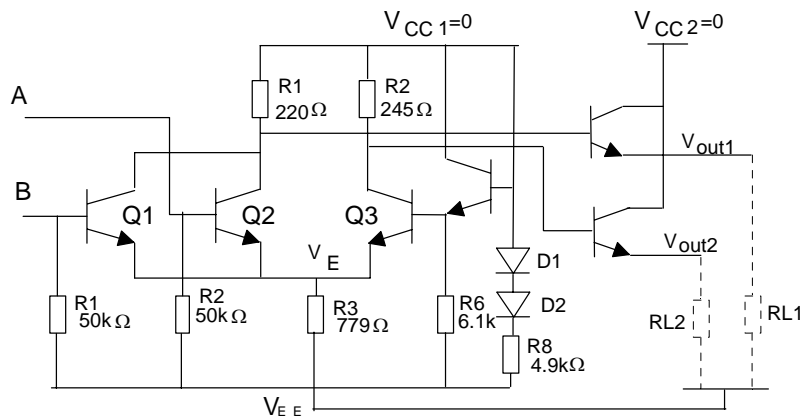


FIG. 3: Two-input ECL 10K OR/NOR gate (10102)

In this circuit, an emitter follower output stage shifts the output levels to match the input levels and provides very high current driving capability, up to 50 mA per output. An internal (R7, D1, D2, R8 and Q4) temperature, and voltage-compensated bias network provides V_{BB} (-1.29V) without the need for separate external power supply. The family is designed to operate with $V_{CC} = 0$ (GND) and $V_{EE} = -5.2V$. This improves noise immunity to power supply noise, because noise

on V_{EE} is a "common mode" signal that is rejected by the input structure's differential amplifier.

A pull down resistor on each input ensures that if the input is left unconnected, it is treated as Low. The emitter-follower outputs used in ECL 10K require external pull-down resistors as shown in the figure. This is because of the fast transmission times (typically 2ns). The short transmission times require special attention as any interconnection longer than a few centimetres must be treated as a transmission line. By removing the internal pull-down resistor, the designer can now select a resistor that satisfies the pull-down requirements as well as transmission line termination requirements. The simplest terminator for short connections is to use a resistor in the range of 270 Ω to 2 K Ω .

ECL SUBFAMILIES

Motorola has offered MECL circuits in five logic families: MECL I, MECL II, MECL III, MECL 10000 (MECL 10K), and MECL 10H000 (MECL 10KH). The MECL I family was introduced in 1962, offering 8 ns gate propagation delay and 30 MHz toggle rates. This was the highest performance from any logic family at that time. However, this family required a separate bias driver package to be connected to each logic function. The ten pin packages used by this family limited the number of gates per package and the number of gate inputs. MECL II was introduced in 1966. This family offered 4 ns propagation delay for the basic gate, and 70 MHz toggle rates. MECL II circuits have a temperature compensated bias driver internal to the circuits, which simplifies circuit interconnections.

MECL III was introduced in 1968. They offered 1 ns gate propagation delays and flip-flop toggle rates higher than 500 MHz. The 1 ns rise and fall times required a transmission line environment for all but the smallest systems. For this reason, all circuit outputs are designed to drive transmission lines and all output logic levels are specified when driving 50-ohm loads. For the first time with MECL, internal input pull down resistors are included with the circuits to eliminate the need to tie unused inputs to V_{EE} .

Motorola introduced MECL 10K series in 1971 with 2 ns propagation delays. In order to make the circuits comparatively easy to use, edge speed was slowed down to 3.5 ns. Subsequently, the basic MECL 10K series has been expanded by a subset of devices with even greater speed. These subfamilies are 10100 and 10500 series (propagation delay of 2 ns, edge speed of 3.5 ns and flip-flop toggle rate of 160 MHz), 10200 and 10600 series (propagation delay of 1.5 ns, edge

speed of 2.5 ns and flip-flop toggle rate of 250 MHz), and 10800 LSI family (propagation delay of 1 - 2.5 ns and edge speed of 3.5 ns)

MECL 10KH family was introduced in 1981. This family provides a propagation delay of 1 ns with edge speed at 1.8 ns. These speeds, which were attained with no increase in power over MECL 10K, are due to both advanced circuit design techniques and new oxide isolated process called MOSAIC. To enhance the existing systems, many of the MECL 10KH devices are pin-out/functional duplications of the MECL 10K family. Also, MECL 10K/10KH are provided with logic levels that are completely compatible with MECL III. Another important feature of MECL 10K/10KH is the significant power reduction over both MECL III and the older MECL II. Because of the power reductions and advanced circuit design techniques, the MECL 10KH family has many new functions not available with the other families.

The latest entrant to the ECL family is ECL 100K, having 6-digit part numbers. This family offers functions, in general, different from those offered by 10K series. This family operates with a reduced power supply voltage -4.5 V, has shorter propagation delay of 0.75 ns, and transition time of 0.7 ns. However, the power consumption per gate is about 40 mW.

ELECTRICAL CHARACTERISTICS OF ECL FAMILY

The input and output levels, and noise margins of ECL gates are given in the Table 1. These values are specified at $T_A = 25^\circ\text{C}$ and the nominal power supply voltage of $V_{EE} = -5.2 \text{ V}$.

TABLE 1: Voltage levels and noise margins of ECL family ICs

Family	V_{IHmin} V	V_{ILmax} V	V_{OHmax} V	V_{OLmax} V	NM Low mV	NM High mV
MECL III	-1.105	-1.475	-1.63	-0.98	155	125
ECL 10K	-1.105	-1.475	-1.63	-0.98	155	125
ECL 10KH	-1.13	-1.48	-1.63	-0.98	150	150
ECL 100K	-1.16	-1.47	-1.62	-1.03	150	130

The noise margin levels are slightly different in High and Low states. This specification by itself does not give complete picture regarding the noise immunity of a system built with a particular set of circuits. In general, noise immunity involves line impedances, circuit output impedances, and propagation delay in addition to noise-margin specifications.

Loading Characteristics: The differential input to ECL circuits offers several advantages. Its common-mode-rejection feature offers immunity against power-supply noise injection, and its relatively high input impedance makes it possible for any circuit to drive a relatively large number of inputs without deterioration of the guaranteed noise margin. Hence, DC fan out with ECL circuits does not normally present a design problem. Graphs given by the vendor showing the output voltage levels as a function load current can be used to determine the actual output voltages for loads exceeding normal operation.

Family	I_{ILmax} μA	I_{IHmax} mA	I_{OLmax} mA	I_{OHmax} mA
MECL III	0.5	350	25	25
ECL 10K	0.5	265	22	22
ECL 10KH	0.5	265	22	22
ECL 100K	0.5	265	55	55

Transition Times and Propagation Delays: The transition times and delays associated with different ECL families are given in the following.

Family	Prop. delay ns	Edge speed ns	Flip-flop toggle rate MHz
MECL III	1	1	500
ECL 10K (10100&10500)	2	3.5	160
ECL 10K (10200&10600)	1.5	2.5	250
ECL 10K (10800)	1 - 2.5	3.5	NA
ECL 10KH	1	1.8	250
ECL 100K	0.75	0.75	300

The rise and fall times of an ECL output depend mainly on two factors, the termination resistor and the load capacitance. Most of the ECL circuits typically have a 7 ohm output impedance and are relatively unaffected by capacitive loading on positive going output signal. However, the negative-going edge is dependent on the output pull down or termination resistor. Loading close to a ECL output pin will cause an additional propagation delay of 0.1 ns per fan-out load

with 50 ohm resistor to $-2.0 V_{dc}$ or 270 ohms to $-5.2 V_{dc}$. The input loading capacitance of an ECL 10K gate is about 2.9 pF. To allow for the IC connector or solder connection and a short stub length 5 to 7 pF is commonly used in loading calculations.

Power Consumption: The power dissipation of ECL functional blocks as specified by the manufacturer does not include power dissipated in the output devices due to output termination. The omission of internal output pull-down resistors permits the use of external terminations designed to yield best system performance. To obtain total operating power dissipation of a particular functional block in a system, the dissipation of the output transistor, under load, must be added to the circuit power dissipation. The power dissipation and power-speed products of various ECL families are given in the Table 4

Family	Power dissipation per gate mW	Power-speed product pJ
MECL III	60	60
ECL 10K (10100&10500)	25	50
ECL 10K (10200&10600)	25	37
ECL 10K (10800)	2.3	4.6
ECL 10KH	25	25
ECL 100K	40	30



Digital Electronics

Module 4: Combinational Circuits: An Introduction

N.J. Rao

Indian Institute of Science



We are familiar with

- How to express a verbal logical statement as a logical expression
- How to simplify a given logical expression using a variety of tools
- How to pictorially represent a logical function in terms of basic logic functions like AND, OR etc.
- How to perform a logical function using electronic circuits when the binary variables are presented by voltage levels



Digital electronic circuits

Classified as:

- Combinational Circuits
- Sequential Circuits



Combinational circuits

The output can be expressed as a logical expression in terms of the input variables

- The present value of the output is dependent only on the present values of the inputs
- All logical expressions consist of logical operations AND, OR and NOT.
- Any logical expression can be realized using these three types of electronic gates.



Sequential Circuits

In a *sequential circuit* the outputs depend on

- The present inputs
- The sequence of all the past inputs



Early era of digital design

“logic gates”

- were built with discrete devices
- were expensive
- consumed considerable power
- occupied significant amount of space on the printed circuit board.
- minimisation of the number of gates was one of the major design objectives



Present day semiconductor technology

- The integration levels are very high
- The delay times are very low and coming down all the time
- Power consumed by them has been coming down.
- Minimization of printed circuit board area is the major design objective



Traditional minimisation methods

- Can help in locating problems like hazards and racing



Combinational SSI, MSI and LSI

- Gates
- Multiplexers
- Demultiplexers
- Arithmetic Units
- Encoders and Code Converters
- Comparators
- Multipliers
- Programmable Logic Devices (PLDs)



Hardware aspects: Electrical Parameters

- propagation delays
- power consumption
- supply voltage levels
- currents
- tolerances (voltages and currents)
- loading
- margins (noise)



Hardware aspects: Mechanical Parameters

- Foot print
- Type of package
- Pin pitch (distance between two adjacent pins)
- Thermal resistance



Present day context of combinational circuits

- Interfacing (propagation delay should be minimum)
- The number of ICs of SSI and MSI level to be considerably restricted



Learning Objectives

- Analyse and design combinational circuits using commercially available ICs belonging to LSTTL and HCMOS/HCTMOS families
- Resolve issues related to interfacing
- Learn to use Polarized Mnemonic Conventions



Polarized Mnemonic Convention





Learning objectives

- Explain the polarized mnemonic conventions of IEEE for representing logic variables and signals used in combinational circuits.
- Implement different logic functions with different logic gates.
- Explain the method of representing Mode signals and binary data unambiguously.
- State the advantages of polarized mnemonic convention.



Standard Convention

Polarised Mnemonic Convention and logic symbology as per IEEE Std. 91/ ANSI Y32.14

The standard convention has two components:

- logic notation including signal designation,
- symbols for digital functional units, available as SSI and MSI packages



What is Truth Table?

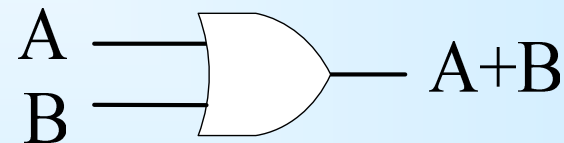
Consider the OR function of two binary variables

Algebraic representation: $Y = A + B$

Truth table

A	B	X
0	0	0
0	1	1
1	0	1
1	1	1

Logic Symbol



- It is simply a listing of the possible combinations of A and B
- Has nothing to do with truth or falsehood of the variables
- Appropriate to treat it as the input-output relation



Logic variables represent Action

Examples of digital signals: START, LOAD, CLEAR etc.

- These are indicative of actions to be performed
- We do not establish *Truth* or *Falsehood* of something

It is appropriate to say

- “when the signal LOAD is Asserted, the intended action of loading takes place”
- **Asserted/ Not Asserted** qualification is more appropriate



Interpretation of Truth Table

- Entry 0: The variable **Not Asserted**
- Entry 1: The variable **Asserted**

<u>A</u>	<u>B</u>	<u>X</u>
0	0	1
0	1	0
1	0	0
<u>1</u>	<u>1</u>	<u>0</u>

Read the first entry as

"X is Asserted when A AND B are Not Asserted" or
"X is Asserted when A is Not Asserted AND B is Not Asserted".



Reading Logic Expressions

Consider $Y = A \cdot B' \cdot C + A \cdot B \cdot C + A \cdot B' \cdot C'$

- The first term $A \cdot B' \cdot C$ is to be read as "A B prime C",
- It is to be interpreted as "A Asserted AND B Not Asserted AND C Asserted"
- A Not Asserted variable is shown in a logical expression with a prime (') next to the mnemonic for the variable.



Electronic Circuits and Logic Functions

- Electronic circuits are used to implement logic functions
- Currents and voltages are associated with these circuits
- Assertion and Not Assertion are associated with voltages
- Need to have a convention to associate voltages with logic variables



Signal Convention

- The voltage levels associated with logic variables are not of a single value
- Normally a band of few hundred milli volts or even a few volts are associated with a logic state
- The more positive of the two voltage levels (voltage ranges) is designated as High Voltage (H)
- The less positive of the two is designated as Low Voltage (L)
- The intended action can take place at either of the voltage level
- This choice can be given to the designer



Signal Convention(2)

Asserted High Signal

- It is Asserted when the voltage level is High (H) and Not Asserted when the voltage level is Low (L)

Asserted Low Signal

- It is Asserted when its voltage level is Low (L) and Not Asserted when the voltage level is High (H)



Convention

- No qualifying symbol or letter is added if the variable is Asserted High
LOAD, CLR etc.
- / is added before the mnemonic if the variable is Asserted Low
/LOAD, /CLR

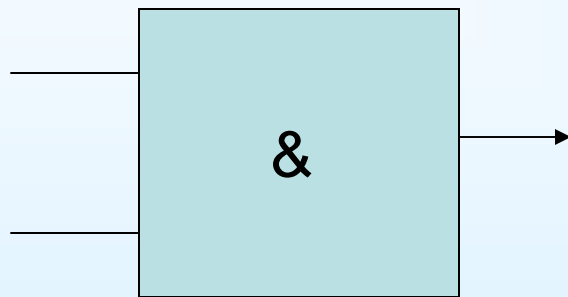


Logic Gates

- Refer to physical electronic units that generate output voltage levels in a well-defined relationship to the input voltage levels
- A given gate may perform a variety of logical functions



2-Input AND Gate



A	B	Y
L	L	L
L	H	L
H	L	L
H	H	H



AND Gate with AH variables

The Truth-Table gets modified as

A	B	Y
0	0	0
0	1	0
1	0	0
1	1	1

- X is Asserted only when A AND B are Asserted
- This AND gate performs AND operation on the two input variables which are Asserted High to produce an output that is Asserted High



AND Gate with AL variables

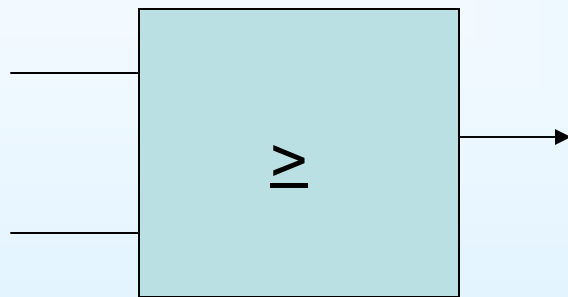
The Truth-Table gets modified as

$\neg A$	$\neg B$	$\neg Y$
1	1	1
1	0	1
0	1	1
0	0	0

- $\neg Y$ is Asserted when $\neg A$ is Asserted OR $\neg B$ is Asserted
- This AND gate performs OR operation on the two input variables which are Asserted Low to produce an output that is Asserted Low



2-Input OR Gate



A	B	Y
L	L	L
L	H	H
H	L	H
H	H	H



OR Gate with AH variables

The Truth-Table gets modified as

A	B	Y
0	0	0
0	1	1
1	0	1
1	1	1

- X is Asserted only when A OR B are Asserted
- This OR gate performs OR operation on the two input variables which are Asserted High to produce an output that is Asserted High



OR Gate with AL variables

The Truth-Table gets modified as

$/A$	$/B$	$/Y$
1	1	1
0	1	0
1	0	0
0	0	0

- $/Y$ is Asserted when $/A$ is Asserted AND $/B$ is Asserted
- This OR gate performs AND operation on the two input variables which are Asserted Low to produce an output that is Asserted Low



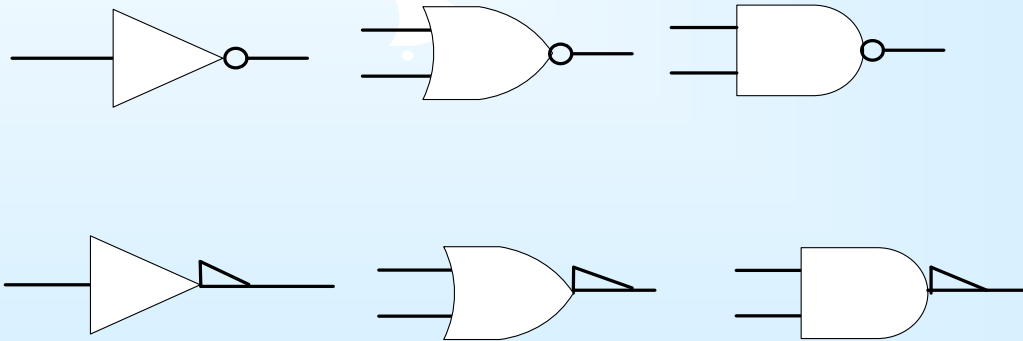
Logic Convention

- Positive Logic Convention: When all variables are treated as Asserted High
- Negative Logic Convention: When all variables are treated as Asserted Low
- Polarised Mnemonic Convention permits the designer to have complete freedom in defining the Assertion levels of all signals



Negation/Polarity Indicator

- As per the IEEE Standard "o" (bubble) or a (small triangle) is used as a negation/polarity indicator



We use the bubble to represent polarity

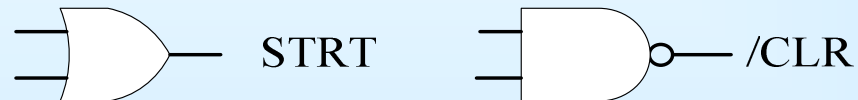


Output Signals

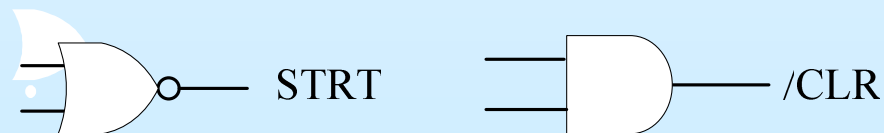
Presence of the polarity indicator at the output: The signal is as Asserted Low

Absence of the indicator at the output: The signal is as Asserted High

Correct examples



Incorrect examples





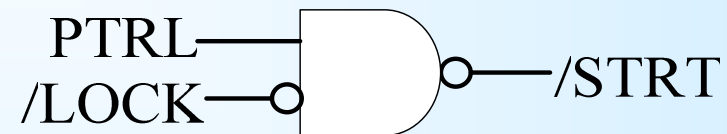
Input Signals

Polarity indicator at the input of a logic unit

- If an Asserted High (AH) variable is given as input to a logic unit without polarising indicator, that variable appears Asserted in the output logic expression.
- If an Asserted Low (AL) signal connected through a polarity indicator, that variable appears as Asserted in the output logic expression.



Input Signals (2)



Asserted Low signal /LOCK and an Asserted High signal PTRL are ANDed to generate an Asserted Low output signal /STRT.

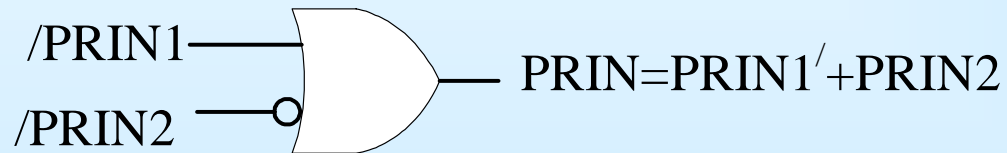


Input Signals (3)

- An AL variable connected to a logic unit without a polarity indicator appears as Not Asserted variable in the logic expression for the output.
- An AH variable connected through a polarity indicator appears as Not Asserted variables in the logic expression for the output.



Examples of Input Signal Designations

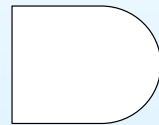




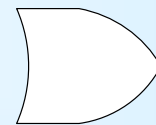
Logic symbols in the Polarised Mnemonic Notation

Each symbol has three distinct elements:

- Distinctive shaped logic symbol indicative of the logic operation being performed,



for AND

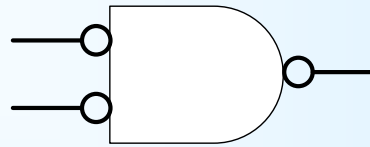


for OR

- The presence or absence of polarity indicators at the outputs.
- The presence or absence of polarity indicators at the inputs.



Example



- The unit performs AND operation.
- The output variable is Asserted Low.
- The AND operation is performed on the Asserted Low input signals



Some good practices

- The use of symbols as shown should be avoided.





Exceptions

Mode Signals

- Assigning Assertion levels is not meaningful
- These signals are indicative of more than one action.
- Different actions take place in both the states of the signals.
- The two actions are mutually exclusive and one of the actions is always implied
- Examples are R/W', U/D' and IO/M'.



Read/Write (R/W) signal

R/W/:

- when the signal takes `High voltage' (H) it is indicative of READ operation
- when it takes `Low voltage' (L) it is indicative of WRITE operation



Binary Data

- We can not use Asserted or Not Asserted conventions with binary data
- Data line will either convey a numerical value of 0 or 1.
- A data line, designated with mnemonics like DBIT-4
- When it takes High voltage it is considered having a numerical value of '1'
- When it takes Low voltage it is considered having a numerical value of '0'.

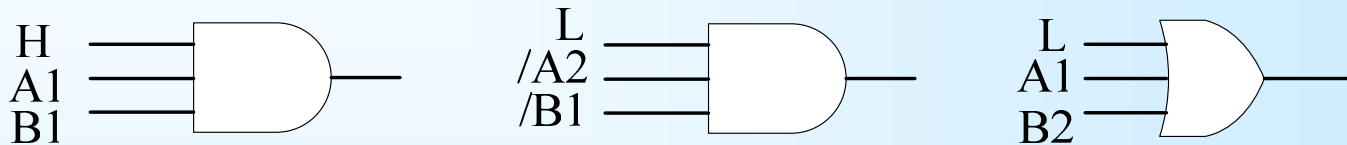


Unused Inputs

- All inputs of an IC may not be utilized
- Unused inputs will have to be tied at known states.
- In a 3-input OR gate that is used only as a 2-input OR gate, the unused input should be kept in Not Asserted state.
- A high voltage input is shown by the letter H and a low voltage input is shown by the letter L.



Examples of unused inputs



The voltage level at which the unused inputs get tied to will depend on the assertion level of the signal.

COMBINATIONAL CIRCUITS

INTRODUCTION

We explored in the earlier learning units

- How to express a verbal logical statement as a logical expression
- How to simplify a given logical expression using a variety of tools
- How to pictorially represent a logical function in terms of basic logic functions like AND, OR etc.
- How to perform a logical function using electronic circuits when the binary variables are presented by voltage levels

An electronic circuit can perform a logical function in extremely short periods of time (time taken from the application of inputs to the appearance of outputs). These periods are of the order of nanoseconds. We mainly use electronic circuits to perform logic functions because of their high speeds.

The electronic circuits that perform logical functions are seen under two broad categories:

- Combinational
- Sequential

The output of a combinational circuit can be expressed as a logical expression in terms of the input variables. The present value of the output of a combinational circuit is dependent only on the present values of the inputs.

The logical expressions mainly consist of logical operations AND, OR and NOT. Therefore, it is possible to physically realise any logical expression using these three types of electronic gates.

In the early era of digital design “logic gates” built with discrete devices, were expensive, consumed considerable power and occupied significant amount of space on the printed circuit board on which these devices were mounted. In those early days the minimisation of the number of gates was one of the major design objectives of Logic and Switching Theory. The semiconductor technology, however, made these gates available in IC packages that occupy very little space and at very low costs. As the technologies improved

- The delay times associated with the logical devices have been coming down
- Power consumed by them has been coming down.
- More and more logic functions are getting integrated into a single package.

This has drastically reduced the number of ICs needed to realise a given function. But the proportional cost of the printed circuit board on which these devices were getting assembled has been increasing. Therefore, one of the main objectives of the present day combinational circuit design is to reduce the printed circuit board area needed for the logic circuits. This implies reduction of the number of IC packages used rather than the number of gates.

Because of these changes in technologies, the design and minimisation methods evolved by the traditional Logic and Switching Theory are not that relevant. It may not be necessary to master the finer aspects of these methods, but a good working knowledge of these methods is still needed to analyse and design combinational circuits, even as per the new criteria. Besides minimisation, these methods can

greatly help in locating problems like hazards and racing, which are mainly the consequence of variations in the electrical characteristics of the physical devices used.

Combinational integrated circuits are available in a wide functional and complexity range in SSI, MSI and LSI packages. These may be classified as:

- Gates
- Multiplexers
- Demultiplexers
- Arithmetic Units
- Encoders and code converters
- Comparators
- Multipliers
- Programmable Logic Devices (PLDs)

A digital designer must get himself thoroughly familiar with the functional and hardware aspects of these combinational ICs. The hardware aspects relate to electrical parameters

- propagation delays
- power consumption
- supply voltage levels
- currents
- tolerances (noise, voltages and currents)
- loading

Mechanical parameters are also important. These include

- foot print
- type of package
- pin pitch (distance between two adjacent pins)
- thermal resistance

The design of any digital circuit is not merely limited to the functional aspects. For example the combinational circuits find applications, in the context of the present day microprocessors, mainly for the interfacing applications. In such applications the propagation delay should be made minimum. The designer will have to use less number of levels of gating and choose the appropriate logic family. With the real estate at the printed circuit board level becoming more and more expensive the number of ICs of SSI and MSI level have to be considerably restricted.

In this module you will mainly learn to analyze and design combination circuits using commercially available Gates, Arithmetic Units, Multiplexers, and Demultiplexers belonging to both LSTTL and HCMOS/HCTMOS families. The issues related to interfacing between circuits belonging to different logic families, as well as interfacing with external world are also addressed.

As there are two logic states and two voltage levels to represent them electrically, communication among digital designers can become very confusing if well-accepted

conventions do not exist. IEEE evolved standards for Logic Convention and Dependency Notation for Medium Scale Integrated Circuits. While these conventions and notations have limited utility when working with the present day PLDs and FPGAs, it is advantageous to adhere to them whenever it is possible.

Initially we will clarify issues related to logic and signal conventions, and then proceed to designing a variety of combinational circuits.

The objectives of this learning unit are

- Explain the polarized mnemonic conventions of IEEE for representing logic variables and signals used in combinational circuits.
- Implement different logic functions with different logic gates.
- Explain the method of representing 'mode' signals and binary data unambiguously.
- State the advantages of polarized mnemonic convention.

POLARIZED MNEOMONIC CONVENTION

You need to present your solution to a design problem in the form of a schematic diagram. This schematic diagram will be used by the packaging designer to convert it into production documentation. The schematic will also be used by the testing and maintenance engineers. This interaction among many people concerned with a digital system requires that all of them have the same understanding of the functionality of the circuit. Therefore, we need a standard convention that unambiguously conveys the intentions of the designer to all the concerned while giving sufficient flexibility to the designer. Many such conventions were evolved in different textbooks and by different organisations. However, no universally accepted convention exists even today for drawing digital schematic diagram.

Polarised Mnemonic Convention and logic symbology as per IEEE Std. 91/ANSI Y32.14, which is based on Dependency Notation, is the only international Standard that has evolved. Here we get ourselves familiar with this convention.

Any standard convention has two components:

- logic notation including signal designation,
- symbols for digital functional units, available as SSI and MSI packages

You are only familiar with the simple logic functions and logic gates. You are urged to make efforts to confine to the conventions presented here, rather than resorting to exceptions. The reward for this additional effort is the ability to communicate your design to others. As you work out more and more examples from the later Modules, you should feel more comfortable with the convention.

Consider an OR function of two binary variables A and B.

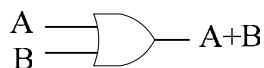
Its algebraic representation is

$$Y = A + B$$

Its truth table representation is

A	B	X
0	0	0
0	1	1
1	0	1
1	1	1

The symbolic representation is



The truth table presents a simple listing of the possible combinations of A and B rather than having anything to do with truth or falsehood of the variables concerned. It will be more appropriate if the truth table can be interpreted more as the input-output relation of a logic function. With this understanding we will continue to use the word truth table.

A digital system may more conveniently be considered as a unit that processes binary input actions and generates binary output actions. Most hardware responses generally are either responses to some physical operation or some conditions

resulting from physical action. For example many of the signals that you come across in digital systems are of the type

- START
- LOAD
- CLEAR

These signals are indicative of actions to be performed rather than establishing the *Truth* or *Falsehood* of something.

For example, to say *when LOAD is true* does not convey the intended meaning. It appears more appropriate to say when the signal LOAD is Asserted, the intended action, namely, loading takes place.

Therefore, Asserted/Not Asserted qualification is more meaningful and appropriate than the True/False qualification in the case of signals that clearly indicate action.

The entries in the truth table can now be interpreted in a different manner.

- The entry 0 is to be read as the corresponding variable Not Asserted
- The entry 1 is to be read as the corresponding variable Asserted

Consider the Truth Table given in the following.

A	B	X
0	0	1
0	1	0
1	0	0
1	1	0

We read the first entry in the table as

"X is Asserted when A AND B are Not Asserted" or "X is Asserted when A is Not Asserted AND B is Not Asserted".

Consider another example

$$Y = A \cdot B' \cdot C + A \cdot B \cdot C + A \cdot B' \cdot C'$$

The first term $A \cdot B' \cdot C$, to be read as "A B prime C", is to be interpreted as "A Asserted AND B Not Asserted AND C Asserted"

Try interpreting the other terms of the expression.

A Not Asserted variable will therefore be shown in a logical expression with a prime (') next to the mnemonic for the variable. Traditionally this is referred to as complementation. Let us note that it sounds right, and is appropriate to say a variable is Asserted or Not Asserted rather than Uncomplemented or Complemented.

Electronic Circuits and Logic Functions

We use electronic circuits to implement logic functions. There are currents and voltages associated with these circuits. We now explore the issues related to associating electrical variables with logic variables.

Signal Conventions

In an actual digital circuit the logic variables are represented as voltage levels. However these voltage levels are not of a single value. Normally a band of few hundred millivolts or even a few volts will be associated with a logic state.

The more positive of the two voltage levels (voltage ranges) is designated as High Voltage (H)

The less positive of the two is designated as Low Voltage (L).

The intended action associated with a variable can take place at either of the voltage levels. This can be given as a choice to the designer. If the choice is to be made available, it is necessary to evolve a convention that unambiguously states at what voltage level a variable gets Asserted.

If a signal is considered Asserted when the voltage level is High (H) and Not Asserted when the voltage level is Low (L), it is designated as Asserted High signal.

Similarly if a signal is considered Asserted when its voltage level is Low (L) and Not Asserted when the voltage level is High (H), it is designated as Asserted Low signal.

We will follow a simple convention:

No qualifying symbol or letter is added if the variable is Asserted High, for example LOAD, CLR etc.

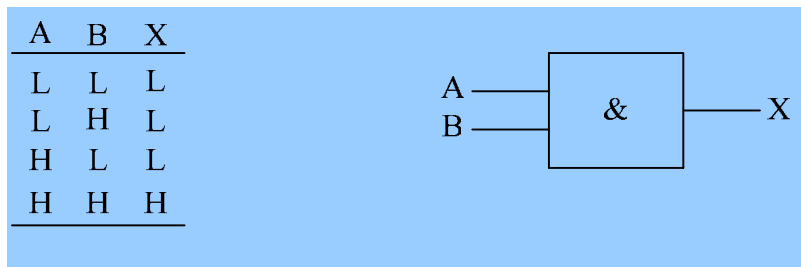
/ is added before the mnemonic if the variable is Asserted Low, for example /LOAD, /CLR

Logic Gates

Logic gate refers to a unit of hardware that generates output voltage levels in a well-defined relationship to the input voltage levels. A given gate may perform a variety of functions depending upon the Assertion levels of the input and output signal levels.

Consider an AND Gate

Figure shows a two input AND gate and the relationship between the input and output voltage levels.



Let us assume the input and output variables are Asserted High. The corresponding truth table can be written as;

A	B	X
0	0	0
0	1	0
1	0	0
1	1	1

We can draw the following conclusions from this truth table:

X is Asserted only when A AND B are Asserted

This AND gate performs **AND operation on the two input variables which are Asserted High to produce an output that is Asserted High.**

If A, B and X are Asserted Low variables, then the truth-table for the same gate would be

/A	/B	/X
1	1	1
1	0	1
0	1	1
0	0	0

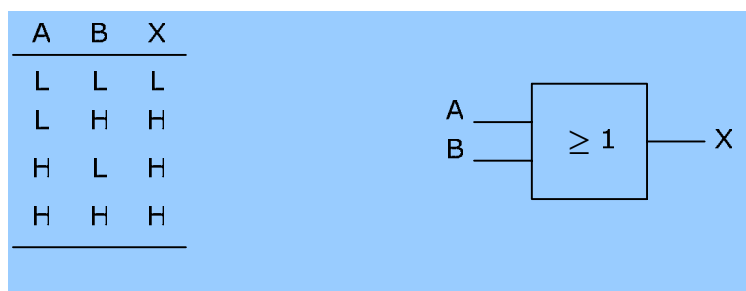
From the truth table we notice that

/X is Asserted when /A is Asserted OR /B is Asserted.

This AND gate performs **OR operation on its input variables which are Asserted Low.**

Consider an OR gate

Figure shows a two input OR gate and the relationship between the input and output voltage levels



If A, B and X are Asserted High, then the truth-table can be written as

A	B	X
0	0	0
0	1	1
1	0	1
1	1	1

We can draw the following conclusions from this truth table:

- X is Asserted when A OR B is Asserted,

- This gate performs OR operation on the Asserted High variables.

When the variables A, B and X are Asserted Low, the Truth Table can be written as

/A	/B	/X
1	1	1
1	0	0
0	1	0
0	0	0

/X is Asserted only when /A AND /B are Asserted

This gate performs [AND operation on Asserted Low variables](#).

In a similar manner each one of the available hardware gates can be used to perform more than one logic operation. From these two examples it is clear that the name given to the hardware gate corresponds to the function it performs on Asserted High inputs to generate an Asserted High output.

Exercises:

1. Find out the function performed by a 2-input NAND gate if its input and output variables are Asserted High?
2. Find out the function performed by a 2-input NAND gate if its input and output variables are Asserted Low?
3. Find out the function performed by a 2-input NAND gate if its input variables are Asserted High and its output variable is Asserted Low?
4. Find out the function performed by a 2-input NOR gate if its input and output variables are Asserted High?
5. Find out the function performed by a 2-input NOR gate if its input and output variables are Asserted Low?
6. Find out the function performed by a 2-input NOR gate if its input variables are Asserted High and its output variable is Asserted Low?
7. Find out the function performed by a 2-input Ex-NOR gate if its input and output variables are Asserted High?
8. Find out the function performed by a 2-input EX-NOR gate if its input and output variables are Asserted Low?
9. Find out the function performed by a 2-input NOR gate if one of its input variables is Asserted High and the other is Asserted Low, and its output variable is Asserted High?

LOGIC CONVENTION

Logic variables can be Asserted High or Asserted Low. Therefore, depending on our preference we can have different conventions.

- If all variables are treated as Asserted High, we call it as Positive Logic Convention. Traditionally digital circuits were mostly designed with Positive Logic Convention.
- If all variables are treated as Asserted Low, we call it as Negative Logic Convention. Sometimes designers found it convenient to design some parts of a digital circuit using Negative Logic Convention.

Whenever it became necessary to combine circuits designed under different conventions there were always possibilities of confusions in handling the interface.

- If the Assertion level a signal can be chosen by the designer we call it Polarised Mnemonic Convention.

Negation/Polarity Indicator: As per the IEEE Standard "o" (bubble) or ∇ (a small triangle) is used as a negation/polarity indicator as shown in the figure 1.

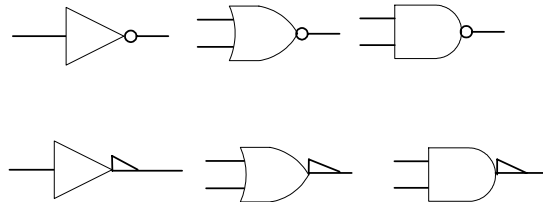


FIG. 1: Convention for indicating the negation of the output

We prefer to use the "o" (bubble) as the negation/polarity indicator.

Output Signals:

- The absence of the polarity indicator at that output of a logic unit defines that signal at that point as Asserted High.
- The presence of the polarity indicator at the output of a logic unit defines the signal at that point as Asserted Low

Typical correct examples are shown in the figure 2.

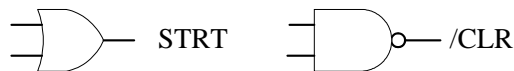


FIG 2: Correct method of indicating the polarities of the outputs

It is incorrect

- To designate an output signal as Asserted High if the polarity indicator is present
- To designate a signal as Asserted Low if no polarity indicator is present

Examples of incorrect designation, which should never be used, are given in the figure 3.

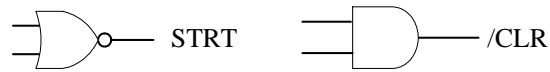


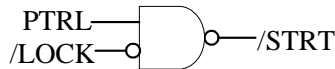
FIG. 3: Incorrect method of indicating the output polarities

Input Signals:

The usage of polarity indicator at the input of a logic unit depends on whether the variable connected to that input appears in the logic expression for the output variable, as Asserted or Not Asserted.

- If an Asserted High (AH) variable is given as input to logic unit without polarising indicator, that variable appears Asserted in the output logic expression.
- If an Asserted Low (AL) signal connected through a polarity indicator, that variable appears as Asserted in the output logic expression.

In the example shown in the figure an Asserted Low signal /LOCK and an Asserted High signal PTRL are ANDed to generate an Asserted Low output signal /STRT.



- An AL variable connected to a logic unit without a polarity indicator appears as Not Asserted variables in the logic expression for the output.
- An AH variable connected through a polarity indicator appears as Not Asserted variables in the logic expression for the output.

Some examples are shown in the figure 4.

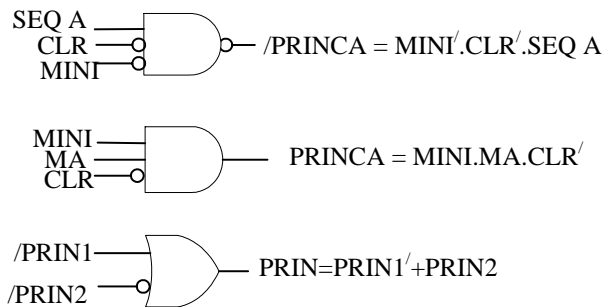


FIG. 4: Examples of logic functions drawn as per polarized mnemonic convention

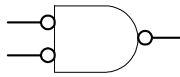
In interpreting the logic symbols in the Polarised Mnemonic Notation each symbol can be considered to have three distinct elements:

- Distinctive shaped logic symbol indicative of the logic operation being performed,



- The presence or absence of polarity indicators at the outputs.
- The presence or absence of polarity indicators at the inputs.

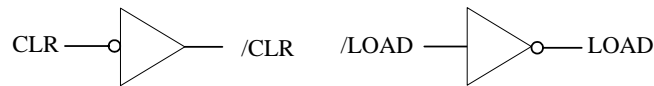
Consider the following symbol;



- The unit performs AND operation.
- The output variable is Asserted Low.
- The AND operation is performed on the Asserted Low input signals.

Some good practices:

Though incompatibility at the inputs of any logic functional unit is permissible, its usage should be avoided in the case of inverters as it is likely to lead to unnecessary confusions without offering any advantage. The use of symbols shown in the following figure should be avoided.



Exceptions:

Mode Signals: There is one class of signals, designated as MODE signals, for which assigning Assertion levels is not meaningful. These signals are indicative of more than one action. Different actions take place in both the states of the signals. Typical examples are R/W', U/D' and IO/M'.

In the case of R/W', when the signal takes 'High voltage' (H) it is indicative of READ operation, and when it takes 'Low voltage' (L) it is indicative of WRITE operation. These two operations are mutually exclusive and one of the operations is always implied.

UP/DOWN' signal is encountered in the counters. When U/D' takes H the counter counts up, and when it takes L the counter counts down.

Usage of such signals should be kept to a minimum. A more convenient way of designating such signals is to say MODE 0, MODE 1 etc.

Binary Data: Digital systems process binary data besides binary signals. It does not sound appropriate to state that a data bit is Asserted or Not Asserted. The line will assume High or Low voltage values as per the numerical value of that data bit. In this sense it is more like the mode signal, which implies different actions in different states of the signal. In this case of data line it will either convey a numerical value of 0 or 1. A data line, designated with mnemonics like DBIT-4, is always Asserted High signal, i.e., when it takes High voltage it is considered having a numerical value of '1' and when it takes Low voltage it is considered having a numerical value of '0'.

Unused Inputs: Integrated circuits are available in standard SSI and MSI packages. These ICs are designed to have widest possible applicability. Therefore, all the

inputs and capabilities may not be used every time an IC is incorporated into a circuit. The unused inputs of such IC gates as well as sequential circuits will have to be tied at known states. For example, if a 3-input OR gate is used only as a 2-input OR gate, the unused input should be kept in Not Asserted state. This may correspond to a high voltage or a low voltage. A high voltage input is shown by the letter H and a low voltage input is shown by the letter L. A few examples with gates are shown in the figure 5.

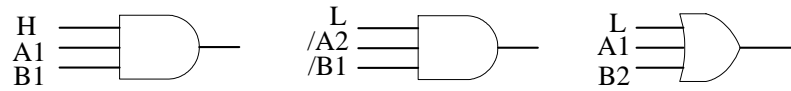


FIG. 5: Examples of designating unused inputs

The voltage level at which the unused inputs get tied to will depend on the assertion level of the signal.



Digital Electronics

Module 4: Combinational Circuits: Logic Functions

N.J. Rao

Indian Institute of Science



Implementation of Logic Functions

- Logic functions can be implemented in any one of the available logic families
- LSTTL and HCMOS family ICs are used for the medium frequency applications
- FAST series and Schottky series ICs are used at higher frequencies

With

- LSIs are becoming popular
- Cost per gate coming down drastically

Need for conventional type of minimisation is much less

Tractability of the design becomes more important



Combinational ICs

- Gates are available as SSIs
- Adders, multiplexers, comparators and encoders are available as MSIs
- SSI gates are mainly used for realising simple logic functions normally encountered in interconnecting LSI and MSI circuits.



Available Gates

	LSTTL 54/74LS	FAST 54/74F	HCMOS 54/74HC
NAND Gates			
Quad 2-input NAND	00	00	00A
Triple 3-input NAND	10	10	10
Dual 4-input NAND	20	20	20
8-input NAND	30	---	30
13-input NAND	133	---	133
NOR Gates			
Quad 2-input NOR	02	02	02A
Triple 3-input NOR	27	---	27



Available Gates (2)

	LSTTL 54/74LS	FAST 54/74F	HCMOS 54/74HC
AND Gates			
Quad 2-input AND	08	08	08A
Triple 3-input AND	11	11	11
Dual 4-input AND	21	21	---
OR Gates			
Quad 2-input OR	32	32	32A
Inverters			
Hex inverter	04	04	04A



Gate level implementation of logic functions

- Logical expressions are available either in the SOP form
POS form.

Consider the expression:

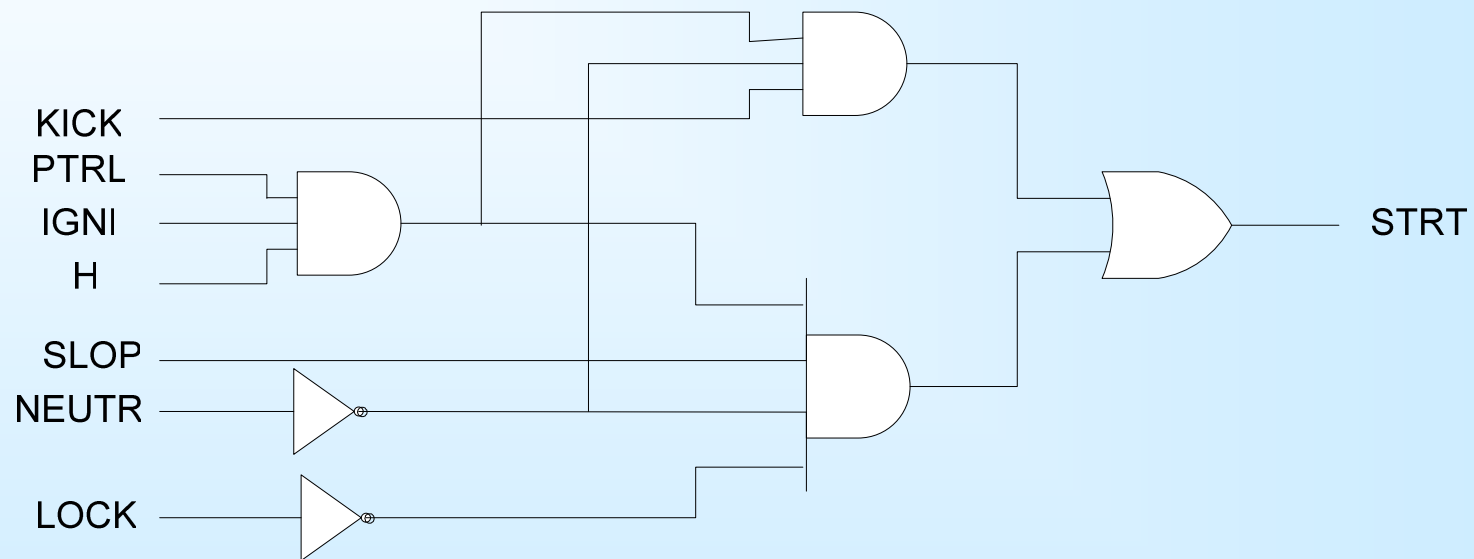
$$\text{STRT} = \text{PTRL}.\text{IGNI}.\text{NEUTR}'.\text{KICK} + \text{PTRL}.\text{IGNI}.\text{SLOP}.\text{NEUTR}'.\text{LOCK}'$$

It is not in canonical form

It can be realized by AND, OR and INVERT gates

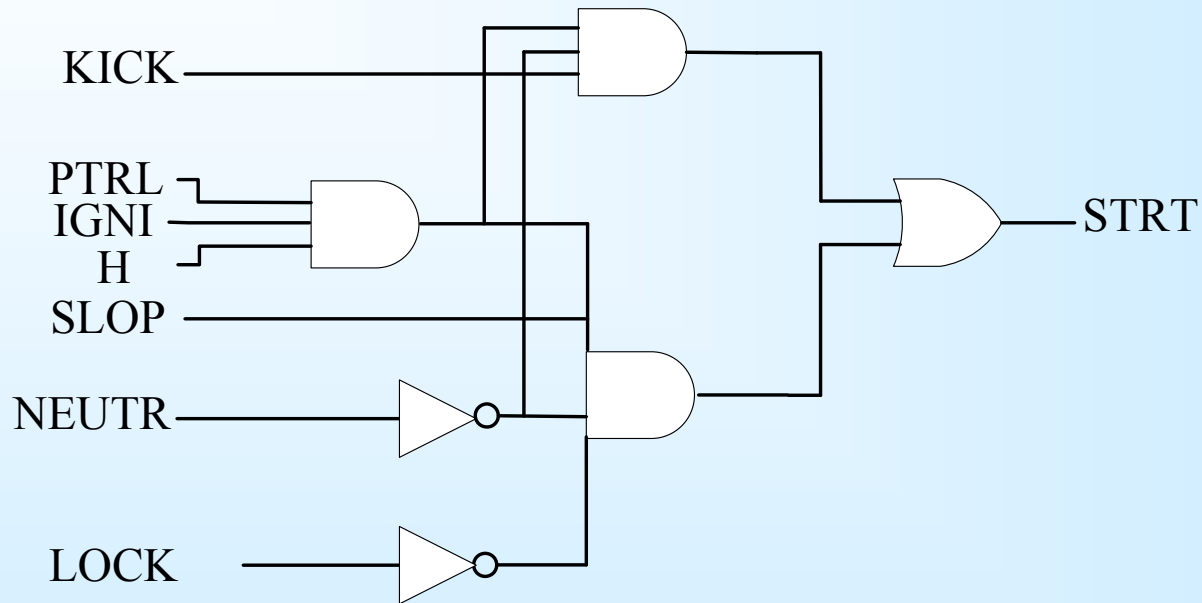


Realization by AND, OR and invert Gates





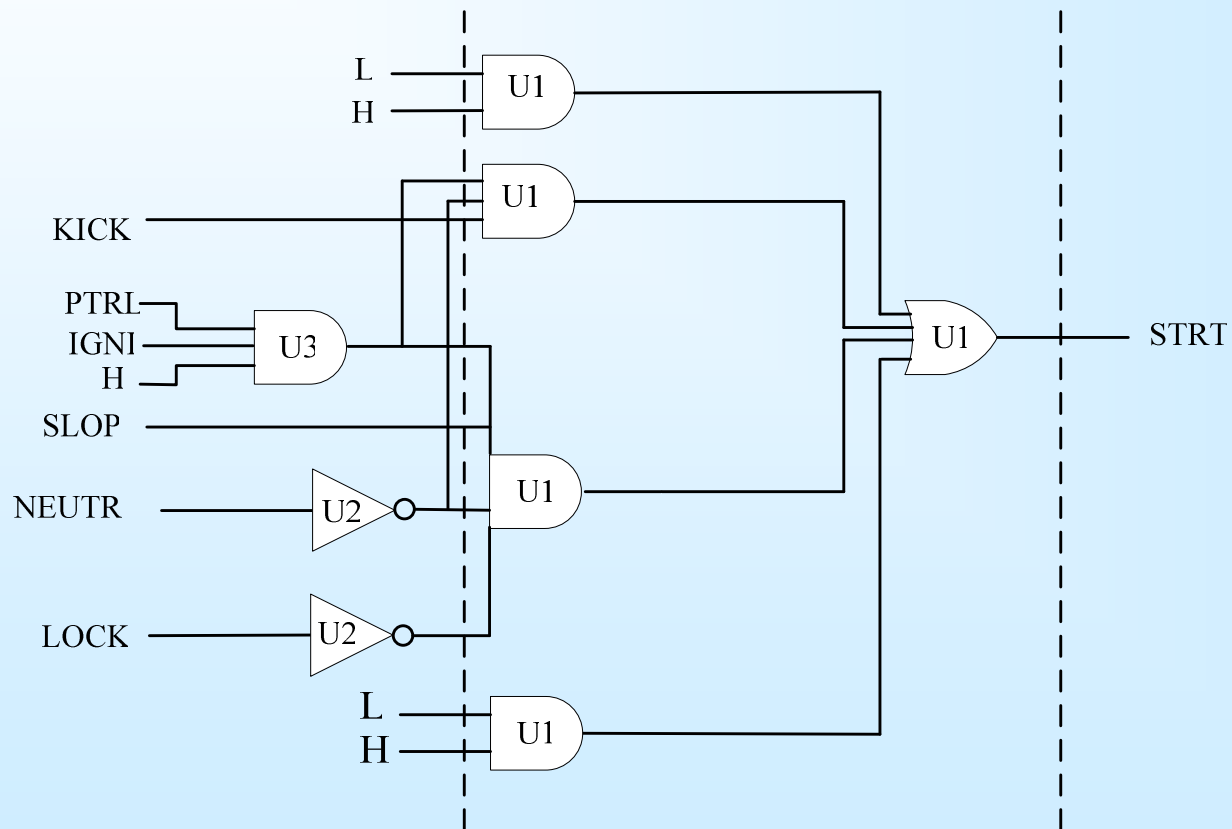
Using commercially AND,OR and NOT gates



We need a 3-level gating and it increases delay



Realization by AO gates





AOI gates

Dual 2-wide 2-input AOI	7451/LS51/S51/ HC51
Expandable Dual 2-input 2-wide AOI	7450
Expandable 2-wide 4-input AOI	74LS55
4-wide 2-input AOI	7454/LS54
Triple 3-input Expander	7461
Dual 4-input Expander	7460
4-2-3-2 input AOI	74S64

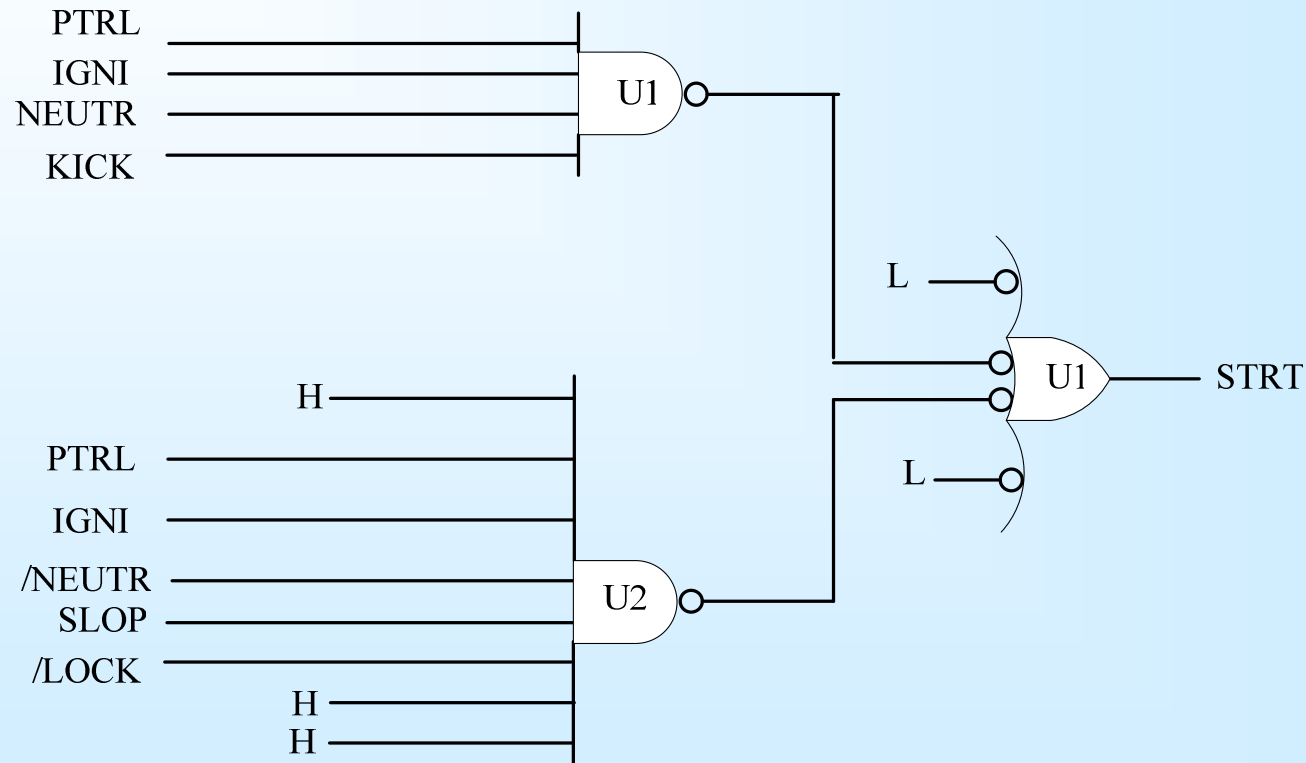


Realization by AOI gates

- It does not necessarily reduce the chip count
- LSTTL family does not offer many varieties of AO or AOI gates.

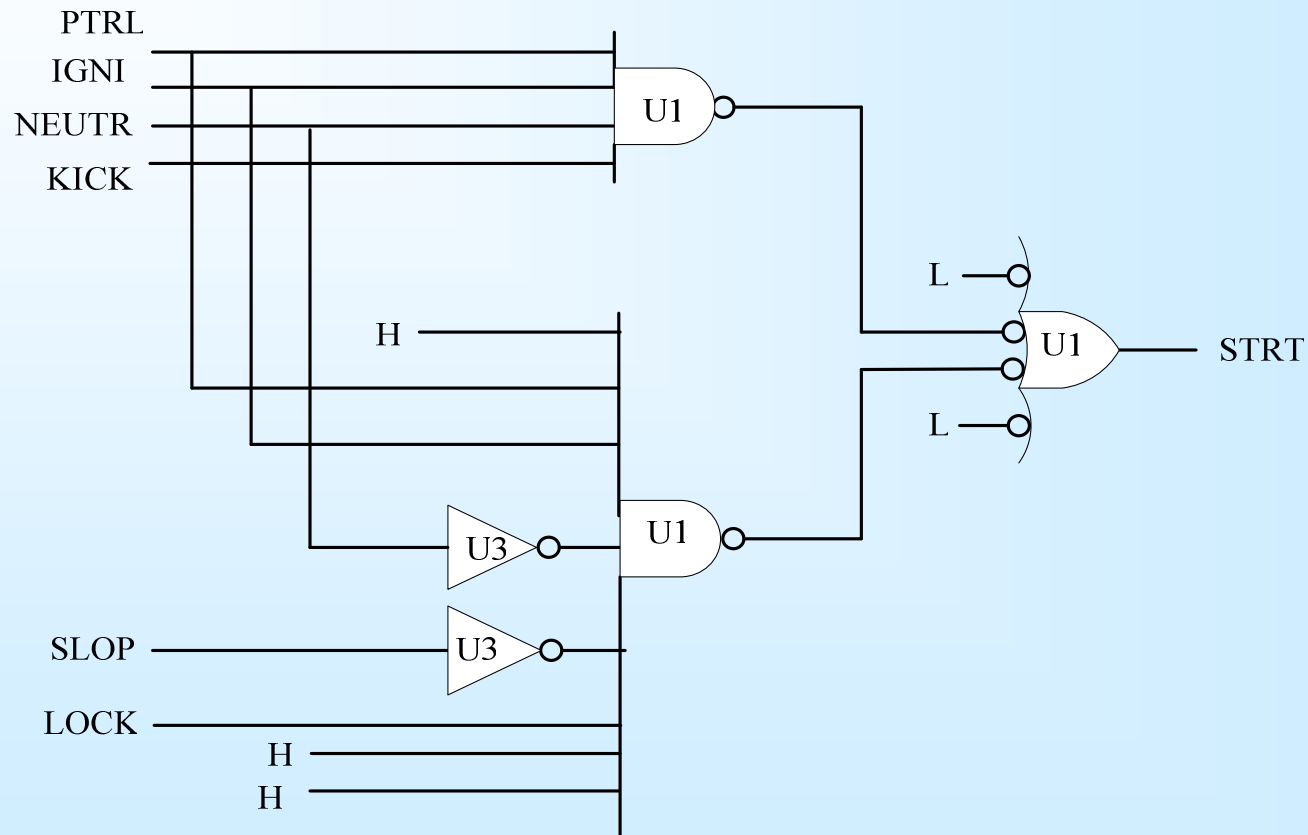


Realization of SOP form by NANDs





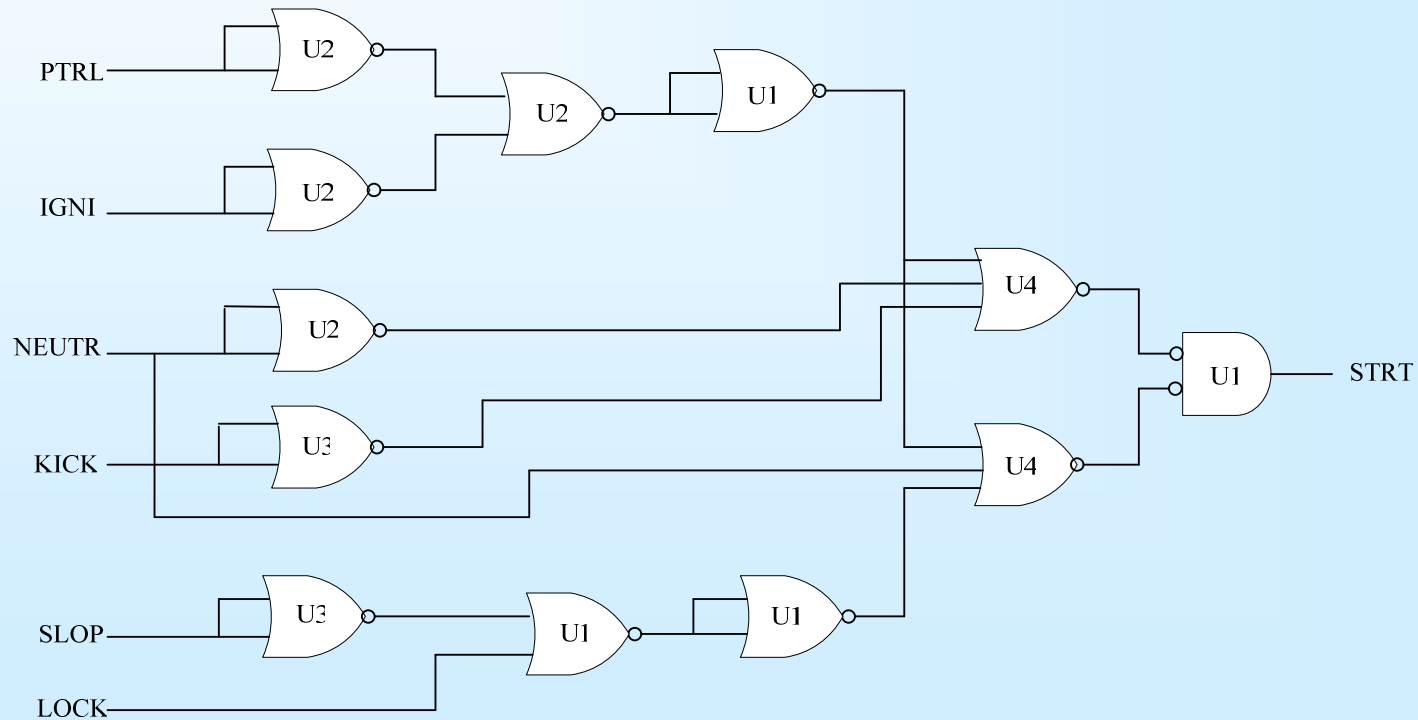
NAND and INVERTER realization





Realization of POS form by NOR gates

$$\text{STRT} = (\text{PTRL} + \text{IGNI} + \text{NEUTR} + \text{KICK}) \cdot (\text{PTRL} + \text{IGNI} + \text{SLOP} + \text{NEUTR} + \text{LOCK})$$





Ex-OR realization

Parity checker

$$EP = A \oplus B \oplus C \oplus D \oplus E$$

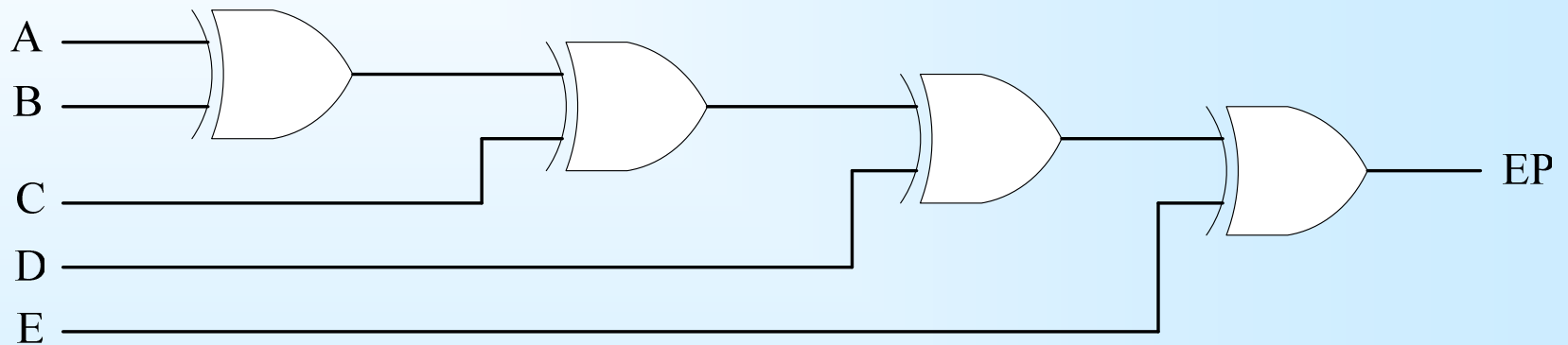
It's canonical version

$$\begin{aligned} EP = & ABCDE + ABC'D'E + ABC'DE' + ABCD'E' + \\ & A'BC'D'E + A'BC'DE' + A'BC'DE' + A'BC'DE' + \\ & A'BCDE' + A'BCDE + AB'C'D'E' + \\ & AB'CDE' + AB'CDE + AB'CDE + \\ & A'BC'D'E' + A'BCDE' + A'BCD'E + \\ & A'BC'DE \end{aligned}$$



Parity checker with Ex-OR

74LS86/HC86s (Quad 2-input EX-OR)



Multiple levels



At this stage of design

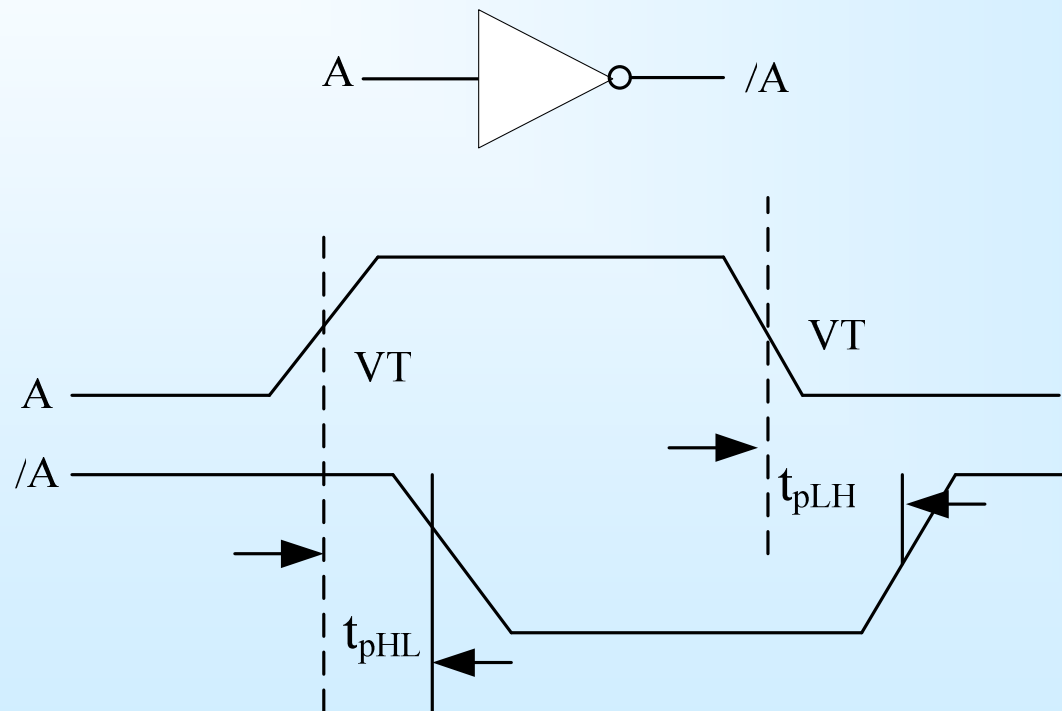
Choice of gates in realising logical expressions should be based on

- number of chips needed to realize the expression
- number of varieties of chips to be kept in the inventory
- number of levels of gating (the maximum number of gates that an input signal has to pass through in a circuit) needed to realize the expression



Delay

Input-Output relationship of an inverter





Manufacturer's specifications

74LS04

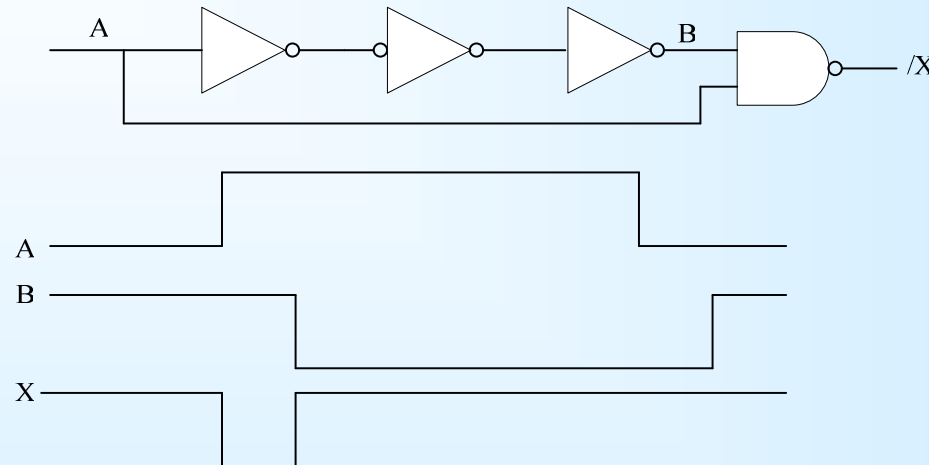
	TYP	MAX	
t_{PHL} -	9.5	15	ns
t_{PLH} -	9.5	15	ns

- Typical value is not a guaranteed value and hence cannot be used as a design parameter
- The designer has to work with the worst case values for these propagation delays
- Manufacturers do not guarantee any minimum delay



Problems of minimum delay

Digital differentiator



What will be the width of the output pulse?

- With typical values: $9.5 \times 3 = 28.5$ ns.
- With maximum values: $15 \times 3 = 45$ ns.
- It can be any value from 0 to 45 ns.

Such a circuit cannot be used



Delays and different realizations

Expression in SOP form can be realized

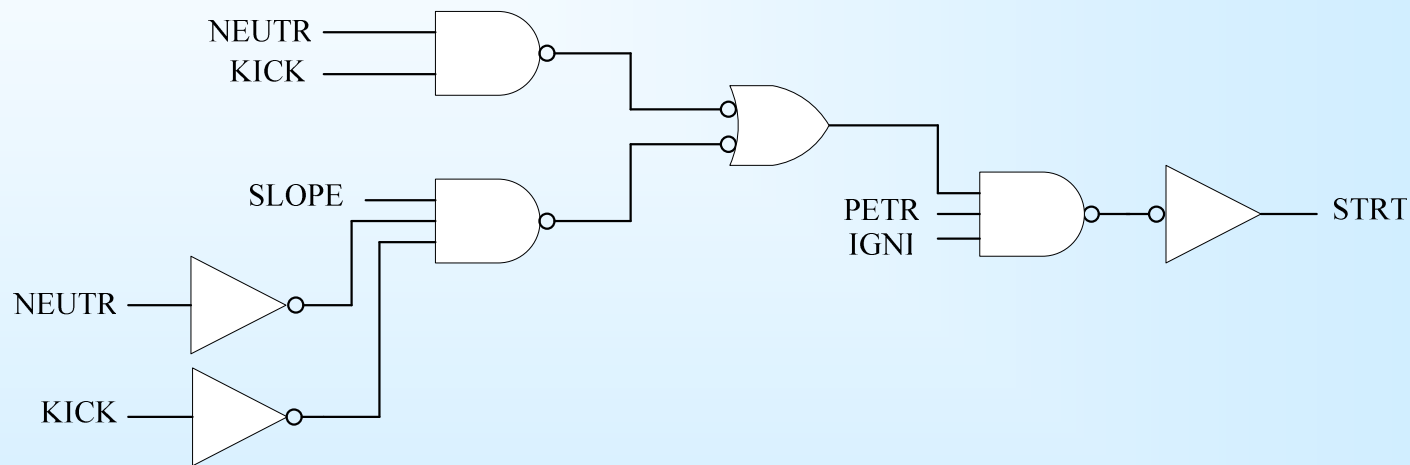
- By 2-level gating if the variables are available in their Asserted High and Asserted Low versions
- By 3-level gating if the variables are not available in their Asserted High and Asserted Low versions

In all other forms the delay is likely to be more



Expression in non-canonical form

$$\text{STRT} = \text{PTRL} \cdot \text{IGNI} \cdot ([\text{NEUTR} \cdot \text{KICK}] + [\text{SLOPE} \cdot \text{NEUTR}' \cdot \text{KICK}'])$$



Minimization of propagation delay may not always be a design objective.

The form of the expression may be chosen to make the design more easily understandable.



Specification of delay

Normally the delays for LSTTL family are defined at

$T = 25^{\circ}\text{C}$, $V = 5\text{ volts}$, $C = 15\text{ pF}$, and $R = 2\text{ K}\Omega$

For HCMOS family the delay times are specified at nine operating points (three voltages and three temperatures)

$\Delta V_{CC} = 2.0\text{ V}$, $T: 25^{\circ}\text{C to } -55^{\circ}\text{C, } < 85^{\circ}\text{C, and } < 125^{\circ}\text{C}$,
 $C_L = 50\text{ pF}$, Input $t_r = t_f = 6\text{ ns}$

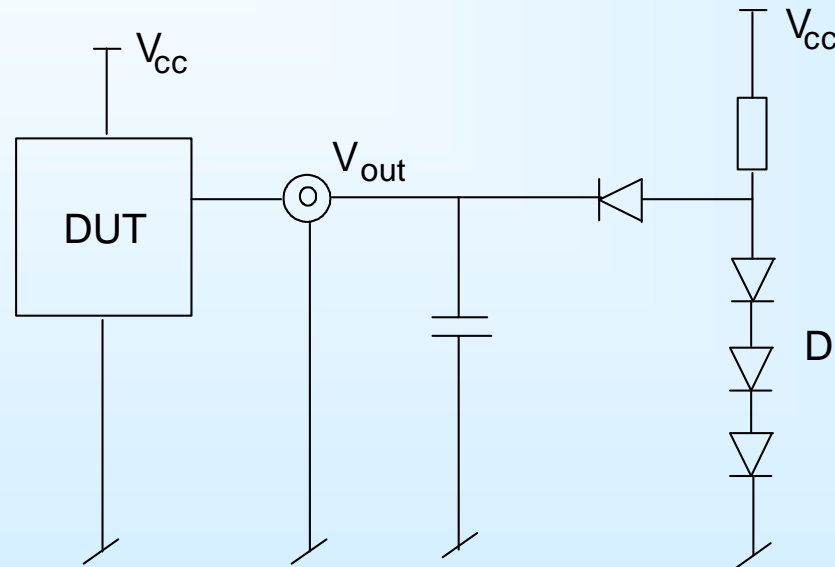
$\Delta V_{CC} = 4.5\text{ V}$, $T: 25^{\circ}\text{C to } -55^{\circ}\text{C, } < 85^{\circ}\text{C, and } < 125^{\circ}\text{C}$,
 $C_L = 50\text{ pF}$, Input $t_r = t_f = 6\text{ ns}$

$\Delta V_{CC} = 6.0\text{ V}$, $T: 25^{\circ}\text{C to } -55^{\circ}\text{C, } < 85^{\circ}\text{C, and } < 125^{\circ}\text{C}$,
 $C_L = 50\text{ pF}$, Input $t_r = t_f = 6\text{ ns}$



Test circuit

Test circuit with which these delays are measured





Load capacitance

Depends on

- PCB track width and the length,
- material of the laminate.

It varies from 20 pF to 150 pF.

Its effect is

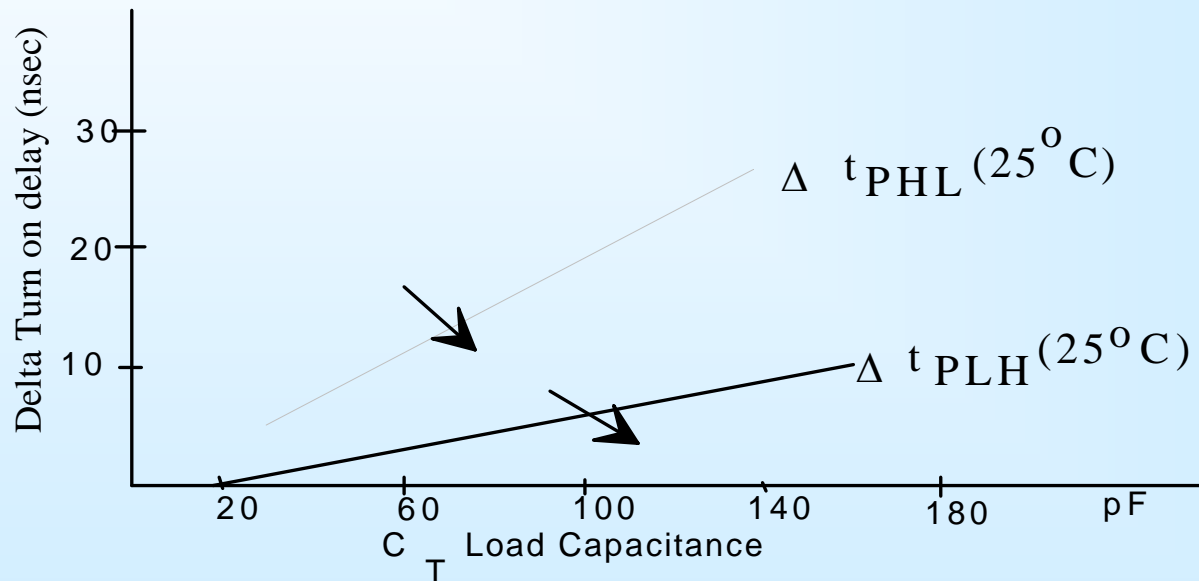
- to increase the propagation delay
- to increase supply current spike amplitude during the transients

Depending on the load circuit, capacitive loading and temperature the propagation delays can increase by as much as 15 ns.



Dependence of the propagation delay

Its dependence on the load capacitance





Glitches in the outputs

- The output is considered only after all the transients that are likely to be produced when the state of the inputs signals change.
- Finite delays make the transient response of a logic circuit different from steady state behaviour.
- These transients occur because different paths from input to output may have different propagation delays.
- These differences in the propagation delays can produce short pulses, known as *glitches*.
- The steady state analysis does not predict this behaviour.



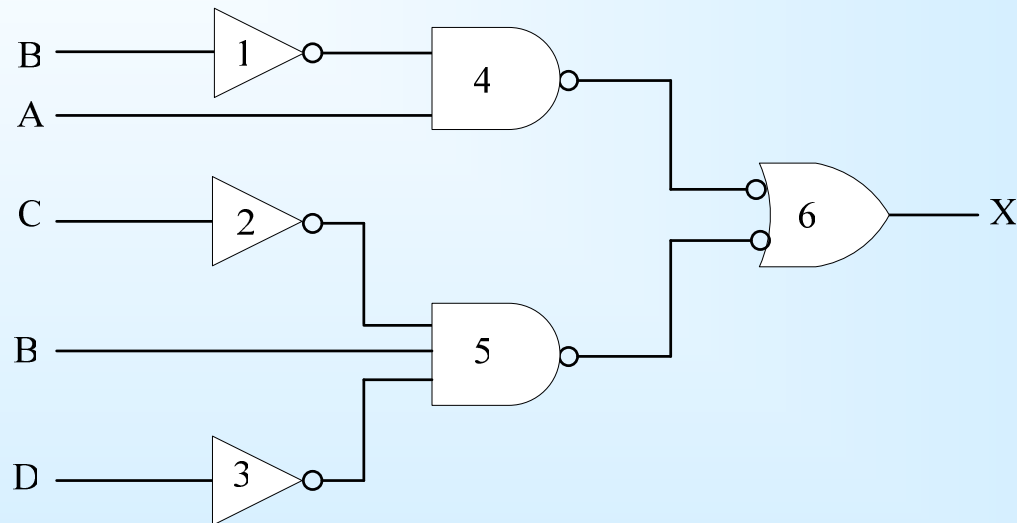
Hazard

- A *hazard* is said to exist when a circuit has the possibility of generating a glitch.
- The actual occurrence of the glitch and its pulse width depend on the exact delays associated with the actual devices used in the circuit.
- Designer has no control over this parameter
- It is necessary to design that avoids the occurrence of glitches.
- One simple method is not to look at the outputs until they settle down to their final value.



Example

Consider the expression $X = A B' + BC'D'$





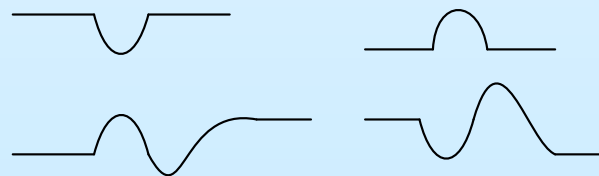
Detection of hazard

- Hazard is caused by the propagation delay associated with the gate-1
- Let A and B be Asserted and C and D are Not-asserted.
- When B changes from its Asserted state to its Not-asserted state with the other variables remaining the same the output should remain in its Asserted state.
- When B changes from 1-to-0 the output of the gate-5 changes from 1-to-0.
- The output of the gate-4 should change from 0-to-1 at the same time.
- But the delay associated with the gate-1 makes this transition of the gate-4 output to happen a little later than that of gate-5.
- This can cause brief transition of X from 1-to-0 and then from 0-to-1



Types of Hazards

- Static-1 hazard: When the output is expected to remain in state 1 as per the steady state analysis it makes a brief transition to 0
- Static-0 hazard: When the output is expected to remain in state 0 as per the steady state analysis it it makes a brief transition to 1.
- Dynamic hazard: When the output is supposed to change from 0 to 1 (or 1 to 0), the circuit may go through three or more transients to produce more than one glitch

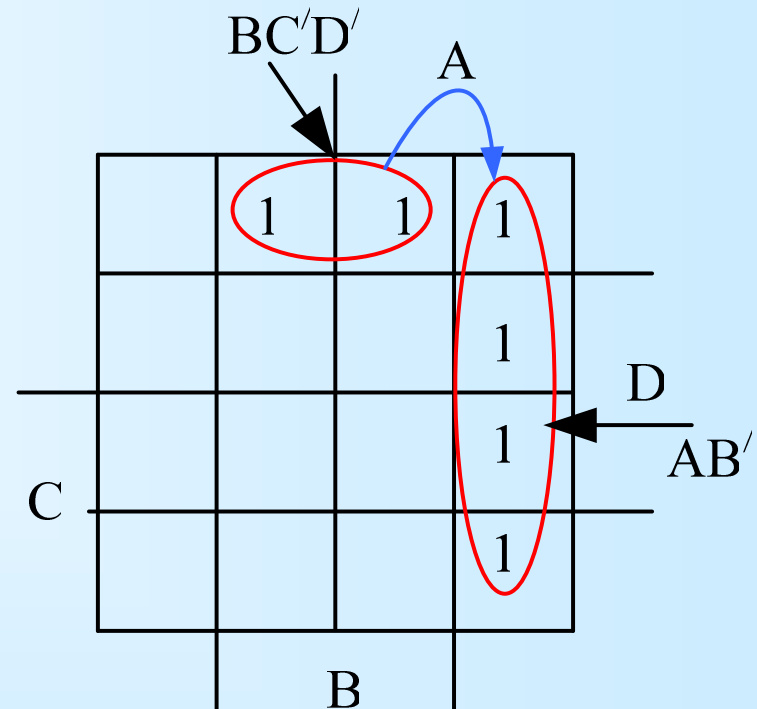




Analysis using K-Map

$$X = A B' + BC'D'$$

Hazard associated with the 1-to-1 transition occurred when the change of state of the variable B caused the transition from one grouping $BC'D'$ to another grouping AB' .





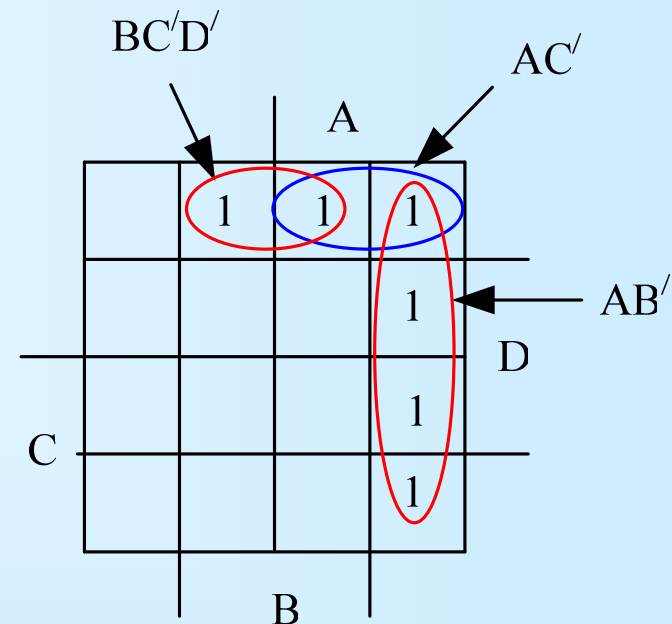
Detection of other hazards

- It is more difficult to detect the other three transitions.
- One result from Logic and Switching Theory states that a two level gate implementation of a logical expression will be hazard free for all transitions of the output if it is free from the hazard associated with 1-to-1 transition.
- When the input variables change in such manner as to cause a transition from one grouping to another grouping, the 1-to-1 transition can occur



Eliminating hazards

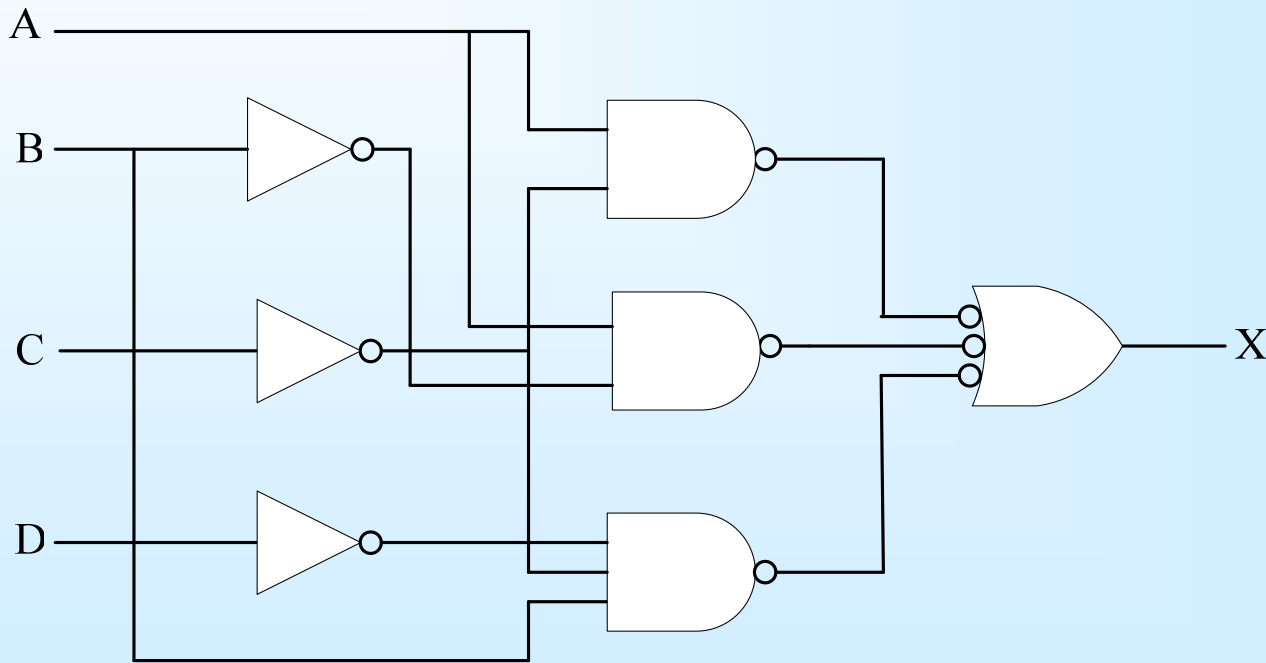
- In a two level gating realization of a logical expression include all 1s which are unit distance apart at least in one grouping
- Group the terms $ABC'D'$ and $AB'C'D'$ together
- This would lead to an additional gate
- The added gate defines the output during the transition of B from one state to the other





Hazard free realization

$$X = AB' + BC'D' \rightarrow X = AB' + BC'D' + AC'D'$$





Loading

- A logic gate has limited capacity to source and sink current at its output.

- The output current capability of LSTTL gate is

$$I_{OH} = -400 \text{ mA} \quad \text{at } V_{OH} = 2.7 \text{ volts}$$

$$I_{OL} = 4 \text{ mA} \quad \text{at } V_{OL} = 0.4 \text{ volts}$$

$$= 8 \text{ mA} \quad \text{at } V_{OL} = 0.5 \text{ volts}$$

$$I_{IH} = 20 \text{ mA}$$

$$I_{IL} = -0.4 \text{ mA}$$

- At $V_{OL} = 0.4 \text{ V}$ LSTTL gates have 2.5 UL capability and can drive 10 LSTTL gates
- At $V_{OL} = 0.5 \text{ V}$ LSTTL gates have 5UL capability and can drive 20 LSTTL gates



HCMOS gates

$I_{in} = + 0.1 \mu\text{A}$ at $V_{CC} = 6.0 \text{ V}$

$I_{OH} = - 4.0 \text{ mA}$ at $V_{OH} = 3.98 \text{ V}$ with $V_{CC} = 4.5 \text{ V}$ and $T: -55^\circ \text{ to } 25^\circ \text{ C}$

at $V_{OH} = 3.84 \text{ V}$ with $V_{CC} = 4.5 \text{ V}$ and $T: < 85^\circ \text{ C}$

at $V_{OH} = 3.70 \text{ V}$ with $V_{CC} = 4.5 \text{ V}$ and $T: < 125^\circ \text{ C}$

$= - 5.2 \text{ mA}$ at $V_{OH} = 5.48 \text{ V}$ with $V_{CC} = 6.0 \text{ V}$ and $T: -55^\circ \text{ to } 25^\circ \text{ C}$

at $V_{OH} = 5.34 \text{ V}$ with $V_{CC} = 6.0 \text{ V}$ and $T: < 85^\circ \text{ C}$

at $V_{OH} = 5.20 \text{ V}$ with $V_{CC} = 6.0 \text{ V}$ and $T: < 125^\circ \text{ C}$

$I_{OL} = 4.0 \text{ mA}$ at $V_{OL} = 0.26 \text{ V}$ with $V_{CC} = 4.5 \text{ V}$ and $T: 25^\circ \text{ to } -55^\circ \text{ C}$,

at $V_{OL} = 0.33 \text{ V}$ with $V_{CC} = 4.5 \text{ V}$ and $T: < 85^\circ \text{ C}$

at $V_{OL} = 0.40 \text{ V}$ with $V_{CC} = 4.5 \text{ V}$ and $T: < 125^\circ \text{ C}$

$= 5.2 \text{ mA}$ at $V_{OL} = 0.26 \text{ V}$ with $V_{CC} = 6.0 \text{ V}$ and $T: 25^\circ \text{ to } -55^\circ \text{ C}$

at $V_{OL} = 0.33 \text{ V}$ with $V_{CC} = 6.0 \text{ V}$ and $T: < 85^\circ \text{ C}$



Buffers

Quad 2 - input NAND Buffer - 74LS37

Dual 4 - input NAND Buffer - 74LS40

These have an output current capability of

$$I_{OL} = 24 \text{ mA}$$

$$I_{OH} = -1200 \text{ mA}$$

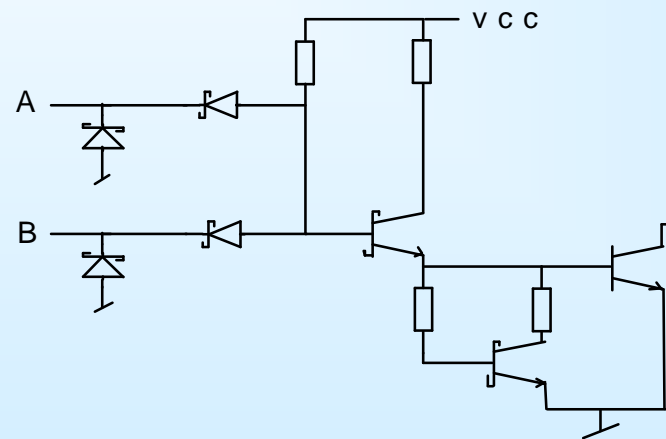
- They can drive as many as 60 LSTTL loads.
- Propagation delay: $t_{PHL} = t_{PLH} = 24 \text{ n secs}$ against the usual 15 n secs
- To drive a load beyond the capability of a buffer, discrete components have to be used.



Output Voltages

The worst case $V_{OH} = 2.7 \text{ V}$ in LSTTL family
= 5.5 V in case of HCMOS if 6.0 V is
used as power supply

If larger output voltages are required use open-collector gates



Open collector terminal can be connected to the
desired supply voltage ($\leq V_{OH(max)}$) through a suitable load resistor



Available open collector LSTTL gates

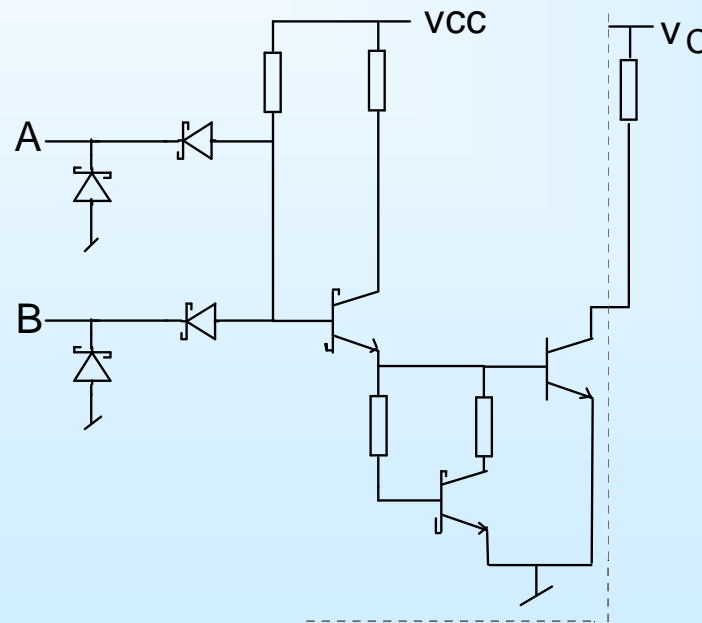
- Quad 2-input NAND(OC) - 74LS03 [V_{OH} (max) = 5.5 V, I_{OL} = 8 mA]
- Quad 2-input NAND(OC) - 74LS26 [V_{OH} (max) = 15 V, I_{OL} = 18 mA]
- Hex Inverter (OC) - 74LS38 [V_{OH} (max) = 5.5 V, I_{OL} = 24 mA]
- Hex Inverter/Buffer (OC) - 7406 [V_{OH} (max) = 30 V, I_{OL} = 40 mA]
- Hex Buffer (OC) - 7407 [V_{OH} (max) = 30 V, I_{OL} = 40 mA]

The HCMOS and HCTMOS families do not offer many open drain circuits



Delay associated with OC gate

74LS26 operated at V_{CC} of 5 V, $R_L = 2 \text{ K}\Omega$ and $C_L = 15 \text{ pF}$ has $t_{PLH} = 32 \text{ ns}$ (max) and a $t_{PHL} = 28 \text{ ns}$ (max) against $t_{PHL} = t_{PLH} = 15 \text{ ns}$ (max)





Tristate Gates

OC gates have limitations

- with regard to the speed
 - the distance between the modules,
 - every signal line requires the usage of a suitable load resistor
- Tristate logic elements provide a solution to the problems of speed and power in bus organized digital systems.



TSL buffers

	LSTTL	HCMOS	HCTMOS
• Quad 3-state noninverting buffer	74LS125A	74HC125A	
• Quad 3-state noninverting buffer	74LS126A	74HC125A	
• Octal 3-state inverting buffer/ line driver/line receiver	74LS240	74HC240A	74HCT240A
• Octal 3-state Noninverting buffer/ line driver/line receiver	74LS241	74HC241	74HCT241A
• Octal 3-state inverting bus transceiver	74LS242	74HC242	
• Octal 3-state noninverting buffer/ line driver/line receiver	74LS244	74HC244A	74HCT244A
• Octal 3-state noninverting bus transceiver	74LS245	74HC245A	74HCT245



TSL buffers

- Hex 3-state noninverting buffer with common enables 74LS365A 74HC365
- Hex 3-state inverting buffer with common enables 74LS366A 74HC366
- Hex 3-state noninverting buffer with 2-bit and 4-bit sections 74LS367A 74HC367
- Hex 3-state inverting buffer with 2-bit and 4-bit sections 74LS368A 74HC368
- Octal 3-state inverting buffer/line driver/line receiver 74LS540 74HC540 74HCT540
- Octal 3-state noninverting buffer/line driver/line receiver 74LS541 74HC541 74HCT541
- Octal 3-state inverting bus transceiver 74LS640 74HC640A 74HCT640



TSL Gate: Characteristics

In Hi-z state the maximum leakage current at the output, which occurs when it is tied to a gate whose output is low-impedance High state, is +20 μA

- sources 2.6 mA at a V_{OH} of 2.7 V, and
- sinks 24 mA at V_{OL} of 0.5 V and 12 mA at a V_{OL} of 0.4 V.

This will permit as many as 128 tristate logic (TSL) outputs to be tied to a common bus and still provide enough sourcing current to drive three LSTTL loads.



TSL Gate: Characteristics

If one device is ON and 127 are OFF the following is valid:

$$127 \times 20\mu\text{A} = 2.54 \text{ mA}$$

$$2.6 \text{ mA} - 2.54 \text{ mA} = 60\mu\text{A}$$

$$= 3 \times 20 \mu\text{A (LSTTL)}$$

- The TSL output will be able to drive reliably a line over 3 meters long
- Provides a far superior High level noise immunity
- Delay from Inhibit to Output Disable, 20 ns(max)
- Delay from Enable to Low State, 25 ns(max)

INTRODUCTION

Logic functions that represent combinational functions can be implemented as hardware in any one of the several logic families that are commercially available. The logic families that are widely used for the medium frequency (up to about 25 MHz) applications are

- LSTTL
- HCMOS

Higher frequency requirements are met by

- FAST series
- Schottky series

74LSTTL ICs are designed to operate over the commercial temperature range, namely, from 0°C to 70°C.

54LS TTL ICs are functionally and pin-to-pin compatible with 74LS units, but operate over the Military temperature range, namely, -55°C to +125°C.

HCMOS family ICs are also available in the same temperature range.

Before the advent of the microprocessors and programmable LSI combinational circuits (PROMs, PLAs and PALs) digital designers had to be content with gates to realise complex combinational circuits. It was, therefore, necessary to simplify the expressions to reduce the number of gates or the number of ICs. When the number of variables was smaller, designers used Karnaugh Maps or Variable Entered Karnaugh Maps (VEM). When the variables were large in number it was necessary to use computer based minimisation techniques.

With LSI combinational circuits becoming popular and the cost per gate coming down drastically, the need for conventional type of minimisation is much less, the tractability of the design became more important. The given logical expressions can now be implemented, however complex they are, using programmable combinational LSI circuits, and keep the chip count low.

Certain standard combinational functions like adders, multiplexers, comparators and encoders are available in MSI packages. Therefore, realisation of these commonly encountered combinational functions need not be done by gates. In view of the availability of certain standard MSI and LSI circuits the SSI gates are mainly used for realising simple logic functions normally encountered in interconnecting LSI and MSI circuits. Design with these gates, therefore, is done predominantly on an intuitive basis, and occasionally using K-Maps or VEMs.

Gates available in the 74 series of LS and HCMOS/HCTMOS families are listed in the following.

	LSTTL	FAST	HCMOS	HCTMOS	
	54/74LS	54/74F		54/74HC	54/74HCT
NAND Gates					
Quad 2-input NAND	00	00		00A	---
Triple 3-input NAND	10	10	10	---	
Dual 4-input NAND	20	20	20	---	
8-input NAND	30	---	30	---	
13-input NAND	133	---	133	---	
NOR Gates					

Quad 2-input NOR	02	02	02A	---
Triple 3-input NOR	27	---	27	---
AND Gates				
Quad 2-input AND	08	08	08A	---
Triple 3-input AND	11	11	11	---
Dual 4-input AND	21	21	---	---
OR Gates				
Quad 2-input OR	32	32	32A	---
Inverters				
Hex inverter	04	04	04A	04A

GATE LEVEL IMPLEMENTATION OF LOGIC EXPRESSIONS

Logical expressions are available in

- Sum-of-Product (SOP) form
- Product-of-Sum (POS) form

But the expressions we have may or may not be in canonical form. By canonical form we mean sum of Minterms in the case of SOP form, and product of Maxterms in the case of POS form. If they are not in the canonical form they would have been arrived at either heuristically or after simplification through a K-Map or a Variable Entered Map. Consider the following expression:

$$\text{STRT} = \text{PTRL}.\text{IGNI}.\text{NEUTR}'.\text{KICK} + \text{PTRL}.\text{IGNI}.\text{SLOP}.\text{NEUTR}'.\text{LOCK}'$$

It may be noticed that this expression is not in canonical form. It can be realized by AND, OR and INVERT gates as shown in the figure 1.

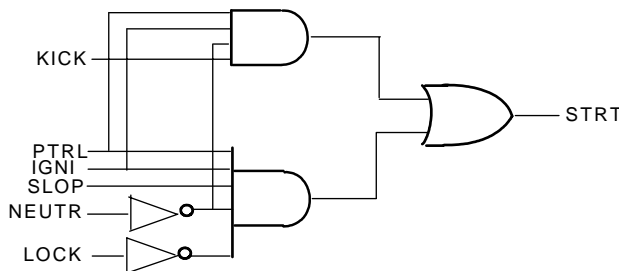


FIG. 1: AND-OR-INVERT realization of a logical expression

We have several problems in realizing this circuit using commercially available gates.

- AND gates with five inputs are not available in LSTTL and HCMOS families.

We can add an extra AND gate with three inputs to overcome the problem of 5-input AND gate. Consider the circuit shown in the figure 2. We now have an extra level of gating. An extra level of gating would always add to the input to output delay. We will address this problem of delay at a later state.

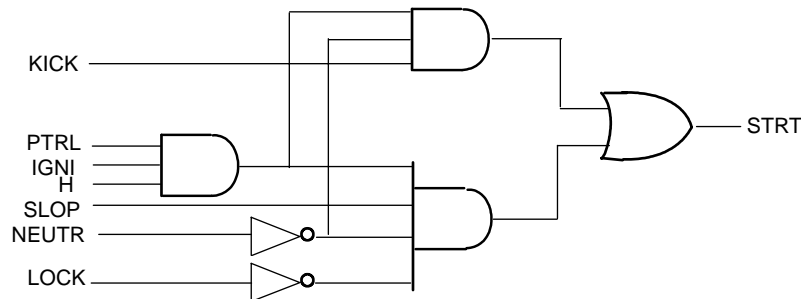


FIG. 2: Implementation of the expression for STRT with commercially available gates

Any logic expression in SOP form can essentially be considered to be ANDing of different groups of variables and ORing the outputs of the AND gates. Therefore, it was considered convenient to make available in the same package and AND and OR gates suitably interconnected as shown in the figure 3.

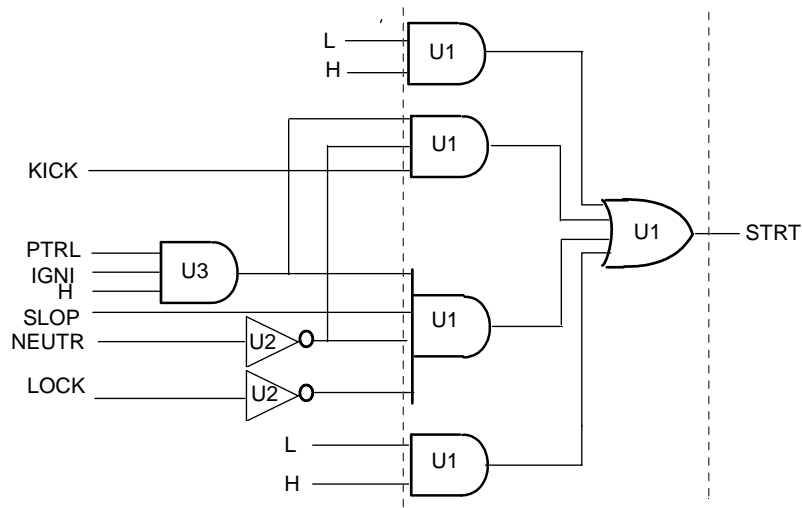


FIG. 3: AO realization of logical expression for START

In some cases the inverted output is made available by incorporating an INVERTER along with AND and OR gates in the same package. Such gate packages are known as AO (AND-OR) or AOI (AND-OR-INVERT) gates. In fact several such gates were made commercially available. They include

Dual 2-wide 2-input AOI	7451/LS51/S51/HC51
4-wide 2-input AOI	7454/LS54
4-2-3-2 input AOI	74S64

But there is problem here. It is not always possible to have the required number of inputs or AND groupings in a given AO or AOI gate. It was, therefore, thought some provision could be made to expand the number of inputs to the OR function. AO gates with expansion facility and the expander gates include

Expandable Dual 2-input 2-wide AOI	7450
Expandable 2-wide 4-input AOI	74LS55
Triple 3-input Expander	7461
Dual 4-input Expander	7460

Consider AOI implementation of the logical expression for START, as in the figure 3. We notice that AOI realization does not necessarily reduce the chip count.

We considered earlier that a NAND gate can be used to realize either an AND function or an OR function according to the assertion levels of the input signals. Therefore, any logical expression in SOP form can be realized by two levels of NAND gates.

- The first level NAND gates perform the AND operation and produce Asserted Low outputs.
- The second level NAND gate performs OR operation on Asserted Low inputs to generate an Asserted High output.

The realization of the expression for START, in the polarized mnemonic notation, is shown in the figure 4.

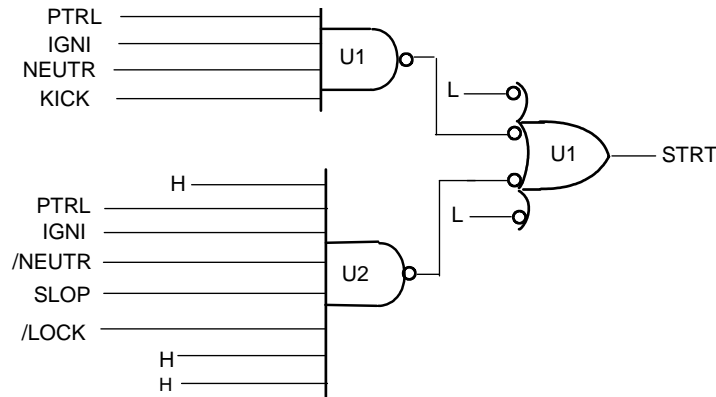


FIG. 4: NAND realization of a logical expression in SOP form

If variables are available both in Asserted High and Asserted Low versions, any logical expression can be realized in its SOP form through two level NAND gates. If variables are not available in both the versions then an additional level of gating, with NANDS used as INVERTERS, would become necessary. Such a realization of the expression for START is shown in the figure 5.

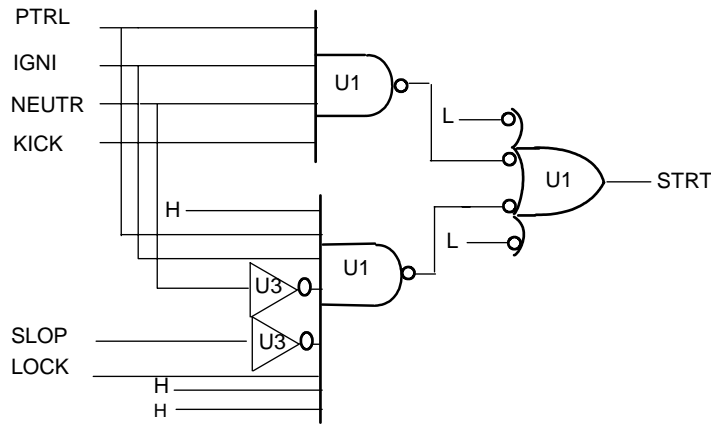


FIG. 5: NAND and INVERTER realization of a logical expression in SOP form with variables in AH form

The major advantage of realizing logical expressions through NAND gates is that the inventory in an organization can be kept to a single variety of gates.

If the expression is available in the POS form then it is better to realize it using NOR gates. Consider the expression for STRT in the POS form as given below.

$$\text{STRT} = (\text{PTRL} + \text{IGNI} + \text{NEUTR} + \text{KICK}) \cdot (\text{PTRL} + \text{IGNI} + \text{SLOP} + \text{NEUTR} + \text{LOCK})$$

Realization using the commercially available NOR gates is shown in the figure 6.

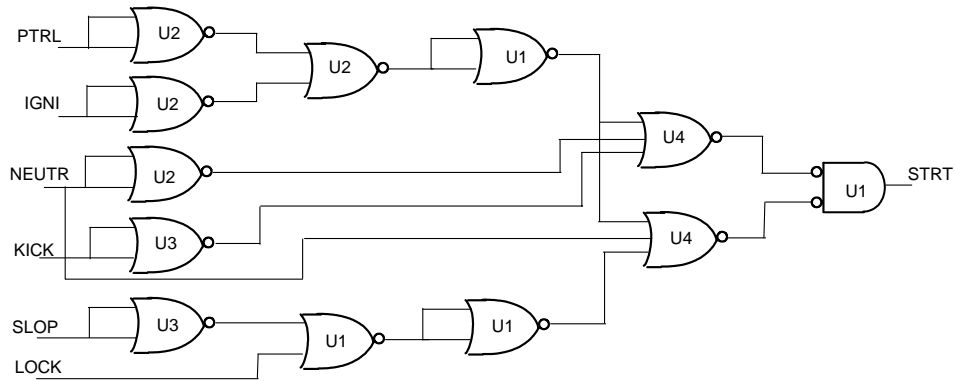


FIG.3.6: NOR realization of a logical expression in POS form

We observe that the number of gating levels had to be increased as NOR gates with larger number of inputs are not available. Besides, logical expressions are more commonly expressed in SOP form than in POS form. Hence implementation of expressions through NOR gates is not particularly popular.

Some logical expressions are more conveniently expressed in terms of EX-OR operations rather than in the standard form. For example the expression for parity checking is given by.

$$EP = A \oplus B \oplus C \oplus D \oplus E$$

This is more conveniently realized in this form rather than realizing it in its canonical version. The logical expression for the parity checking, in its canonical form is

$$\begin{aligned}
 EP = & A B C D E + A B C' D' E + A B C' D E' + A B C D' E' + \\
 & A' B' C' D' E + A' B' C' D E' + A' B' C D' E' + A' B' C D E + \\
 & A B' C' D' E' + A B' C D E' + A B' C D' E + A B' C' D E + \\
 & A' B C' D' E' + A' B C D E' + A' B C D' E + A' B C' D E.
 \end{aligned}$$

Its implementation using 74LS86/HC86s (Quad 2-input EX-OR) is shown in the figure 7. Notice that while this realization appears simple, the number of levels of gating is considerably more. This would mean more delay to generate the output variable.

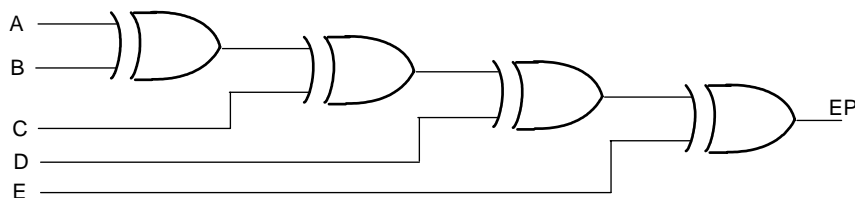


FIG. 7: Realization with EX-OR gates

At this stage of design, the choice of gates in realizing logical expressions should be based on the following factors:

- Number of chips needed to realize the expression
- Number of varieties of chips to be kept in the inventory

- Number of levels of gating (the maximum number of gates that an input signal has to pass through in a circuit)

Each expression may lead to the usage of a unique combination of gates in minimizing the chip count. In such a case one has to keep all the available gates in the inventory. However, if one wishes to minimize the inventory it is more convenient to limit the realization of logical expressions to NANDs and INVERTERS. This is particularly advantageous as the expressions are more commonly available in the SOP form. The number of levels of gating depends on the number of variables, the form in which the variables are available and the fan-in of the available gates, which in turn determines the delay in generating the output.

DELAY

Any hardware logic unit will have some propagation delay associated with it. The output appears with a time delay after the application of inputs. The time relationship between the input and output of an INVERTER is shown in the figure 1. Two different time delays are identified in the figure,

- t_{PHL} represents the propagation delay when the output makes a transition from high voltage to low voltage,
- t_{PLH} indicates the propagation delay associated when the output makes a transition from low voltage to high voltage.

These two propagation delays are not necessarily the same. When they are not the same they should be considered independently, and no averaging should be done.

The IC manufacturers mention typical and maximum values in their specification sheets. For example the propagation delays of 74LS04 are:

	TYP	MAX	
t_{PHL} -	9.5	15	ns
t_{PLH} -	9.5	15	ns

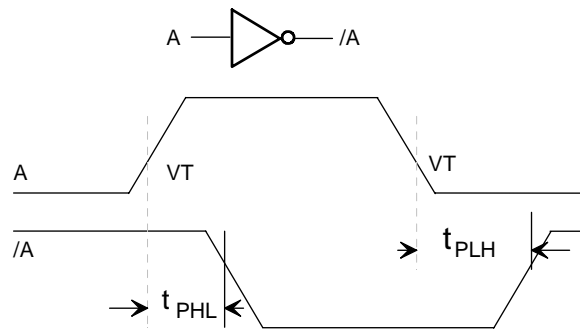


FIG.1: Input-output timing relationship in an INVERTER

The typical values of these propagation delays are used by the manufacturers to indicate the speed of the circuits. Possibly most of the ICs in a given lot will actually have delays equal to or even less than these typical values. But the typical value is not a guaranteed value and hence cannot be used as a design parameter. You have to always work with the worst case values for these propagation delays, which happen to be the maximum values in this case.

It should also be noted that the manufacturers of LSTTL family ICs do not guarantee any minimum delay. This can create problems in certain types of circuits. Consider the digital differentiator shown in the figure 2.

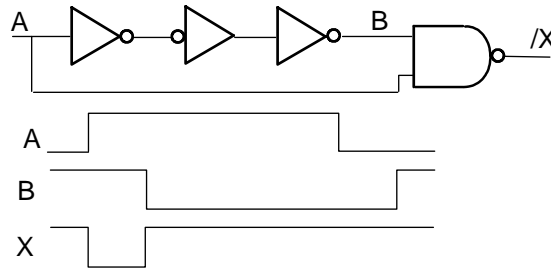


FIG.2: Digital differentiator

The timing diagram shows that the output is a pulse of width T. What will be the width of the output pulse?

- If we take typical values for the associated gates it would be $9.5 \times 3 = 28.5$ ns.
- If we consider maximum values the width would be $15 \times 3 = 45$ ns.
- While we may agree it would be some nonzero value we cannot guarantee any minimum value to this pulse. It can be any value from almost 0 to 45 ns.

If we want to generate a pulse with a guaranteed width of 30 ns, this circuit cannot be used. Therefore, you will have to be careful in applications similar to this in assuring the performance of the circuit.

Propagation delay is an important parameter in a digital circuit, as it is indicative of the speed with which the given task would be done. One of the aims of digital systems is to do more and more in less and less time. Therefore, in applications where speed is an important criterion, you will have to keep a close watch on the propagation delays and make attempts to reduce them as much as possible.

When a logical expression is given in a SOP either in canonical or non-canonical form and the variables are available in their Asserted High and Asserted Low versions, it can be realised by two level NAND gating, if the number of inputs do not exceed 13 (74S134).

If the variables are available only in one form then the expression in its canonical form can be realized through three levels of gates.

If the expression is to be realised in any other form the delay is likely to be more. Consider the expression for STRT as given below:

$$\text{STRT} = \text{PTRL} \cdot \text{IGNI} \cdot ([\text{NEUTR} \cdot \text{KICK}] + [\text{SLOPE} \cdot \text{NEUTR}' \cdot \text{KICK}'])$$

Obviously, this expression is not in its canonical form. Its realisation is shown in the figure 3. The propagation delay of this realisation is equal to that of five stages.

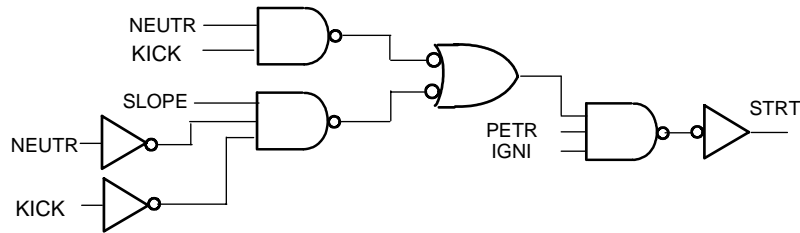


FIG. 3: Realisation of the logic expression for START in its non-canonical form

You should note that the minimization of propagation delay may not always be the design objective. In such cases you may use other forms of the logical expression if they do not increase the chip count. The form of the expression may be chosen to make the design more easily understandable.

Let us consider some hardware aspects of propagation delay. The value given for t_{PHL} and t_{PLH} are not the guaranteed maximums under all operating conditions. Normally the delays for LSTTL family are defined at the following operating conditions:

$$T = 25^{\circ} \text{ C}, V = 5 \text{ volts}, C = 15 \text{ pF}, \text{ and } R = 2 \text{ K } \Omega$$

For HCMOS family the delay times are defined at many operating conditions, as these devices can be operated at voltage levels below 6 volts. The dc and ac characteristics including the time delays are specified at nine operating points (three voltages and three temperatures)

1. $\Delta V_{CC} = 2.0 \text{ V}$, $T: 25^{\circ} \text{ C to } -55^{\circ} \text{ C, } < 85^{\circ} \text{ C, and } < 125^{\circ} \text{ C}$, $C_L = 50 \text{ pF}$, Input $t_r = t_f = 6 \text{ ns}$
2. $\Delta V_{CC} = 4.5 \text{ V}$, $T: 25^{\circ} \text{ C to } -55^{\circ} \text{ C, } < 85^{\circ} \text{ C, and } < 125^{\circ} \text{ C}$, $C_L = 50 \text{ pF}$, Input $t_r = t_f = 6 \text{ ns}$
3. $\Delta V_{CC} = 6.0 \text{ V}$, $T: 25^{\circ} \text{ C to } -55^{\circ} \text{ C, } < 85^{\circ} \text{ C, and } < 125^{\circ} \text{ C}$, $C_L = 50 \text{ pF}$, Input $t_r = t_f = 6 \text{ ns}$

As HCMOS family is compatible with LSTTL family the AC electrical characteristics are defined only at one voltage, namely, at $V_{CC} = 5 \text{ V}$ in the following manner.

$$V_{CC} = 5.0 \text{ V}, T: 25^{\circ} \text{ C to } -55^{\circ} \text{ C, } < 85^{\circ} \text{ C, and } < 125^{\circ} \text{ C}, C_L = 50 \text{ pF}, \\ \text{Input } t_r = t_f = 6 \text{ ns}.$$

The test circuit with which these delays are measured is given in the figure 4. The propagation delays change with temperature, load capacitance and type of load circuit. The circuit shown in the figure 4 simulates the input of a LSTTL and HCMOS gates.

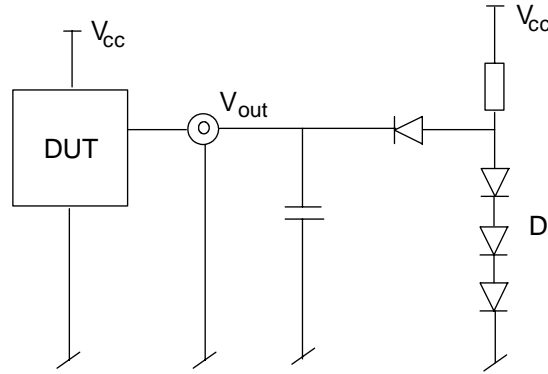


FIG. 4: Test circuits for LSTTL ICs with totem-pole outputs and for HCMOS ICs
Other types of load circuits, we are likely to encounter, are shown in the figure 5.

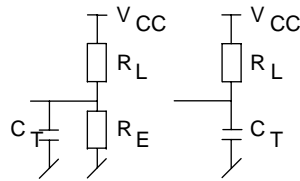


FIG. 5: Load circuits encountered in digital systems

The load capacitance will, in turn, depend on the PCB track width and the length, and on the material of the laminate. The capacitance encountered in actual practice can vary from 20 pF to 150 pF. The effect of this capacitance is to increase the propagation delay and supply current spike amplitude during the transients. Depending on the load circuit, capacitive loading and temperature the propagation delays can increase by as much as 15 ns. The nature of dependence of the propagation delay on the load capacitance is shown in the figure 6.

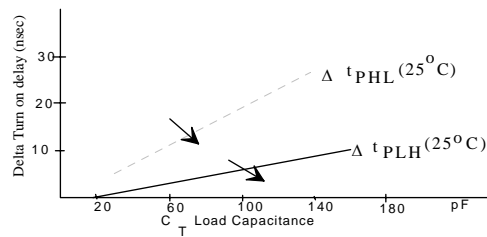


FIG. 6: Dependence of turn-on delay on the load capacitance

The designer is required to pay special attention to the PCB layout to minimize the capacitive loading, the designer is advised to consult the performance curves published by the manufacturer when the circuits are to be designed at high/low temperatures and/or under high capacitive load conditions.

HAZARDS

The analysis and minimisation methods presented so far predict the behaviour of combinational circuits under steady state. This means that the output of the circuit is considered only after all the transients that are likely to be produced when the state of the inputs signals change. However, the finite delays associated with gates makes the transient response of a logic circuit different from steady state behaviour. These transients occur because different paths that exist from input to output may have different propagation delays. Because of these differences in the propagation delays combinational circuits, as we will demonstrate, can produce short pulses, known as *glitches*, under certain conditions, though the steady state analysis does not predict this behaviour. A *hazard* is said to exist when a circuit has the possibility of generating a glitch. However, the actual occurrence of the glitch and its pulse width depend on the exact delays associated with the actual devices used in the circuit. Since the designer has no control over this parameter it is necessary for him to design the circuit in a manner that avoids the occurrence of glitches. While a given circuit can be analysed for the presence of glitches, it is necessary to design the system in a manner that hazard analysis of the circuit would not be necessary. One simple method is not to look at the outputs until they settle down to their final value.

Consider the realization of logical expression $X = AB' + BC'D'$ as shown in the figure 3.14. In this circuit the hazard is caused by the propagation delay associated with the gate-1. Let A and B be Asserted and C and D are Not-asserted. When B changes from its Asserted state to its Not-asserted state with the other variables remaining the same the output should remain in its Asserted state. However, when B changes from 1-to-0 the output of the gate-5 changes from 1-to-0. The output of the gate-4 should change from 0-to-1 at the same time. But the delay associated with the gate- 1 makes this transition of the gate-4 output to happen a little later than that of gate-5. This can cause brief transition of X from 1-to-0 and then from 0-to-1, as shown in the figure 1.

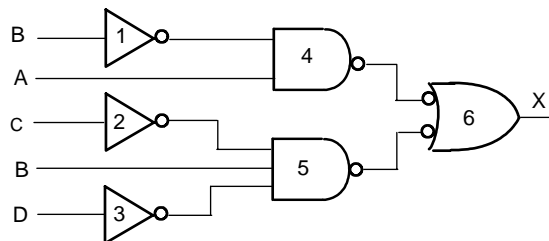


FIG. 1: Realisation of the expression $X = AB' + BC'D'$

A hazard of this nature is known as *static-1 hazard*, because the circuit is likely produce a 0-glitch when the output is expected to remain in state 1 as per the steady state analysis. Similarly, if the circuit is likely to produce a 1-glitch when the output is expected to remain in state 0 as per the steady state analysis it is known as *static-0 hazard*. When the output is supposed to change from 0 to 1 (or 1 to 0), the circuit may go through three or more transients to produce more than one glitch. Such multiple glitch situations are known as dynamic hazards. The static and dynamic hazards are illustrated in the figure 2. Obviously these hazards are undesirable when these outputs happen to be critical in a given digital system.

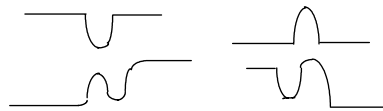


FIG. 2: Different types of static and dynamic hazards

The K-Map of the expression given above is shown in the figure 3.

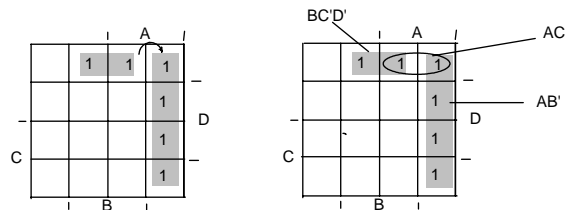


FIG. 3: K-maps of the logic expression $X = AB' + BC'D'$

It is clear from the K-Map that the hazard associated with the 1-to-1 transition occurred when the change of state of the variable B caused the transition from one grouping $BC'D'$ to another grouping AB' . This jump made it necessary for the signal B to go through another path of longer delay to keep the output at the same state. While the K-Map makes it easy to identify the hazard associated with 1-to-1 transition it is much more difficult to detect the other three transitions. Fortunately one result from Logic and Switching Theory comes to our rescue. The theorem for the hazard free design states that a two level gate implementation of a logical expression will be hazard free for all transitions of the output if it is free from the hazard associated with 1-to-1 transition. This theorem makes it very easy to detect and correct for the hazards in a combinational circuit, since the 1-to-1 transition can easily be detected through K-Map. When the input variables change in such manner

as to cause a transition from one grouping to another grouping, the 1-to-1 transition can occur. Therefore, the procedure to eliminate hazards in two level gating realization of a logical expression is to include all 1s which are unit distance apart at least in one grouping. In the example considered above the hazard occurred because when B changed its state, it caused a transition from $BC'D'$ grouping to $A B'$ grouping. Therefore the solution to remove hazard is to group the terms $ABC'D'$ and $AB'C'D'$ together. This would lead to an additional gate. This procedure is illustrated in the figure 4. The added gate defines the output during the transition of B from one state to the other. This procedure can be applied to all two level gate situations to eliminate hazards.

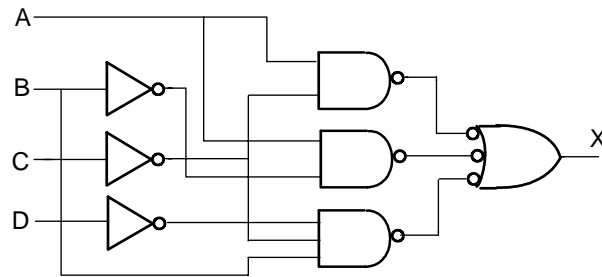


FIG.4: Hazard free realisation of the expression
 $X = AB' + BC'D'$ as $X = AB' + BC'D' + AC'D'$

LOADING

A logic gate has limited capacity to source and sink current at its output. As the output of a gate is likely to be connected to more than one similar gate, the designer has to ensure that the driving unit has the necessary current capability. The loading in the case of digital circuits, built with TTL integrated circuits, is defined in terms of Unit Loads (UL). One UL is defined as that of the input of Std.TTL gate. This is given by,

I_{IL} : Input LOW Current (The current flowing out of an input when a specified LOW level voltage is applied to that input)

$$= -1.6 \text{ mA (with } V_{CC} \text{ at Maximum and } V_i = 0.4 \text{ volts)}$$

I_{IH} : Input HIGH Current (The current flowing into an input when a specified HIGH level voltage is applied to that input)

$$= 40\mu\text{A (with } V_{CC} \text{ at Maximum and } V_i = 2.4 \text{ volts)}$$

A Std. TTL gate has a fanout of 10 ULs. This is equivalent to,

I_{OL} : Output LOW Current (The current flowing into an output which is in the LOW state)

$$= 16 \text{ mA (with } V_{CC} \text{ and } V_{IH} \text{ at Minimum and } V_{OL} = 0.4 \text{ volts)}$$

I_{OH} - Output HIGH Current (The current flowing out of an output which is in HIGH state)

$$= -400 \mu\text{A (with } V_{CC} \text{ at Minimum, } V_{IL} \text{ at Maximum and } V_{OH} = 2.4 \text{ volts)}$$

The output current capability of LSTTL gate is

$$I_{OH} = -400 \mu\text{A at } V_{OH} = 2.7 \text{ volts}$$

$$I_{OL} = 4 \text{ mA at } V_{OL} = 0.4 \text{ volts}$$

$$= 8 \text{ mA at } V_{OL} = 0.5 \text{ volts}$$

If the LOW state output V_{OL} is to be maintained at 0.4 volts LSTTL gates have 2.5 UL capability, and if V_{OL} can be tolerated at 0.5 volts it can support 5 ULs. However, it is unlikely that we need to drive Std.TTL gates. The LSTTL gate has the input characteristics as given below:

$$I_{IH} = 20 \mu\text{A at } V_i = 2.7 \text{ volts}$$

$$I_{IL} = -0.4 \text{ mA at } V_i = 2.7 \text{ volts}$$

Therefore, an LSTTL gate can drive 10 LSTTL gates with V_{OL} of 0.4 volts and 20 LSTTL gates with a V_{OL} of 0.5 volts. The loading on an LSTTL gate, that is, the number of other LSTTL gates that can be connected to it, should be kept within these limits. If these limits are exceeded, initially the logic voltage levels deteriorate from the specified values, and subsequently the gate would be damaged due to the excessive power consumption.

The input and output current specifications of a HCMOS gate are given by;

$$I_{in} = + 0.1 \mu\text{A at } V_{CC} = 6.0 \text{ V at } T: 25^\circ \text{ C to } -55^\circ \text{ C,}$$

$$= + 1.0 \mu\text{A at } V_{CC} = 6.0 \text{ V at } T: < 85^\circ \text{ C}$$

$$= + 1.0 \mu\text{A at } V_{CC} = 6.0 \text{ V at } T: < 125^\circ \text{ C}$$

$$I_{OH} = - 4.0 \text{ mA at } V_{OH} = 3.98 \text{ V with } V_{CC} = 4.5 \text{ V and } T: -55^\circ \text{ to } 25^\circ \text{ C}$$

$$\text{at } V_{OH} = 3.84 \text{ V with } V_{CC} = 4.5 \text{ V and } T: < 85^\circ \text{ C}$$

$$\text{at } V_{OH} = 3.70 \text{ V with } V_{CC} = 4.5 \text{ V and } T: < 125^\circ \text{ C}$$

$$= - 5.2 \text{ mA at } V_{OH} = 5.48 \text{ V with } V_{CC} = 6.0 \text{ V and } T: -55^\circ \text{ to } 25^\circ \text{ C}$$

$$\text{at } V_{OH} = 5.34 \text{ V with } V_{CC} = 6.0 \text{ V and } T: < 85^\circ \text{ C}$$

$$\text{at } V_{OH} = 5.20 \text{ V with } V_{CC} = 6.0 \text{ V and } T: < 125^\circ \text{ C}$$

$$I_{OL} = 4.0 \text{ mA at } V_{OL} = 0.26 \text{ V with } V_{CC} = 4.5 \text{ V and } T: 25^\circ \text{ to } -55^\circ \text{ C,}$$

$$\text{at } V_{OL} = 0.33 \text{ V with } V_{CC} = 4.5 \text{ V and } T: < 85^\circ \text{ C}$$

$$\text{at } V_{OL} = 0.40 \text{ V with } V_{CC} = 4.5 \text{ V and } T: < 125^\circ \text{ C}$$

$$= 5.2 \text{ mA at } V_{OL} = 0.26 \text{ V with } V_{CC} = 6.0 \text{ V and } T: 25^\circ \text{ to } -55^\circ \text{ C}$$

$$\text{at } V_{OL} = 0.33 \text{ V with } V_{CC} = 6.0 \text{ V and } T: < 85^\circ \text{ C}$$

$$\text{at } V_{OL} = 0.40 \text{ V with } V_{CC} = 6.0 \text{ V and } T: < 125^\circ \text{ C}$$

As it can be seen the designer has to consider a wide range of operating conditions to take loading effects into consideration when working with HCMOS family circuits. For the HCMOS family ICs the currents specified at $V_{CC} = 4.5 \text{ V}$ need only to be considered.

There may arise certain occasions, like a clock source driving many units and setting up LOW(L) and HIGH (H) voltage levels to be connected to unused inputs, wherein it may become necessary to provide more drive capability than the standard values. In such cases buffers have to be used. The available buffers in LSTTL family are;

Quad 2 - input NAND Buffer - 74LS37

Dual 4 - input NAND Buffer - 74LS40

These have an output current capability of

$$I_{OL} = 24 \text{ mA}$$

$$I_{OH} = -1200 \mu\text{A}$$

They have the capacity to drive as many as 60 LSTTL loads. There is a small price to be paid in terms of increased propagation delay ($t_{PHL} = t_{PLH} = 24 \text{ n secs}$ against the usual 15 n secs) for this enhanced drive capability. This increased time delay should not normally make any difference as these buffers are unlikely to be used for implementing logic expressions. There are no similar buffers available in the HCMOS and HCTMOS families. When we are required to drive a load even beyond the capability of a buffer, discrete components have to be used.

LARGER OUTPUT VOLTAGE SWING

The worst case output voltage level of a gate when it is in HIGH state can be as low as 2.7 volts in the case of LSTTL family and only 2.4 volts in the case of Std. TTL family. In the case of HCMOS family the output voltage levels can go up to 5.5V if 6.0V power supply is used. If it is desired to have a higher output voltage swing one simple way is to connect a 1 K Ω or a 2 K Ω resistor from V_{CC} to the output terminal. However, it should be remembered that this modification of the output circuit would increase the propagation delay. Larger output voltage swings can be obtained with the help of open-collector gates. In the open-collector (OC) gates the active pull-up circuit of the output totem-pole configuration in the LSTTL circuit is deleted as shown in the figure 1.

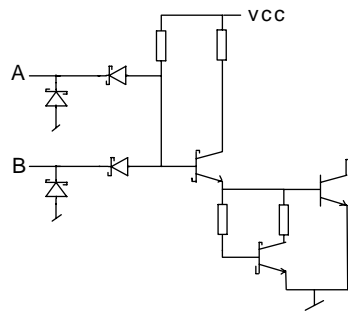


FIG. 1: 2-input LSTTL NAND gate with open collector output

The designer can now have the choice of returning the open collector terminal to the desired supply voltage, as long as its value is less than or equal to the $V_{OH(max)}$ specified, through a suitable load resistor.

The available open collector LSTTL gates are:

Quad 2-input NAND(OC) gate - 74LS03 [$V_{OH(max)} = 5.5$ V, $I_{OL} = 8$ mA]

Quad 2-input NAND(OC) gate - 74LS26 [$V_{OH(max)} = 15$ V, $I_{OL} = 18$ mA]

Hex Inverter (OC) - 74LS38 [$V_{OH(max)} = 5.5$ V, $I_{OL} = 24$ mA]

Hex Inverter/Buffer (OC) - 7406 [$V_{OH(max)} = 30$ V, $I_{OL} = 40$ mA]

Hex Buffer (OC) - 7407 [$V_{OH(max)} = 30$ V, $I_{OL} = 40$ mA]

The manner in which the load resistor is to be connected is shown in the figure 2. As the pull-up is through a passive resistor the propagation delay will be higher than that of the gate with the totem-pole output. For example 74LS26 operated at V_{CC} of

5 V, $R_L = 2 \text{ K}\Omega$ and $C_L = 15 \text{ pF}$ has $t_{PLH} = 32 \text{ ns}$ (max) and a $t_{PHL} = 28 \text{ ns}$ (max) against $t_{PHL} = t_{PLH} = 15 \text{ ns}$ (max) in the case of 74LS00 under the same operating conditions. Open collector gates are useful for interfacing ICs from different logic families, and ICs with discrete circuits operating with different supply voltages.

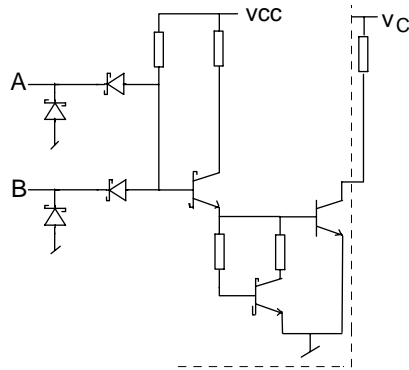


FIG. 2: Connecting a load resistor to an OC gate

The HCMOS and HCTMOS families do not offer many open drain circuits. Whenever larger voltage swings are needed it is possible to use CD4000 series circuits. The only open drain gate that is available in the HCMOS family is 74HC03, which is quad 2-input NAND gate. The major application of open-collector gates is in implementing wired-logic operation needed in bussing signal lines.

WIRED-LOGIC OPERATIONS

If the outputs of the gates can be tied together as shown in the figure 1 it would be possible to realise AND operation without the actual use of hardware.

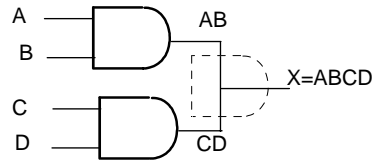


FIG.1: Wired AND operation

Such connections are referred to as wired-AND and implied-AND. This is because the voltage at the interconnecting point is High only if the outputs of both the gates are High at the same time. Such wired-logic connections are very useful in bussing signals in large digital systems wherein the hardware has to be implemented on a number of printed circuit boards. Consider the situation shown in the figure 2.

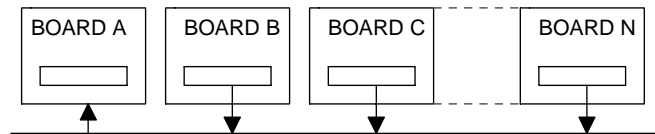


FIG.2: Common signal line in Bus organised digital system

Board A has to take some action after verifying the change of state in all the other boards. Though this operation can be performed through using combinational circuits, it is more conveniently performed through wired-AND interconnection of the outputs from all the boards and connecting this wired-AND signal to be input line of board-A. This would substantially reduce the amount of hardware to be used.

Let us explore the possibility of implementing such wired-logic connections with LSTTL combinational ICs. The actual circuit that would result when we connect the outputs of two LSTTL gates with totem-pole output configurations is shown in the figure 3. It can be seen from the circuit diagram that if one of the outputs is in Low state while the other one is in High state there will occur a low impedance path between the supply and ground leading to a large value of current. This can lead to the destruction of the components in the output circuits of the ICs. Therefore, it is not possible to short the outputs of two or more LSTTL gates to realize wired-logic operations. However, wired logic operations can be implemented with the help of open-collector gates.

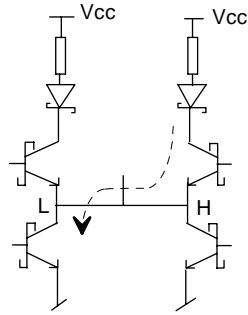


FIG.3: Outputs of two LSTTL gates tied together

When the outputs of the open collector gates are tied together it becomes necessary to connect a load resistance R from the output point to the supply. The value of this load resistance should be carefully chosen to maintain the logic state within the TTL limits under worst operating conditions. The most general interconnection situation that can occur is shown in the figure 4.

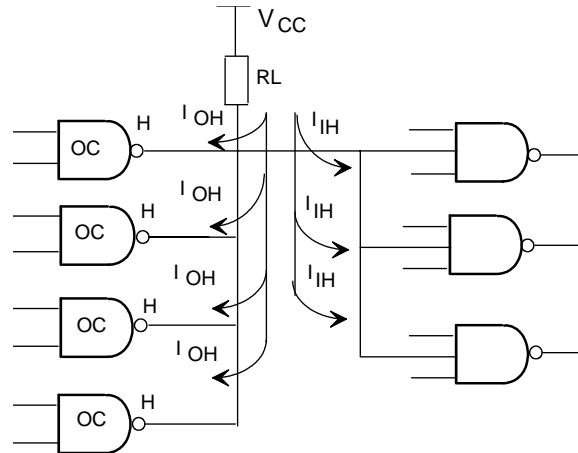


FIG.4: Connection of OC gates in parallel with all the outputs in the High state

It may be noted that when two OC gates are interconnected to perform wired-AND operation they are capable of driving one to nine Unit Loads, and when an OC gate is not paralleled with other gates then it can drive up to ten Unit Loads. The maximum value of the load resistance R must be selected to ensure that sufficient load current (to drive the output gates) output is High. Using the worst case values for the High and Low states for designing the load resistor R_L , will give a guaranteed dc noise margin of 700 mV in the logic High state. Since 2.7 V should be present no more than 2.3V can be dropped across R_L . The current through R is composite of current into the loads, $m \cdot I_{IH}$, and leakage current into output transistors which are biased into off state, $n \cdot I_{OH}$. Both I_{OH} and I_{IH} are data sheet specifications; they are $250 \mu A$

and 20 μA respectively in the case of 74LS38. The maximum value of the load resistor is calculated from the relationship given below:

$$R_{L(\text{max})} = \frac{V_{CC} - V_{OH(\text{required})}}{n.I_{OH} + m.I_{IH}}$$

with $n = 4$, $m = 3$ and $V_{CC} = 5\text{ V}$ and $V_{OH}(\text{required}) = 2.7\text{ V}$ the maximum value of R_L is 2170 ohms. A greater value will result in the deterioration of the High state voltage value. The minimum value of R_L is found by considering Low state at the output of the paralleled gates as shown in the figure 5. R_L is permitted to drop a maximum voltage dictated by the noise margin in the Low state, which is 400 mV. In the circuit shown in the figure 5, wherein the worst case situation is indicated, the output of one gate is in Low state while the outputs of the remaining gates are in High state. The resistor must be able to maintain the Low level while sinking the load current from all the gates connected as load.

The minimum value of the load resistor R_L may now be calculated from the relationship given as below:

$$R_{L(\text{min})} = \frac{V_{CC} - V_{OL(\text{required})}}{I_{OL(\text{capability})} - I_{\text{sink}(\text{load})}}$$

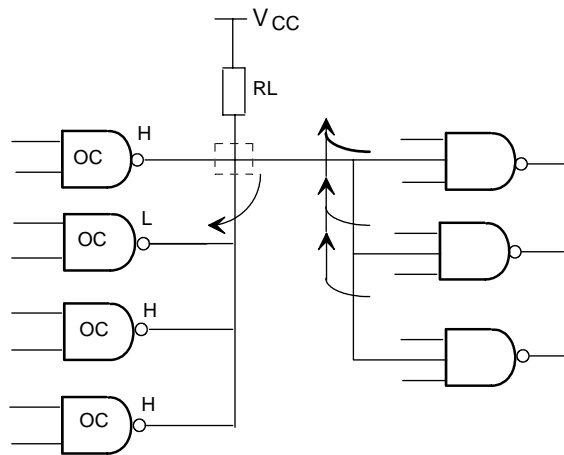


FIG. 5: OC gates connected for wired-AND operation with their outputs in Low state

With $I_{OL} = 24\text{ mA}$ and $I_{IL} = 0.4\text{ mA}$ the minimum value of R_L is 201 ohms. The value of the load resistor may be chosen between $R_L(\text{max})$ and $R_L(\text{min})$. It is essential to note that the output impedance of the OC gates will be significantly higher in the High state due to the pull-up resistor in comparison to that of the gate with the totem-pole output. This also results in a slightly higher propagation delay.

TRISTATE GATES

Wired-logic operations are important in the design of bus-structured digital systems. The open-collector gates can meet the requirements of bussing, but have limitations with regard to the speed and the distance between the modules, and every signal line requires the usage of a suitable load resistor. These factors limit the operation of OC based bus structured systems to about 2 MHz operation over a distance of a few meters. Tristate logic elements provide a solution to the problems of speed and power in bus organized digital systems. Tristate gates are essentially gates with output stages that assume three states. Two of these three are normal low impedance High and Low states. The third one is a high-impedance (Hi-z) state. When the device is in Hi-z state both the transistors in the output totem-pole circuit are in off conditions. When the output of such a gate in Hi-z state is tied to the output of a gate that is in Lo-z state, the High-z state gate does not influence (in any significant manner) the output circuit of a Lo-z state gate. This enables us to tie the outputs of many tristate devices, and share a common (bus) signal line. These units have the speed of the regular devices, higher line-drive capability and higher noise immunity. By eliminating the pull-up resistors these tristate gates cut bus delays to a few nanoseconds. The available TSL buffers are listed in the following:

	LSTTL	HCMOS	HCTMOS
Quad 3-state noninverting buffer	74LS125A	74HC125A	
Quad 3-state noninverting buffer	74LS126A	74HC125A	
Octal 3-state inverting buffer/ line driver/line receiver	74LS240	74HC240A	74HCT240A
Octal 3-state Noninverting buffer/ line driver/line receiver	74LS241	74HC241	74HCT241A
Octal 3-state inverting bus transceiver	74LS242	74HC242	
Octal 3-state noninverting buffer/ line driver/line receiver	74LS244	74HC244A	74HCT244A
Octal 3-state noninverting bus transceiver	74LS245	74HC245A	74HCT245
Hex 3-state noninverting buffer with common enables	74LS365A	74HC365	
Hex 3-state inverting buffer with common enables	74LS366A	74HC366	
Hex 3-state noninverting buffer with 2-bit and 4-bit sections	74LS367A	74HC367	
Hex 3-state inverting buffer with 2-bit and 4-bit sections	74LS368A	74HC368	
Octal 3-state inverting buffer/ line driver/line receiver	74LS540	74HC540	74HCT540
Octal 3-state noninverting buffer/ line driver/line receiver	74LS541	74HC541	74HCT541
Octal 3-state inverting bus transceiver	74LS640	74HC640A	74HCT640

When the output of an LSTTL tristate gate is in Hi-z state the maximum leakage current at the output, which occurs when it is tied to a gate whose output is low-impedance High state, is +20 μ A (into the output terminal). When the device is placed in its low impedance state it has all the desirable properties of the usual LSTTL gate. Another important factor in driving a bus line is the current capability in sinking and sourcing. For this reason the output stage of a tristate gate is designed to source 2.6 mA at a V_{OH} of 2.7 V, and sink 24 mA at V_{OL} of 0.5 V and 12 mA at a V_{OL} of 0.4 V. This is 6.5 times more sourcing capability than a LSTTL gate. This will permit as many as 128 tristate logic (TSL) outputs to be tied to a common bus and still provide enough sourcing current to drive three LSTTL loads. If one device is ON and 127 are OFF the following is valid:

$$\begin{aligned}
 127 \times 20\mu\text{A} &= 2.54 \text{ mA} \\
 2.6 \text{ mA} - 2.54 \text{ mA} &= 60\mu\text{A} \\
 &= 3 \times 20 \mu\text{A (LSTTL)}
 \end{aligned}$$

The device that is ON, therefore, is capable of maintaining LSTTL speeds while driving the bus. Another advantage of the high current sourcing feature is that the LSTTL gate with 400 μ A maximum sourcing capability can only drive about 25 to 35 cms of line before the noise problems become prohibitive. The TSL output will be able to drive reliably a line over 3 meters long. The greater sourcing capability also provides a far superior High level noise immunity that is better than the usual LSTTL devices. TSL gates are designed in such a way that the delay from Inhibit to Output Disable, 20 ns(max), is less than the delay from Enable to Low State, 25 ns(max). Therefore, the device that is disabled off the line is removed before the device that is being enabled into Low state is brought on to the bus. This prevents the occurrence of heavy currents during the transients from Hi-Z state to Low-Z state and vice-versa. In addition the output state is designed to take care of shorted conditions between two TSL gates. Even if two devices are simultaneously switched on, the pull down transistors are designed to withstand as much as 40 mA. But long before it reaches that limit the transistors begin to come out of saturation.

At present many of the combinational and sequential MSI circuits are available commercially with tristate outputs. This option makes the usage of these ICs very convenient.



Digital Electronics

Module 4: Combinational Circuits: Multiplexers

N.J. Rao

Indian Institute of Science

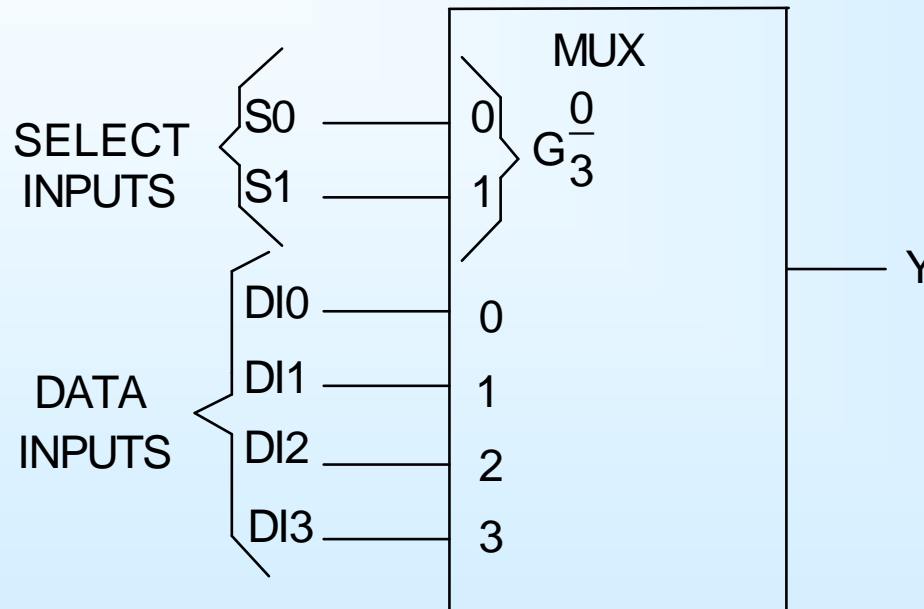


Multiplexers

- A multiplexer is a combinational circuit that gates one out of its several inputs to a single output.
- It is also called a “data selector”.
- The input selected for connection to the output is controlled by a set of SELECT inputs.



4-Input Multiplexer





Functioning of the Multiplexer

- S_0 and S_1 are select inputs.
- Together S_0 and S_1 determine the input, among the Data Inputs, DI_0 , DI_1 , DI_2 , and DI_3 , that gets connected to the output Y .

The output of the multiplexer is given by:

$$Y = DI_0.S_1/.S_0/ + DI_1.S_1/.S_0 + DI_2. S_1.S_0/ + DI_3.S_1.S_0$$

- The relationship between the SELECT inputs and the DATA inputs is G dependency.



Parameters of concern

The main parameters of concern to us are:

- Number of inputs
- Nature of outputs
- Propagation delay



Available LSTTL multiplexers

LSTTL	FAST	HCMOS	HCTMOS
54/74LS	54/74F	54/74HC	54/74HCT

Quad 2-input multiplexers

2-state noninverting outputs	157	157A	157	157A
2-state inverting outputs	158	158A		
3-state noninverting outputs	257B	257A	257	
3-state noninverting outputs	258B	258A		



Available LSTTL multiplexers

	LSTTL 54/74LS	FAST 54/74F	HCMOS 54/74HC	HCTMOS 54/74HCT
Dual 4-input Multiplexer				
2-state noninverting outputs	153	153	153	
2-state inverting outputs	352	352		
3-state noninverting outputs	253	253	253	
3-state inverting outputs	353	353		
8-input Multiplexer				
2-state noninverting outputs	151	151	151	
3-state noninverting outputs	251	251	251	
16-input Multiplexer				
2-state noninverting outputs	150			



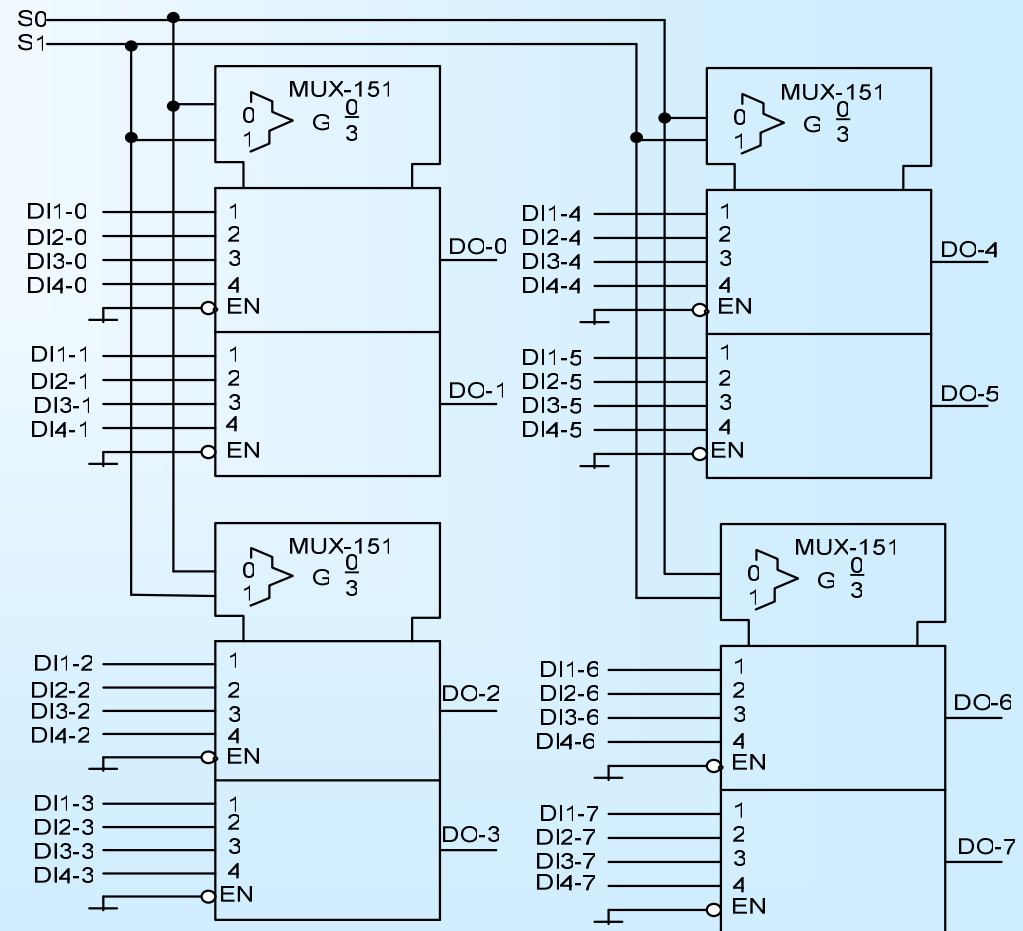
Multiplexer ICs can be used for

- selection of data from multiple sources
- realising logic expressions



Data Selection

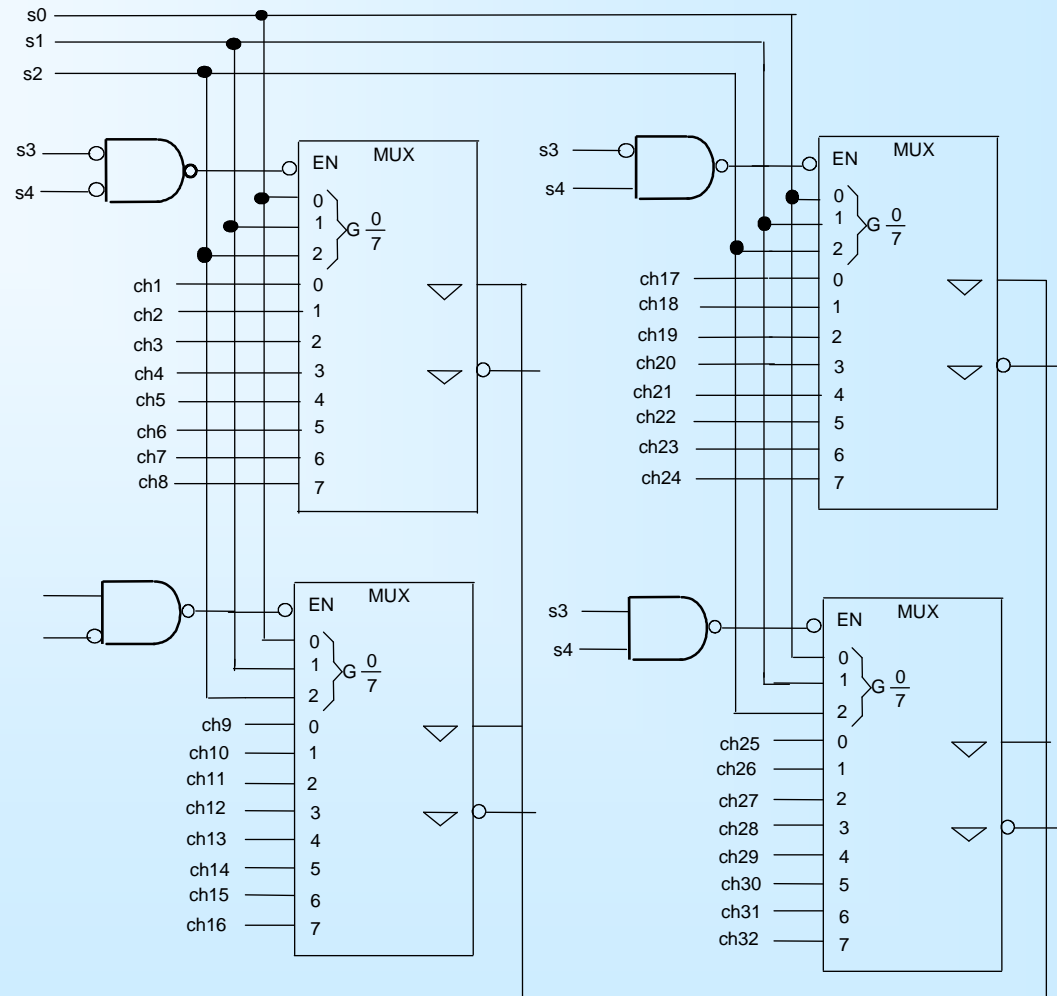
Selecting 8-bit data from four sources





Data Selector

1-of-32 data selector





Multiplexers for Logic Realization

Consider the function Y

$$Y = A/B/C/ + A/BC + AB/C + ABC/$$

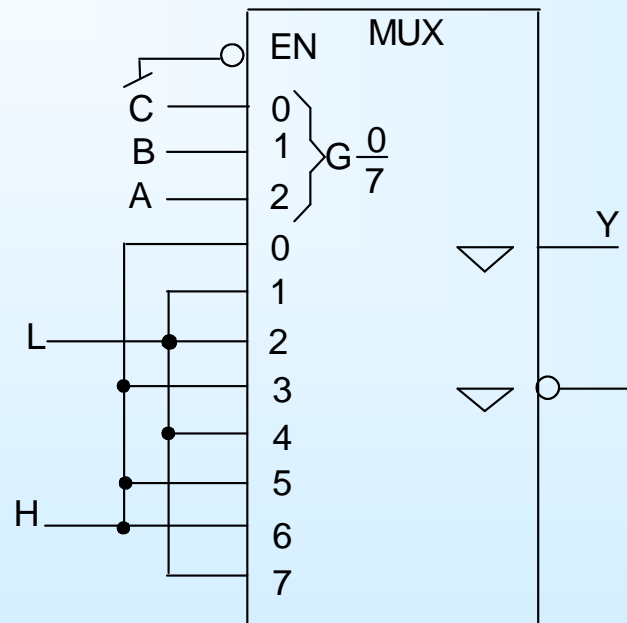
$$Y = m_0 (IP_0) + m_1 (IP_1) + \dots + m_{2^n} (IP_{2^n})$$

$$Y = m_0 + m_3 + m_5 + m_6$$

$$Y = m_0(IP_0=1) + m_1(IP_1=0) + m_2(IP_2=0) + m_3(IP_3=1) + m_4(IP_4=0) + m_5(IP_5=1) + m_6(IP_6=1) + m_7(IP_7=0).$$



Realization of Y





Example

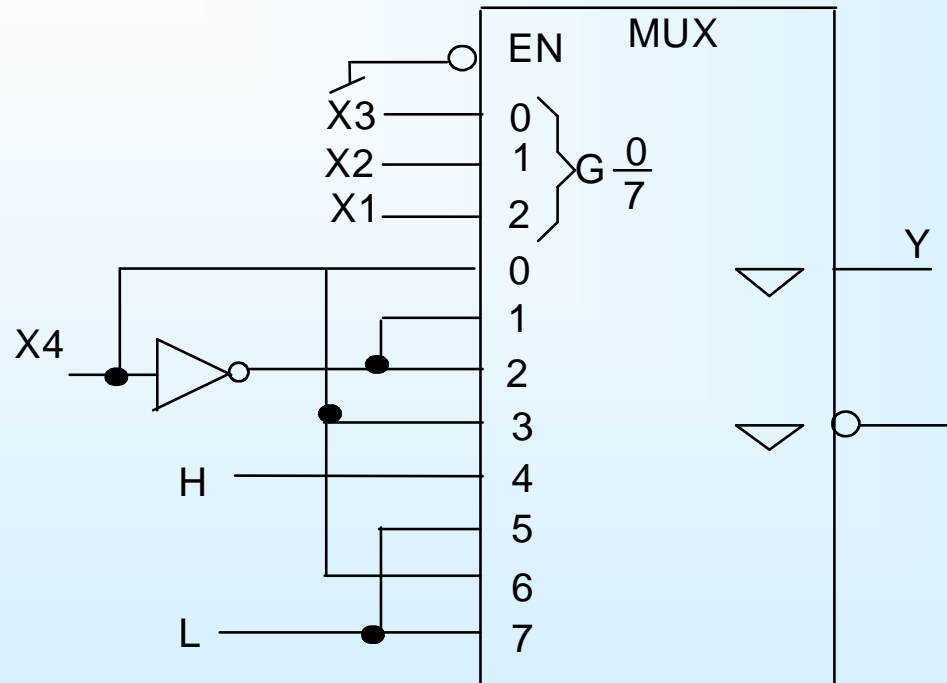
$$Y = \Sigma (1, 2, 4, 7, 8, 9, 13)$$

X1	X2	X3	X4	Y		X1	X2	X3	Y
0	0	0	1	1		0	0	0	X4
0	0	1	0	1		0	0	1	X4 /
0	1	0	0	1		0	1	0	X4 /
0	1	1	1	1		0	1	1	X4
1	0	0	0	1		0	1	1	X4 /
1	0	0	1	1		1	0	0	X4
1	1	0	1	1		1	1	0	X4

$$\begin{aligned} Y &= X4 (0, 3, 4, 6) + X4 / (1, 2, 4) \\ &= X4 (0, 3, 6) + X4 / (1, 2) + (1) 4 \end{aligned}$$



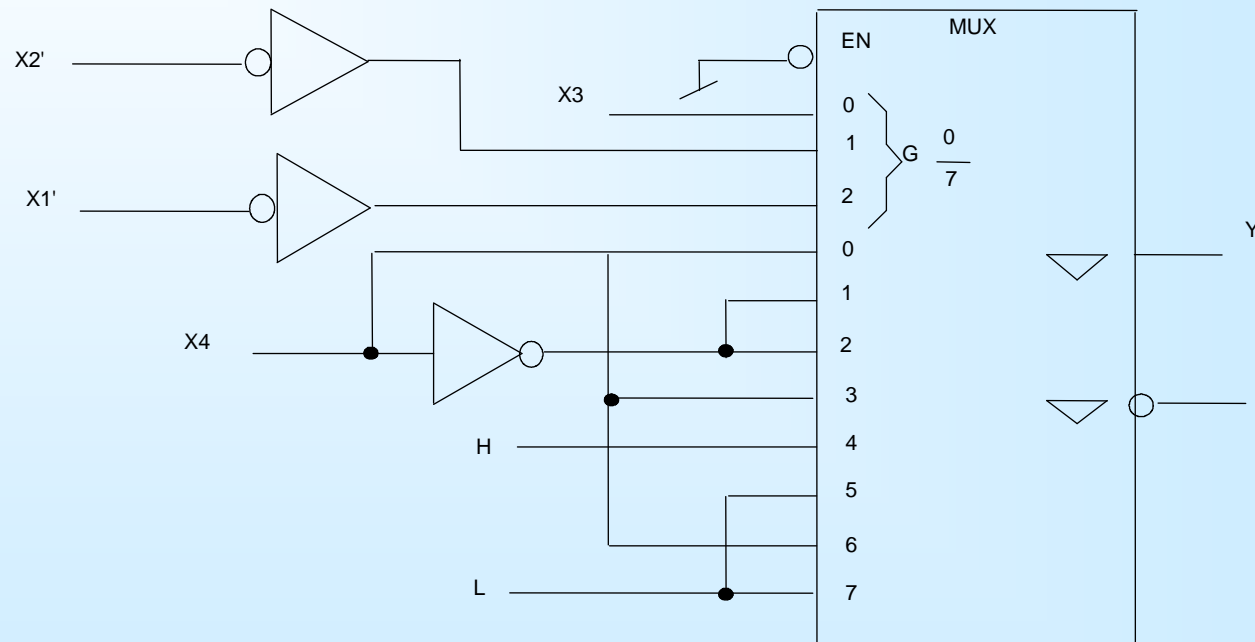
Example





Some variables are Asserted Low

X1 and X2 are asserted low



MULTIPLEXERS

A multiplexer is a combinational circuit that gates one out of its several inputs to a single output. As it selects one out of many inputs, it is also called a "data selector". The input selected for connection to the output is controlled by a set of SELECT inputs. A typical 4-input multiplexer is illustrated in the figure 1.

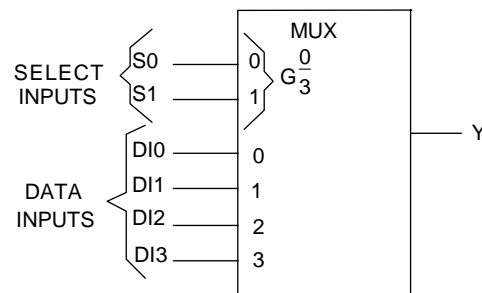


FIG. 1: Schematic of a 4-input multiplexer

S0 and S1 are select inputs. Together S0 and S1 determine the input, among the Data Inputs, DI0, DI1, DI2, and DI3, that gets connected to the output Y.

The output of the multiplexer is given by:

$$Y = DI0.S1'.S0' + DI1.S1'.S0 + DI2.S1.S0' + DI3.S1.S0$$

Notice that the relationship between the SELECT inputs and the DATA inputs is G dependency.

The main parameters of concern to us are:

- Number of inputs
- Nature of outputs
- Propagation delay

The choice on the number of inputs enables us to select the appropriate multiplexer, to minimize the number of ICs needed to implement a given logic function.

For example, if data is to be selected from two 16-bit sources, it is more convenient to use 2-input multiplexers, than 4-input or 8-input multiplexers.

Some additional features:

- Higher drive capability of a multiplexer enables the designer to save on buffers and the consequent delay in certain situations.

- Availability of complementary outputs often results in the saving of additional inverters.
- Availability of tristate outputs make it easy to tie the outputs of a number of multiplexers without using additional gates.

There are two propagation delays that are of interest to designers:

- Delay from the data inputs to the output
- Delay from the select input to the output

These timing relationships are shown in figure 2.

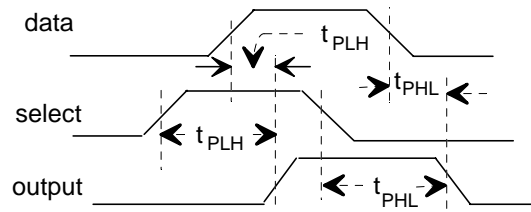


FIG. 2: Timing relationship between signals of a multiplexer

Some of the commonly available multiplexers as MSIs in the LSTTL family are:

	LSTTL	FAST	HCMOS	HCTMOS
	54/74LS	54/74F	54/74HC	54/74HCT
Quad 2-input multiplexers				
2-state noninverting outputs	157	157A	157	157A
2-state inverting outputs	158	158A		
3-state noninverting outputs	257B	257A	257	
3-state noninverting outputs	258B	258A		
Dual 4-input Multiplexer				
2-state noninverting outputs	153	153	153	
2-state inverting outputs	352	352		
3-state noninverting outputs	253	253	253	
3-state inverting outputs	353	353		
8-input Multiplexer				
2-state noninverting outputs	151	151	151	
3-state noninverting outputs	251	251	251	
16-input Multiplexer				
2-state noninverting outputs	150			

As can be seen from the ICs listed above, there are available, a variety of combinations of parameters in the case of 2-input multiplexers, while in the other

cases, the main choice is between the normal output and 3-state outputs. Multiplexer ICs can be used for

- selection of data from multiple sources
- realising logic expressions

These two aspects are explored in this Unit

Data Selection

The multiplexer was mainly designed for selecting data from several sources. For example, if we are required to select an 8-bit data from one of four possible sources, then, it can be realised through four dual 4-input multiplexers, like 74LS153. The circuit that realises such a data selection is shown in figure 3

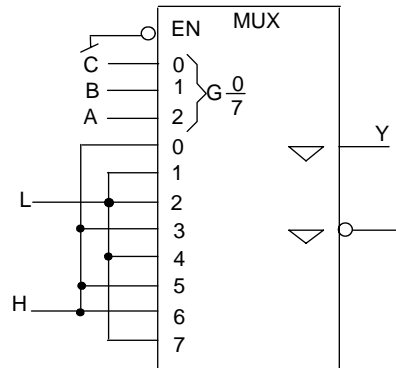


FIG.3: Circuit for selecting 8-bit data from four sources

Another conventional use of the multiplexers is one of time-division gating of several data lines on to a transmission channel using SELECT lines. This is done by using a `Multiplexer' as the sending unit, and a `Demultiplexer' as a receiving unit. The sending end of such a transmission system which multiplexes 32 data lines is shown in Figure 4.

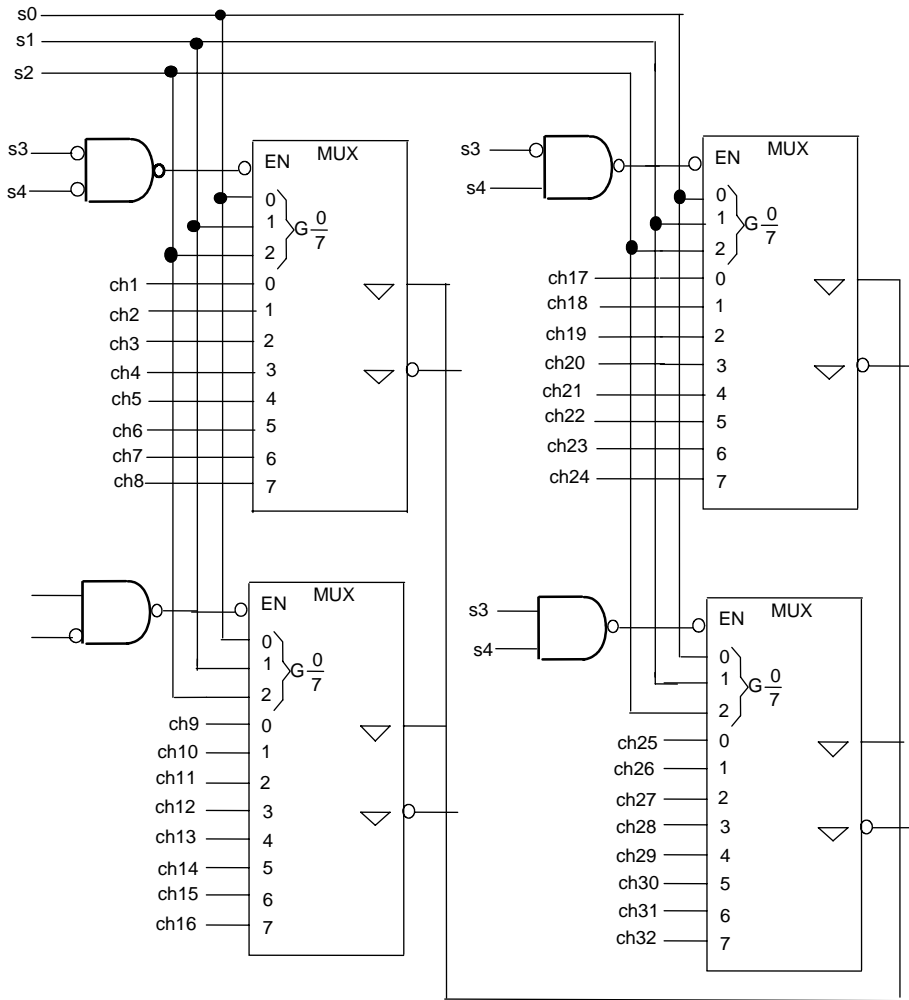


FIG. 4: 1-of-32 data selector

Multiplexers for Logic Realization

The multiplexer also finds application in realising logical functions, sometimes in a more effective manner than with the gates. Consider the following example.

Example 1: Consider the function Y

$$Y = A'B'C' + A'BC + AB'C + ABC'$$

The general expression that gives the input-output relationship of a multiplexer is

$$Y = m_0 (IP_0) + m_1 (IP_1) + \dots + m_2^n (IP_2^n)$$

This expression for Y can be written in terms of MINTERMS as:

$$Y = m_0 + m_3 + m_5 + m_6$$

This expression can in turn be rewritten as:

$$Y = m_0(IP0=1) + m_1(IP1=0) + m_2(IP2=0) + m_3(IP3=1) + m_4(IP4=0) + m_5(IP5=1) + m_6(IP6=1) + m_7(IP7=0).$$

Connect the logic variables A, B, and C to the Select Inputs and binary inputs to the Data lines of an 8-input multiplexer as indicated in the figure 5. This is a very general method and it allows any expression of n-logic variables to be realized by a 2^n -input multiplexer.

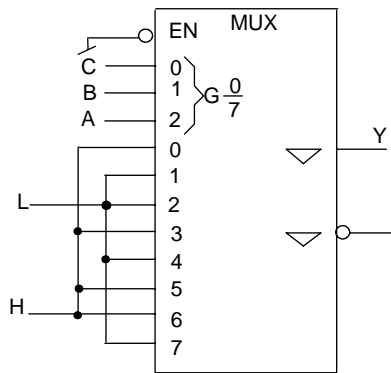


FIG. 5: Realisation of the function given in example 1

Example 2: Implement the logic expression given below, using 74LS251 (8-input multiplexer)

$$Y = \Sigma (1, 2, 4, 7, 8, 9, 13).$$

X1	X2	X3	X4	Y	X1	X2	X3	Y
0	0	0	1	1	0	0	0	X4
0	0	1	0	1	0	0	1	X4'
0	1	0	0	1	0	1	0	X4'
0	1	1	1	1	0	1	1	X4
1	0	0	0	1	0	1	1	X4'
1	0	0	1	1	1	0	0	X4
1	1	0	1	1	1	1	0	X4

Let X1, X2, X3 and X4 be the four variables of which X1 is the most significant and X4 is the least significant variable. All variables are considered Asserted High. Consider the truth table given in the following. A 4-input function can be reduced to a 3-input function by expressing the output Y in terms of X4.

$$Y = X4 (0, 3, 4, 6) + X4' (1, 2, 4) \\ = X4 (0, 3, 6) + X4' (1, 2) + (1) 4$$

The realisation of the above expression with a 3-input (8- data input) multiplexer is shown in the figure 6.

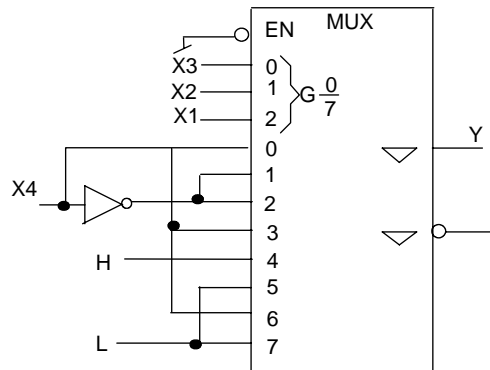


FIG. 6: Realisation of the logical expression in the example 2

What happens when some of the variables are Asserted Low while others are Asserted High? Multiplexers can still be used advantageously to realise expressions using variables with mixed assertion levels. One simple method is to change the assertion levels of all the signals to High level by using inverters. Let X1 and X2 variables in the logic expression given in the example 2 be Asserted Low, while the variables X3 and X4 be Asserted High. Implementation of this expression using the inverters along with the multiplexer is shown in Figure 7.

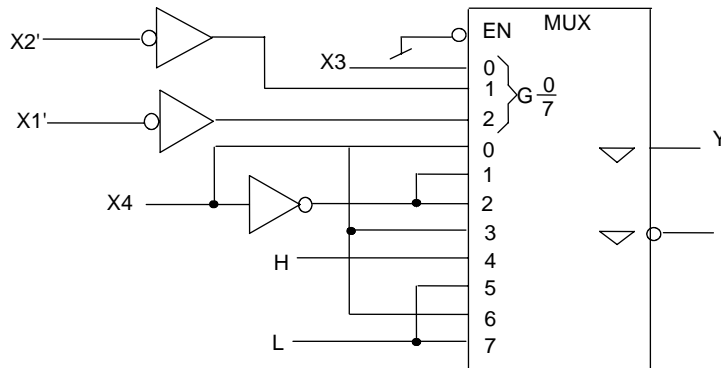


FIG. 7: Realisation of the expression in Example 2 when some of the variables are Asserted Low



Digital Electronics

Module 4: Combinational Circuits: Demultiplexers

N.J. Rao

Indian Institute of Science

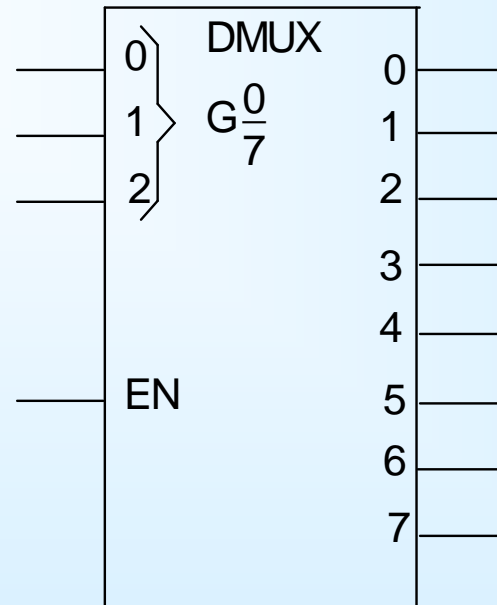


Demultiplexers

- It is a combinational circuit that asserts one of several outputs in response to a unique input code.
- It is a unit with n -inputs and m -outputs, where $m < 2^n$.
- An output switches from Not Asserted state to an Asserted state, when the input code is switched to a specific one.
- When $m = 2^n$, each one of the outputs can be associated with a Minterm of n -variables.
- Hence, such a decoder is known as Minterm Recogniser



3-input demultiplexer



Each one of the outputs have an AND (G) dependence on one of the input codes.

Enable input can be used to disable/enable the entire functional unit.



LSTTL/HCMOS Demultiplexers

Dual 1-of-4 demultiplexer

2-state AL outputs:

74LS139/
74HC139A

2-state AL outputs and common addressing:

74LS155

AL OC outputs and common addressing:

74LS156

3-state AH outputs:

74LS539

1-of-8 demultiplexer

AL outputs and 3 Enable inputs:

74LS138/
74HC138A

AL outputs, 2 Enable, Address latch with latch enable:

74LS137

1-of-10 demultiplexer (2-state AL outputs):

74LS42

1-of-16 demultiplexer (AL outputs and 2 Enable inputs):

74LS154/
74HC154



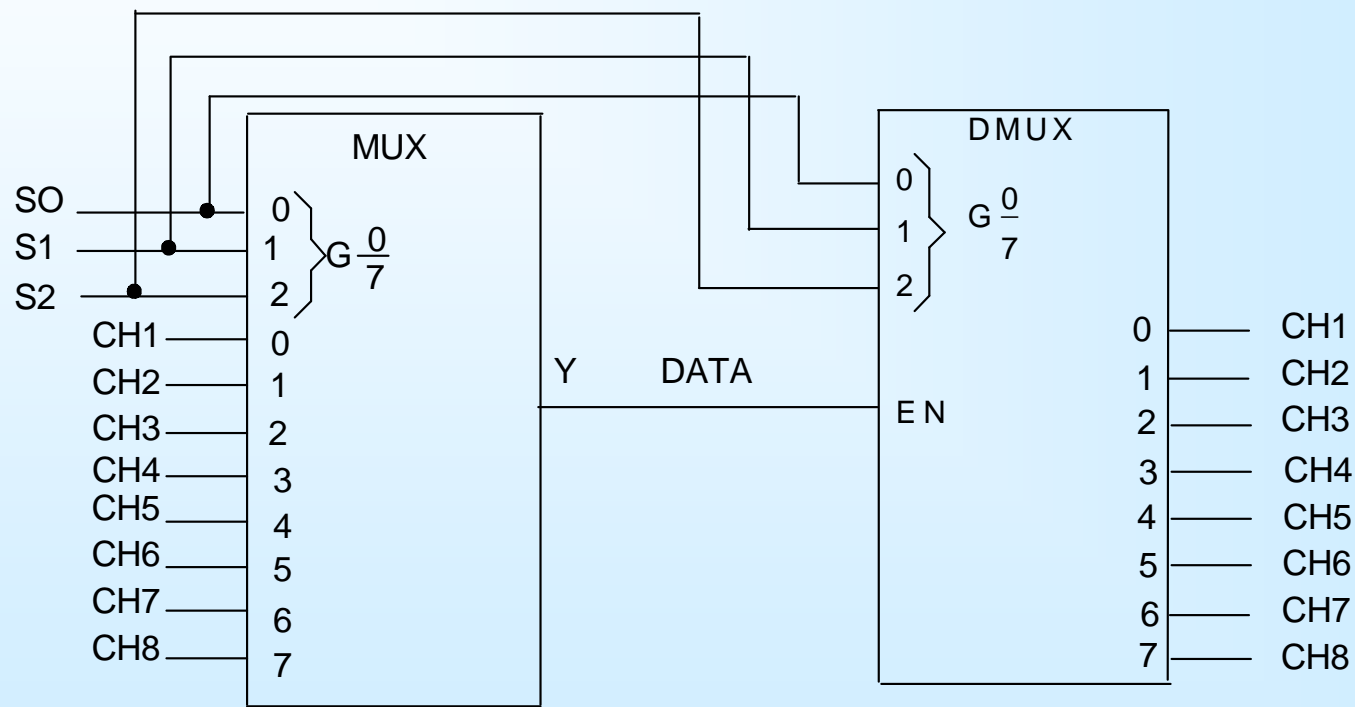
Uses of a demultiplexer

- Demultiplexing
- Realisation of logic functions



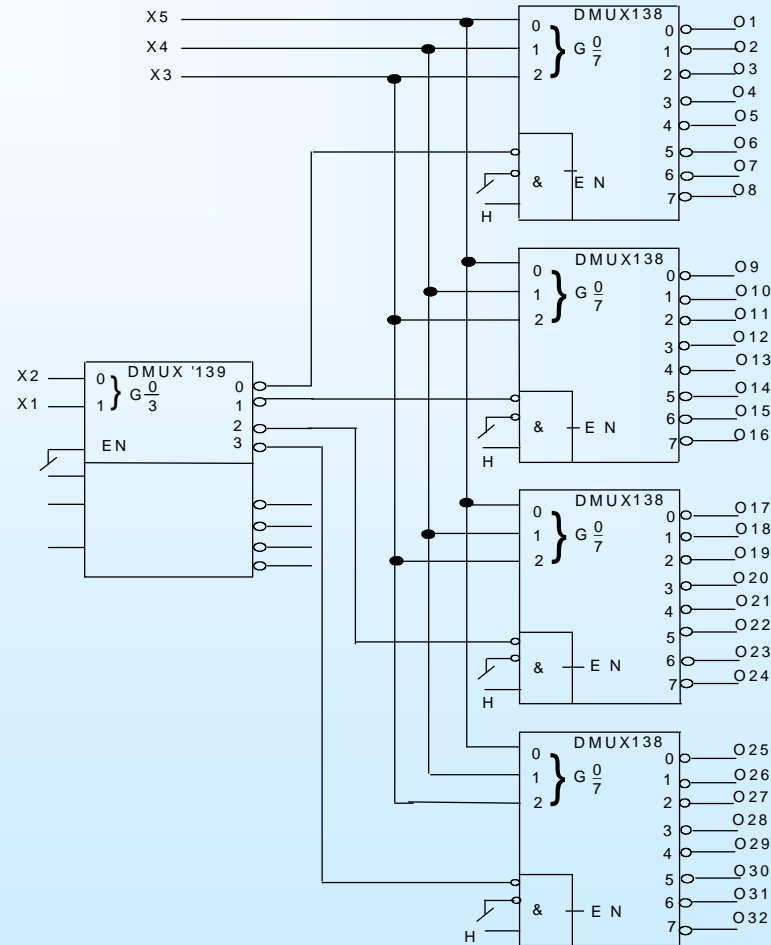
Decoding

An 8-channel multiplexer-demultiplexer combination





1-to-32 demultiplexer





Delays

74LS138: Propagation delays

Address to output $t_{PLH} = 27 \text{ ns}$ $t_{PHL} = 39 \text{ ns}$ (max)

Enable to output $t_{PLH} = 26 \text{ ns}$ $t_{PHL} = 38 \text{ ns}$ (max)

74LS139: Propagation delays

Address to output $t_{PLH} = 29 \text{ ns}$ $t_{PHL} = 38 \text{ ns}$ (max)

Enable to output $t_{PLH} = 24 \text{ ns}$ $t_{PHL} = 32 \text{ ns}$ (max)

The worst case delay time from the most significant bits of the input address to output of is 76 ns

The delay from the data input to output is 70 ns



Realization of Logic functions

- Demultiplexer is essentially a Minterms generator
- Do the necessary ORing of the required Minterms to realize the logic expression.
- One demultiplexer which generates all the Minterms, and a number of OR gates can realize multiple logic expressions of the same set of variables



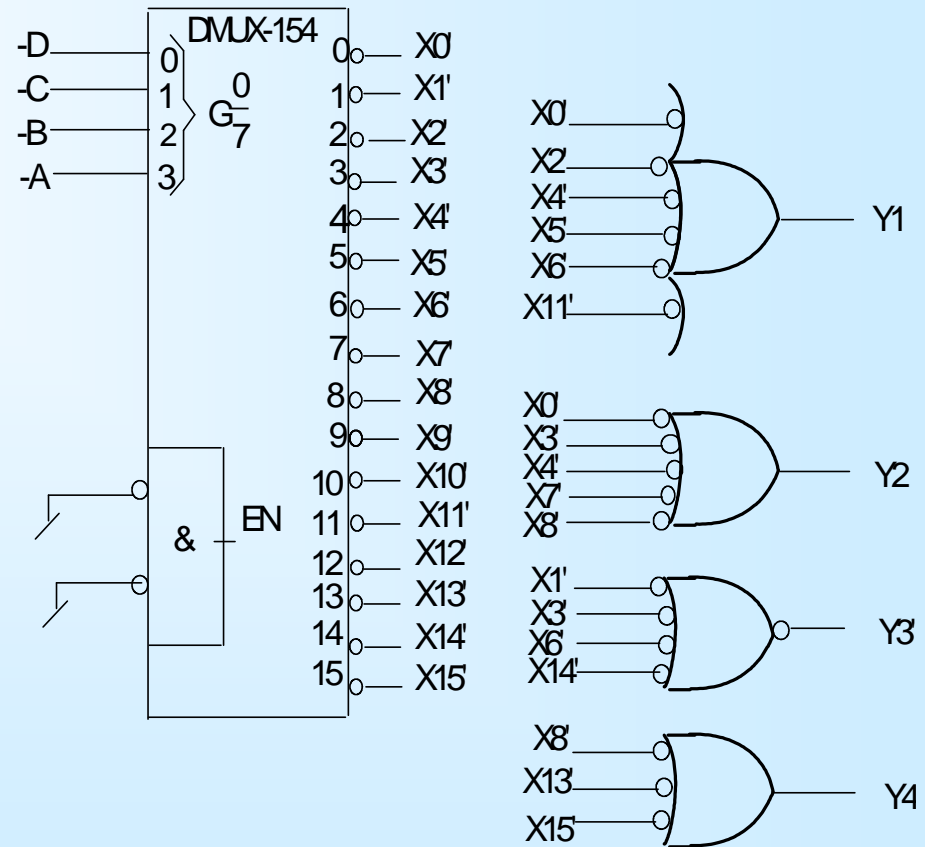
Example 1

$$Y1 = S(0, 2, 4, 5, 6, 11)$$

$$Y2 = S(0, 3, 4, 7, 8)$$

$$Y3 = S(1, 3, 6, 14)$$

$$Y4 = S(8, 13, 15)$$





Example 1 (2)

74LS154: Propagation delays

Address to output $t_{PLH} = 36 \text{ ns}$ $t_{PHL} = 33 \text{ ns}$ (max)

Enable to output $t_{PLH} = 30 \text{ ns}$ $t_{PHL} = 27 \text{ ns}$ (max)

74LS20: Propagation delay $t_{PLH} = t_{PHL} = 15 \text{ ns}$ (max)

74LS30: Propagation delay $t_{PLH} = 15 \text{ ns}$, $t_{PHL} = 20 \text{ ns}$ (max)

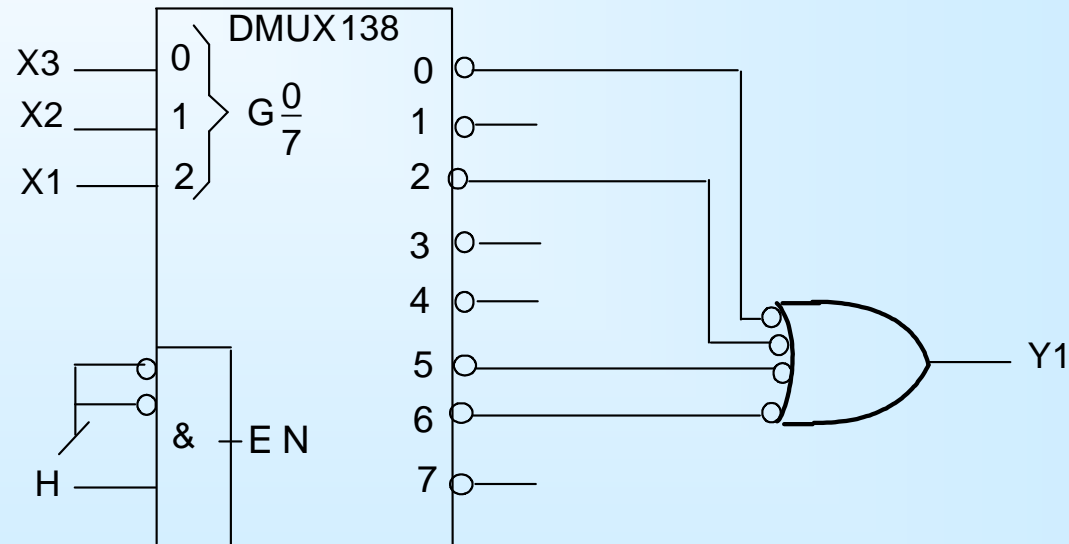
Net Propagation delay = $36 + 20 = 56 \text{ n secs}$ (max)

- Realization by INVERTERS and NAND gates results in a propagation delay of 55 (15+20+20) ns
- Demultiplexer solution to the realisation of logical expressions can reduce the net chip count



Example 2

$$Y1 = \Sigma (0, 2, 5, 6)$$





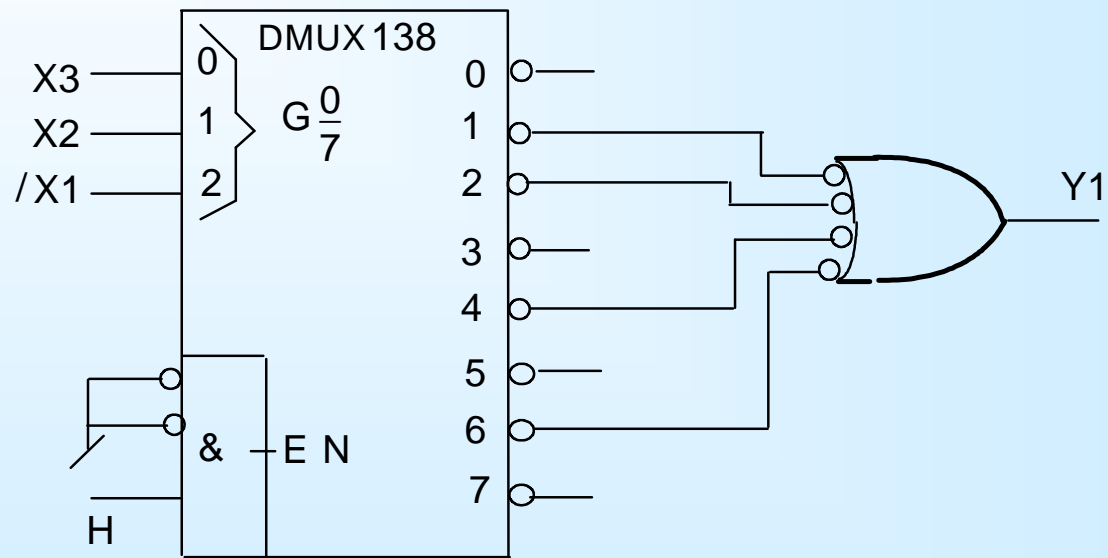
Example 2 (2)

If one of the variables $X1$ is Asserted Low

$X1$	$X2$	$X3$	<u>$/X1$</u>	$X2$	$X3$	Y
0	0	0	1	0	0	1
0	1	0	1	1	0	1
1	0	1	0	0	1	1
1	1	0	0	1	0	1



Example 2 (3)



Demultiplexer

A decoder/demultiplexer is a combinational circuit that asserts one of several outputs in response to a unique input code. It is a unit with n -inputs and m -outputs, where $m < 2^n$. An output switches from Not Asserted state to an Asserted state, when the input code is switched to a specific one. When $m = 2^n$, each one of the outputs can be associated with a Minterm of n -variables. Hence, such a decoder is known as Minterm Recogniser. Schematic of a 3-input demultiplexer is shown in figure 1.

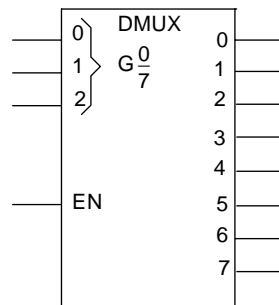


FIG. 1: Schematic of a 3-input demultiplexer

In the demultiplexer illustrated, each one of the outputs have an AND (G) dependence on one of the input codes, while, Enable inputs can be used to disable/enable the entire functional unit. Some of the available decoders/demultiplexers in the bipolar and CMOS families are listed below:

Dual 1-of-4 demultiplexer

2-state AL outputs:	74LS139/74HC139A
2-state AL outputs and common addressing:	74LS155
AL OC outputs and common addressing:	74LS156
3-state AH outputs:	74LS539

1-of-8 demultiplexer

AL outputs and 3 Enable inputs:	74LS138/ 74HC138A
AL outputs, 2 Enable, Address latch with latch enable:	74LS137

1-of-10 demultiplexer (2-state AL outputs): 74LS42

1-of-16 demultiplexer (AL outputs and 2 Enable inputs): 74LS154/74HC154

The uses of a demultiplexer include traditional demultiplexing operations as well as realisation of logic functions.

Decoding and Demultiplexing Functions

One of the traditional uses of a demultiplexer is to use it in combination with a multiplexer to transmit a number of signals over a single line. An 8-channel multiplexer-demultiplexer combination is shown in the figure 2.

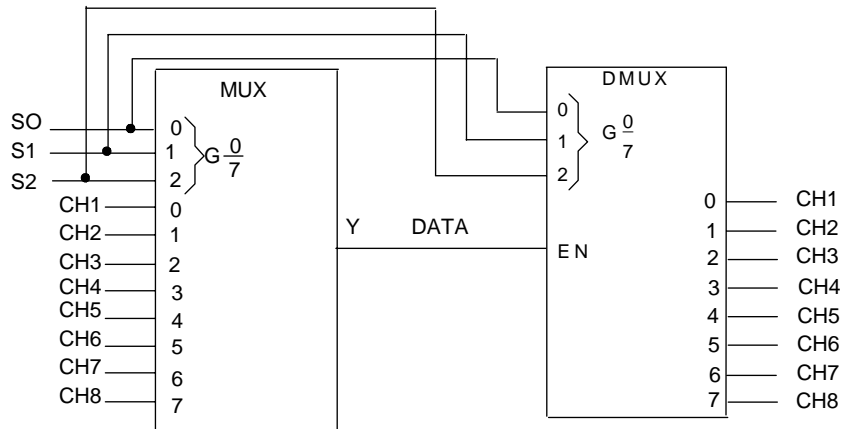


FIG. 2: An 8-channel multiplexer-demultiplexer combination

Notice that one of the Enable inputs of the demultiplexers is used as its data input. Though this illustration indicates that the address lines are tied together, in an actual signal transmission unit that uses such a MUX-DEMUX combination a different method will have to be used to change the addresses of both the units simultaneously.

Demultiplexers/decoders are extensively used in interfacing display units in a digital system with the rest of the hardware, and in decoding the addresses of the memory systems. In some of the applications, it may become necessary to string a number of demultiplexers together. Figure 3 presents a 1-to-32 demultiplexer using four 74LS138 units and one 74LS139.

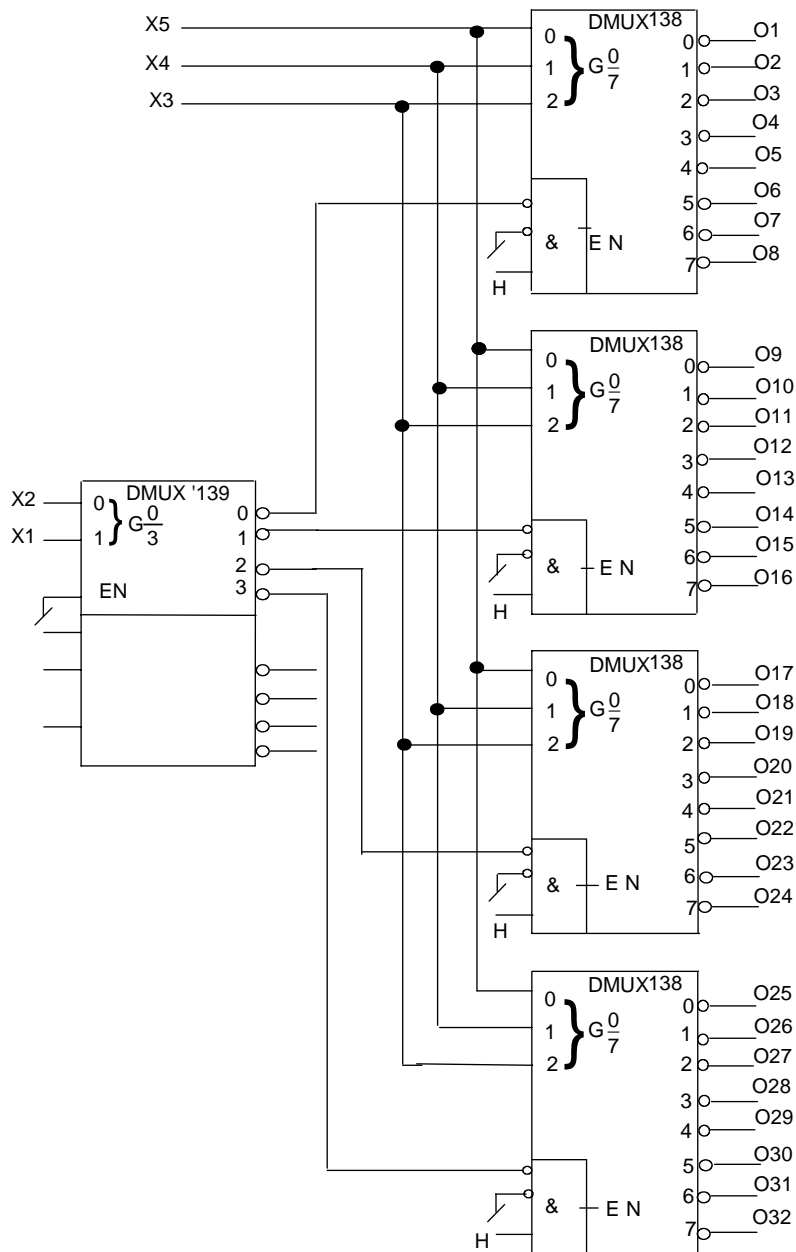


FIG. 3: 1-to-32 demultiplexer

The important characteristics the designer must compute and take into account are the delay times from the data and the address inputs to the output. The delay times associated with 74LS138 are:

74LS138: Propagation delays

Address to output $t_{PLH} = 27 \text{ ns}$ $t_{PHL} = 39 \text{ ns (max)}$

Enable to output $t_{PLH} = 26 \text{ ns}$ $t_{PHL} = 38 \text{ ns}$ (max)

74LS139: Propagation delays

Address to output $t_{PLH} = 29 \text{ ns}$ $t_{PHL} = 38 \text{ ns}$ (max)

Enable to output $t_{PLH} = 24 \text{ ns}$ $t_{PHL} = 32 \text{ ns}$ (max)

The worst case delay time from the most significant bits of the input address to output of 1-to-32 demultiplexer is 76 n secs. The delay from the data input to output is 70 n secs.

Realization of Logic functions

A logical expression in the Sum-of-Product form is nothing but ORing of a selected set of Minterms. As a demultiplexer is essentially a Minterms generator, it is possible to use a demultiplexer to realise a logical expression along with a gate to do the necessary ORing of the required Minterms. In comparison to the multiplexer, a demultiplexer needs additional hardware to realise a logical expression. However, this can be turned into an advantage in situations where more than one expression of the same logic variables has to be implemented. One demultiplexer which generates all the Minterms, and a number (equal to the number of logical expressions) of OR gates, will suffice. The following example illustrates this use of demultiplexers.

Example 1: Realise the following logical expressions using demultiplexers:

$$Y1 = \Sigma (0, 2, 4, 5, 6, 11)$$

$$Y2 = \Sigma (0, 3, 4, 7, 8)$$

$$Y3 = \Sigma (1, 3, 6, 14)$$

$$Y4 = \Sigma (8, 13, 15)$$

As the expressions are in four variables, 74LS154 (1-to-16 demultiplexer) is used. The hardware realisation is shown in the figure4. Note that the OR function can actually be realised by a NAND gate, as the outputs of the demultiplexer are Asserted Low.

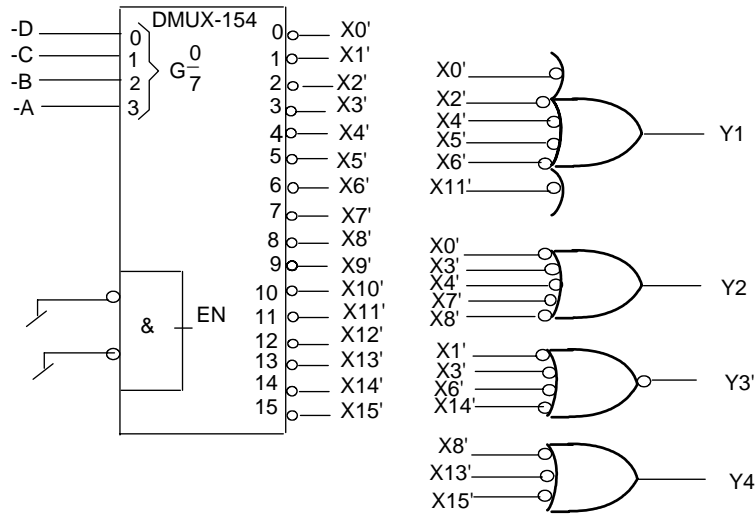


FIG. 4: Realisation of the functions given in Example 1

The Propagation delay of this circuit can be computed as:

74LS154: Propagation delays

Address to output $t_{PLH} = 36 \text{ ns}$ $t_{PHL} = 33 \text{ ns (max)}$

Enable to output $t_{PLH} = 30 \text{ ns}$ $t_{PHL} = 27 \text{ ns (max)}$

74LS20: Propagation delay

$t_{PLH} = t_{PHL} = 15 \text{ ns (max)}$

74LS30: Propagation delay

$t_{PLH} = 15 \text{ ns}$, $t_{PHL} = 20 \text{ ns (max)}$

Net Propagation delay = $36 + 20 = 56 \text{ n secs (max)}$

If these expressions are to be realised using INVERTERS and NAND gates, we require three-level gating (one level of INVERTERS and two levels of NANDs), which would result in a propagation delay of 55 ($15+20+20$) n secs. Hence, the demultiplexer solution does not give any speed advantage over the traditional realisation of logical expressions using gates, whereas, the multiplexer realisation gave a marginal speed advantage. However, demultiplexer solution to the realisation of logical expressions can greatly reduce the net chip count, at least in some cases.

It is also possible to take into account if some of the variables in the logic expression are Asserted Low. The solution is very similar to the procedure adapted in the case of multiplexers, viz., either through changing assertion levels of the Asserted Low

variables or by taking into account the fact that incompatibility at the input results in the complementation of the variables in the output logic expression. This is illustrated in the example 2

Example 2: Realise the logical expression $Y1 = \Sigma (0, 2, 5, 6)$ of three variables $X1$, $X2$ and $X3$ using 74LS138. Indicate how the realization of the expression would vary if the variable $X1$ is changed to an asserted-low variable

Figure 5 shows the realization of logical expression for $Y1$ by a demultiplexer solution where.

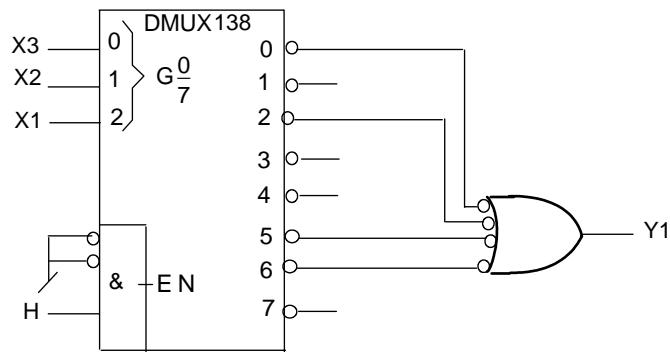


FIG. 5: Realisation of the function given in the Example 2

The modified truth-table for this expression is as given in the following. The corresponding hardware realisation of the logic expression, where the assertion level of the variable $X1$ is not altered is given in the figure 6.

<u>X1</u>	<u>X2</u>	<u>X3</u>	<u>/X1</u>	<u>X2</u>	<u>X3</u>	<u>Y</u>
0	0	0	1	0	0	1
0	1	0	1	1	0	1
1	0	1	0	0	1	1
1	1	0	0	1	0	1

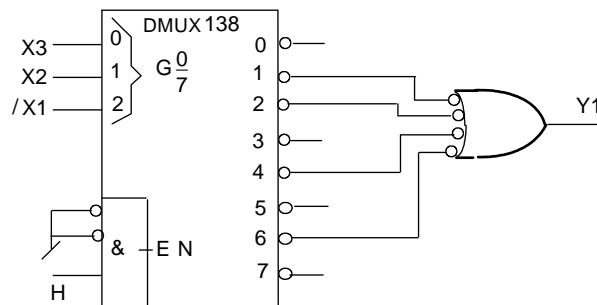


FIG.6: Modified realisation of the function given in the example 2



Digital Electronics

Module 4: Combinational Circuits: Addition

N.J. Rao

Indian Institute of Science



Addition

- Addition is the most fundamental arithmetic operation.
- All the other arithmetic operations can be expressed in terms of addition.
- It is desirable for a digital designer to be familiar with the realisation of simple arithmetic functions using combinational circuits.
- Many of these conventions and procedures are carried over to the software level while designing with LSIs.

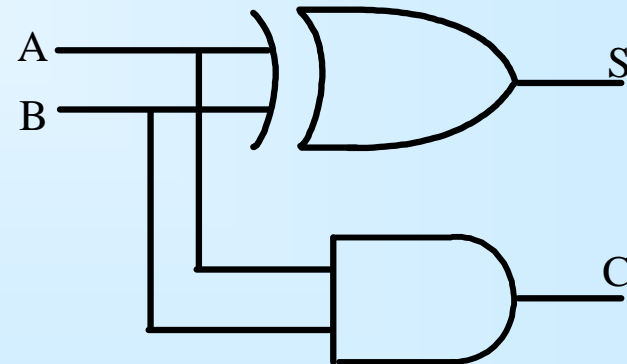


Simple Adders

Adding two one-bit numbers

A	B	S	C
0	0	0	0
0	1	1	0
1	0	1	0
1	1	0	1

$$S = A B' + A' B = A \oplus B$$
$$C = A \cdot B$$





Addition of multi-bit numbers

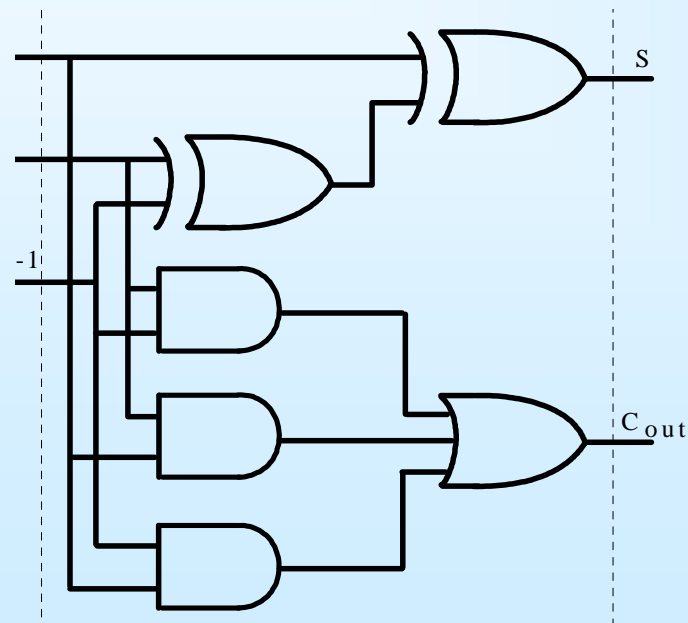
- This requires an adder unit that performs addition with three bits.
- Such an adder is called Full-Adder.

A_i	B_i	C_{i-1}		S_i	C_i
0	0	0		0	0
0	0	1		1	0
0	1	0		1	0
0	1	1		0	1
1	0	0		1	0
1	0	1		0	1
1	1	0		0	1
1	1	1		1	1



Addition of multi-bit numbers (2)

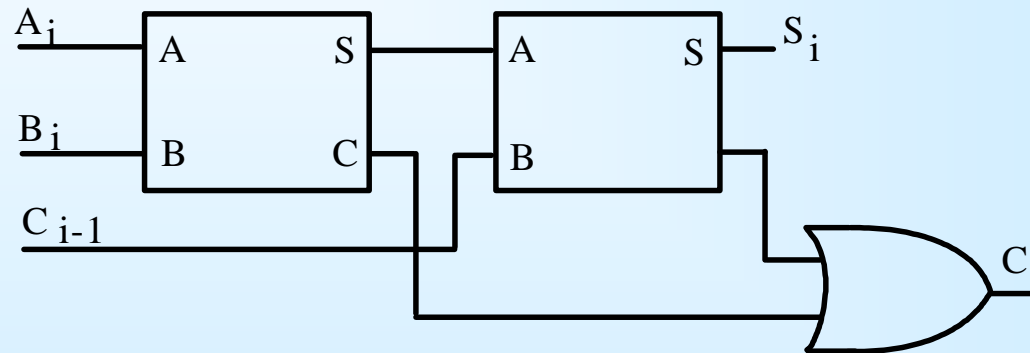
$$S_i = A_i' B_i' C_{i-1} + A_i' B_i C_{i-1}' + A_i B_i' C_{i-1}' + A_i B_i C_{i-1}$$
$$C_i = A_i' B_i C_{i-1} + A_i B_i' C_{i-1} + A_i B_i C_{i-1}' + A_i B_i C_{i-1}$$
$$= B_i C_{i-1} + A_i C_{i-1} + A_i B_i$$





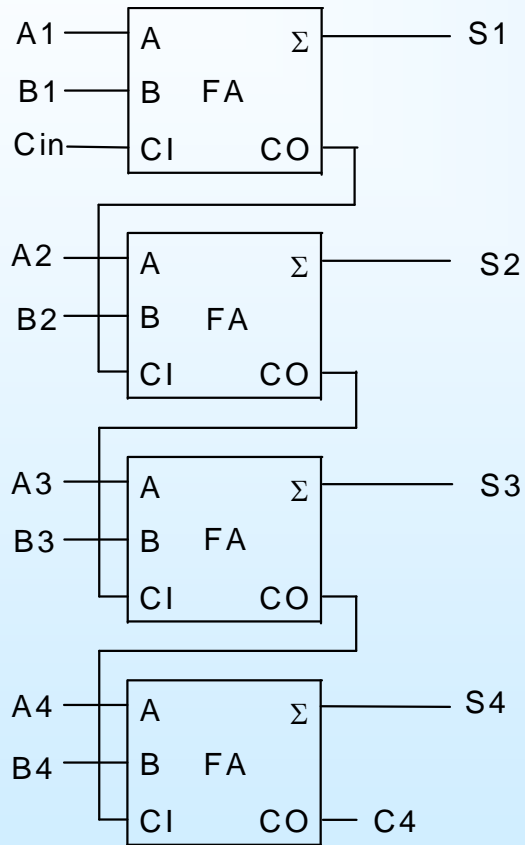
Addition of multi-bit numbers (3)

Full adder in terms of half-adders





4-bit adders



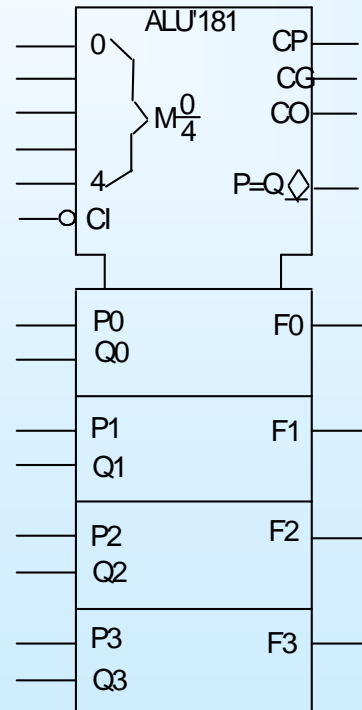
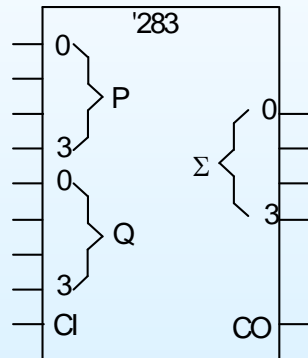
The carry bit will have to ripple through all the stages and the delay of the four bit adder will be four times the delay associated with single bit full adders.



MSI adders

74LS283 (4-bit full adder)

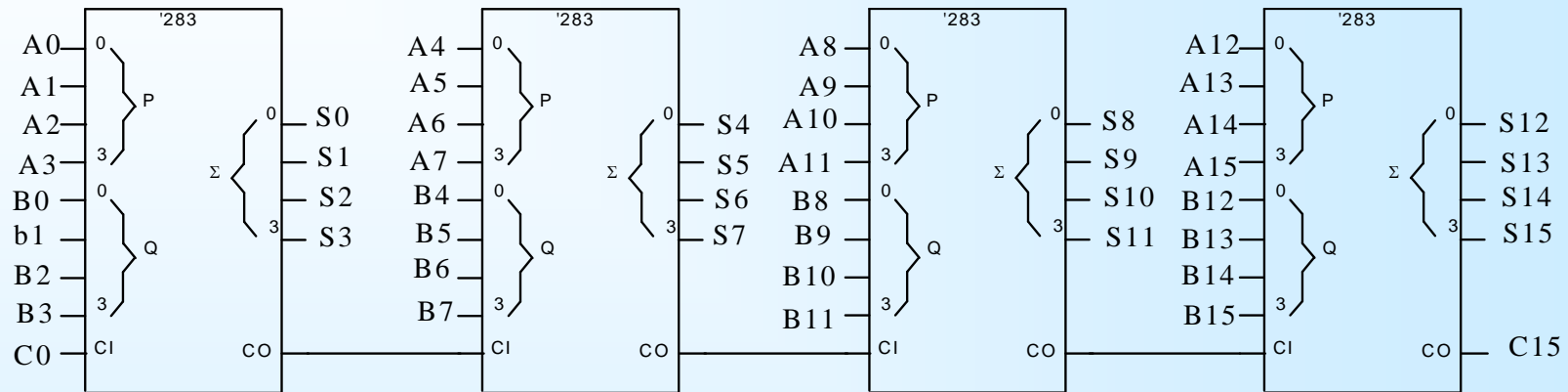
74LS181 (4-bit arithmetic logic unit)



	t_{PLH}	t_{PHL}	
CI to S (max)	24	24	ns
CI to CO (max)	17	22	ns
A, B to S (max)	24	24	ns
A, B to CO (max)	17	17	ns



16-bit adders



$$\begin{aligned}
 \text{Addition time} &= t_p(\text{C11 to CO1}) + t_p(\text{C12 + CO2}) + t_p(\text{C13 to CO3}) + \\
 &\quad t_p(\text{C14 to S}) \\
 &= 22 + 22 + 22 + 24 \\
 &= 90 \text{ ns}
 \end{aligned}$$

Addition time is 108 ns if 74LS181 is used

Addition time is 42 ns if 74S181 is used



Limitations of 4-bit adders

- Internal circuitry of the 4-bit adders is optimised to provide minimum delay
- The carry bit has to ripple from one group of bits to the next group in the case of 16-bit, 32-bit and 64-bit adders
- This will increase the addition time significantly.
- Add extra circuitry that can determine the final carry bit without waiting for it to ripple through all the stages.
- Such an arrangement is called Carry Look Ahead feature.



Carry Look Ahead

Carry Generator, $G_i = A_i B_i$

Carry Propagator, $P_i = A_i + B_i$

$$C_1 = A_0 B_0 + C_0 (A_0 + B_0) = G_0 + C_0 P_0$$

$$C_2 = A_1 B_1 + C_1 (A_1 + B_1)$$

$$= G_1 + C_1 P_1 = G_1 + P_1 G_0 + P_1 P_0 C_0$$

$$C_3 = A_2 B_2 + C_2 (A_2 + B_2) = G_2 + C_2 P_2$$

$$= G_2 + P_2 G_1 + P_2 P_1 G_0 + P_2 P_1 P_0 C_0$$

$$C_4 = A_3 B_3 + C_3 (A_3 + B_3) = G_3 + C_3 P_3$$

$$= G_3 + P_3 G_2 + P_3 P_2 G_1 + P_3 P_2 P_1 G_0 + P_3 P_2 P_1 P_0 C_0$$

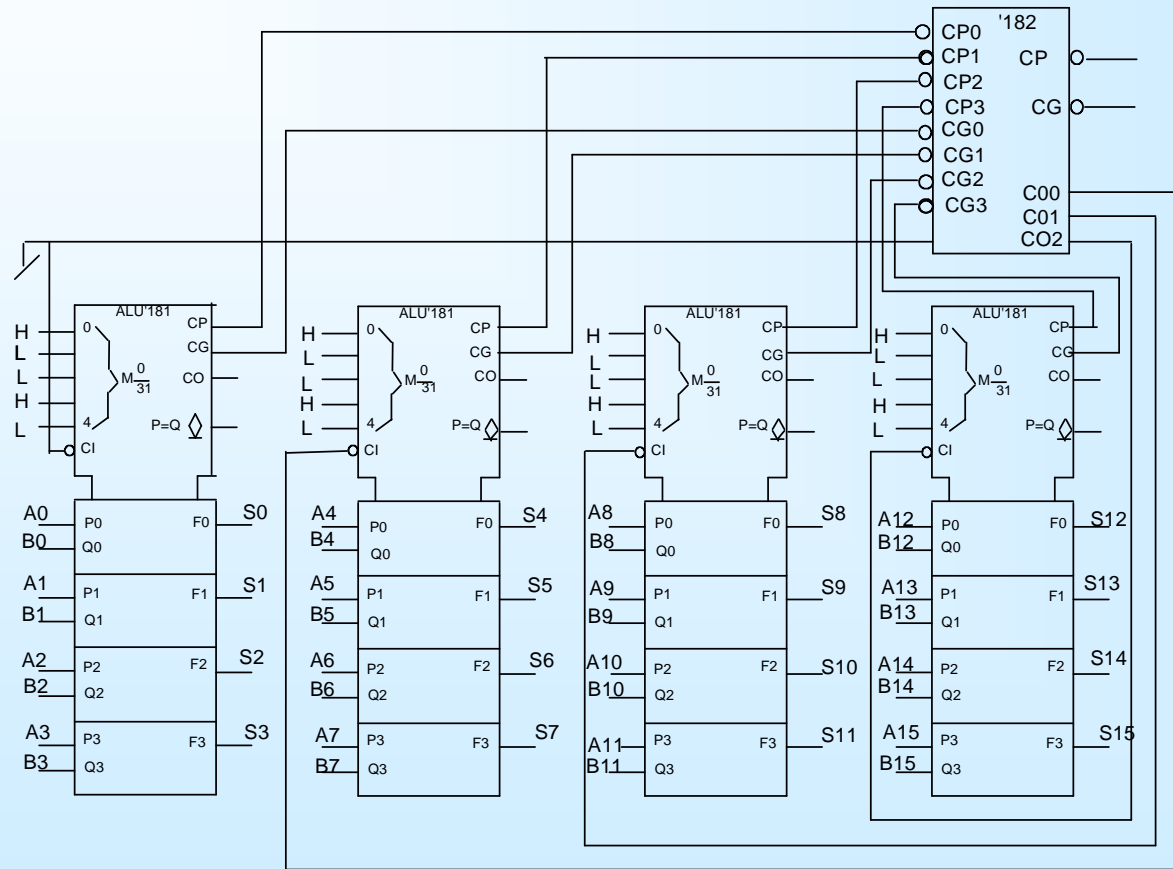


Carry Look Ahead (2)

- 74LS283 incorporates this feature to minimise the associated delay.
- 74LS182, called Carry Look Ahead Generator, can accept these group-carry signals from the four ALUs to generate final carry bit in the case of 16-bit addition
- If 64-bit adder is to be built, a second level carry look ahead generator, taking the group carry signals from each group of 16 bits, will have to be used.



16-bit adder with carry look ahead





Subtraction

Normally subtraction is performed by changing the sign of subtrahend and adding it to the minuend.

Ways of representing the signed numbers:

- sign-magnitude
- one's complement
- two's complement forms
- BCD representations



Addition and subtraction (2's complement)

“Add the two numbers and ignore the carry”

“Overflow occurs when there is a carry into the sign-bit position and no carry out of the sign-bit position, and vice-versa”

The overflow may, therefore be realised by

$$OF = C_n \oplus C_{n-1}$$

The sign changing is done by complementing the subtrahend and adding a 1 in the least significant bit position.

A mode signal has to be created to instruct the unit whether the addition or subtraction should take place.

Addition

Addition is the most fundamental arithmetic operation. All the other arithmetic operations can be expressed in terms of addition. Some time ago the design of the central processing unit and the consequent speed of the digital computer depended greatly on the design of the adder hardware. Design of a multi-bit fast adder was one of the skills that a digital designer had to acquire in the early era of computers. The availability of low cost general purpose LSI circuits like microprocessors and digital signal processors, and the availability cost effective technology for realising special purpose LSIs changed the scene radically. At present the need for designing an arithmetic unit from a large collection of SSI and MSI circuits does not exist. However, it is desirable for a digital designer to be familiar with the realisation of simple arithmetic functions using combinational circuits. Many of these conventions and procedures are carried over to the software level while designing with LSIs. This Unit presents only the very basics of adders based on combinational circuits.

Simple Adders

The simplest binary addition is to add two one-bit numbers. When the sum of two bits is more than 1 it is considered as an overflow and we generate a 'carry' bit. The truth-table associated with this addition process is given in the following, with A and B as the input one-bit numbers, S as the sum and C as the carry.

A	B	S	C
0	0	0	0
0	1	1	0
1	0	1	0
1	1	0	1

The combinational circuit for the addition of two one-bit numbers is known as Half Adder. The logical expressions for the two outputs, S and C, may be written from the above truth-table as;

$$S = A B' + A' B = A \oplus B$$

$$C = A \cdot B$$

The gate level realisation of a half-adder is shown in the figure 1.

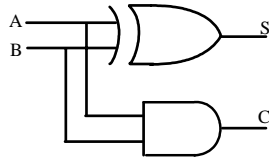


FIG. 1: Half adder

A half-adder has only provision to add two bits. If multi-bit numbers are to be added provision is to be made to take the carry bits coming from the previous stages. This requires an adder unit that performs addition with three bits. Such an adder is called Full-Adder. Let A_i and B_i be the i 'th bits of an n -bit number, C_{i-1} be the carry bit from the $i-1$ stage of addition, S_i be the i 'th bit of the sum, and C_i be the carry bit from the i 'th stage of addition. The truth-table of a full adder is

A_i	B_i	C_{i-1}	S_i	C_i
0	0	0	0	0
0	0	1	1	0
0	1	0	1	0
0	1	1	0	1
1	0	0	1	0
1	0	1	0	1
1	1	0	0	1
1	1	1	1	1

The logical expressions for the Sum and Carry bits can be written as in the following

$$S_i = A_i' B_i' C_{i-1} + A_i' B_i C_{i-1}' + A_i B_i' C_{i-1}' + A_i B_i C_{i-1}$$

$$C_i = A_i' B_i C_{i-1} + A_i B_i' C_{i-1} + A_i B_i C_{i-1}' + A_i B_i C_{i-1}$$

$$= B_i C_{i-1} + A_i C_{i-1} + A_i B_i$$

The realisation of the full adder using gates is shown in the figure 2.

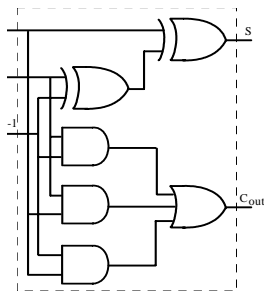


FIG. 2: Full adder realised with basic gates

However, the full adder can also be realised in terms of half-adders as shown in the figure 3.

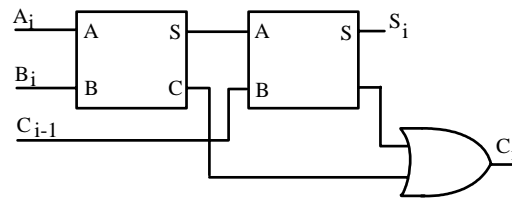


FIG. 3: Full adder realised by two half-adders

Adders for adding single bit numbers are of hardly any use in practice. Addition of multiple bit numbers requires cascading of a number of full adders. A 4-bit adder put together with four single bit full adders is shown in the figure 4.

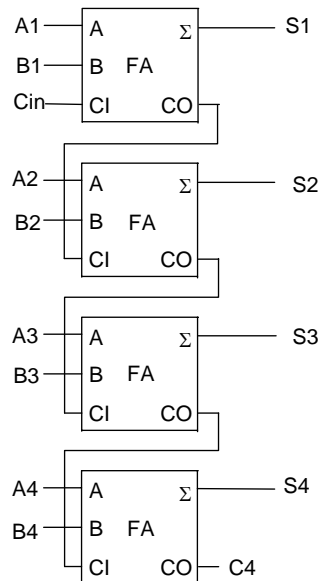


FIG. 4: 4-bit binary adder

It may be noted that the carry bit will have to ripple through all the stages and the delay of the four bit adder will be four times the delay associated with single bit full adders. Besides, building such a circuit with basic gates or half adders requires large number of SSI circuits. There are two MSI circuits that offer four bit addition, available from all the vendors. These are 74LS283 (4-bit full adder) and 74LS181 (4-bit arithmetic logic unit). 74LS181 is more than a adder, and can perform a variety of arithmetic and logic functions which can be selected by a set of control and mode signals. The logical symbols of 74LS283 and 74LS181 are shown in the figure 5.

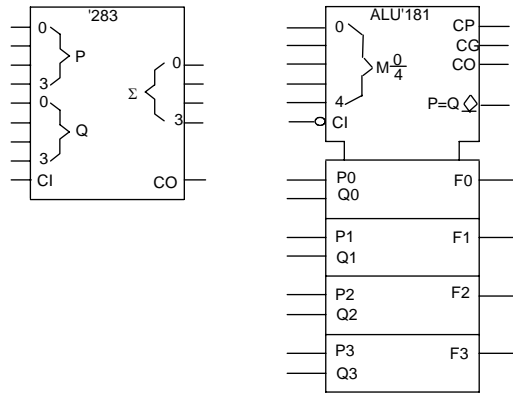


FIG. 5: Schematic representations of 74LS181 and 74LS283

The internal circuitry of the 74LS283 is optimised to give minimum possible delay times between all the inputs and outputs. These propagation delays are listed in the following:

	t_{PLH}	t_{PHL}	
CI to Σ (max)	24	24	ns
CI to CO (max)	17	22	ns
A, B to Σ (max)	24	24	ns
A, B to CO (max)	17	17	ns

Adders with Features

It often becomes necessary to build adders for numbers much larger than 4-bit numbers. A 16-bit adder built with four units of 74LS283s is shown in the figure 6.

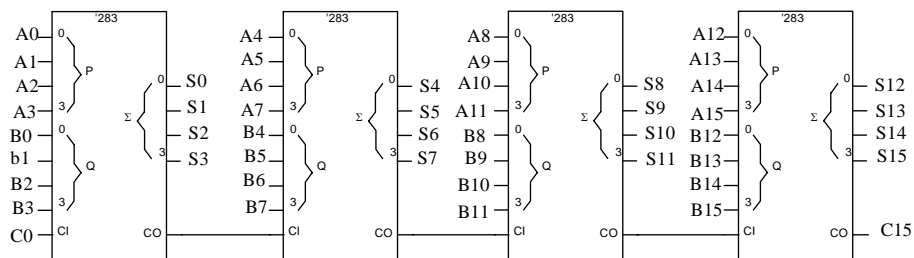


FIG. 6: 16-bit adder using 74LS283s

The most important parameter of an adder is the addition time. The addition time for the 16-bit adder using 74LS283s is given by;

$$\begin{aligned}
 \text{Addition time} &= t_p(\text{CI1 to CO1}) + t_p(\text{CI2 to CO2}) + t_p(\text{CI3 to CO3}) + t_p(\text{CI4 to } \Sigma) \\
 &= 22 + 22 + 22 + 24 \\
 &= 90 \text{ ns}
 \end{aligned}$$

If 74LS283 is replaced by 74LS181 the delay time will be slightly larger, as the circuitry within this unit is more complex. The net addition time for a 16-bit adder will be 108 ns. If a faster unit like 74S181 is used the addition time gets reduced to 42 ns.

While the internal circuitry of the available adder units is optimised to provide minimum delay for the addition of 4-bit numbers, the carry bit has to ripple from one group of bits to the next group in the case of a 16-bit adder. When the addition involves numbers that are 32-bit or 64-bit long, the carry bit will have to ripple through 8 and 16 stages of adders respectively. This will increase the addition time significantly. One method of reducing the addition time is to add extra circuitry that enables the determination of the final carry bit without waiting for it to ripple through all the stages. Such an arrangement is called Carry Look Ahead feature. This is based on deciding independently whether a particular stage in addition generates a carry bit or merely propagates the carry bit coming from the previous stage. Let A_i and B_i be the two i 'th bits of multi-bit numbers A and B respectively. A carry bit is generated from this stage to the next one, whether there is a carry bit from the previous stage or not, if both bits are 1s. The carry bit from the previous stage is propagated to the next stage if one of the bits or both of them are 1s. These two functions, namely carry generate and carry propagate, can be defined as;

$$\text{Carry Generator, } G_i = A_i B_i$$

$$\text{Carry Propagator, } P_i = A_i + B_i$$

Let, in a 4-bit adder, C_0 be the carry bit into the first stage and C_1, C_2, C_3 and C_4 be the carry bits from the four stages of addition. G_0, G_1, G_2 and G_3 are the carry generates and P_0, P_1, P_2 and P_3 are the carry propagates from the four stages of addition of the 4-bit adder. Then the relationships can be stated as below:

$$C_1 = A_0 B_0 + C_0 (A_0 + B_0) = G_0 + C_0 P_0$$

$$C_2 = A_1 B_1 + C_1 (A_1 + B_1) = G_1 + C_1 P_1 = G_1 + P_1 G_0 + P_1 P_0 C_0$$

$$\begin{aligned} C_3 &= A_2 B_2 + C_2 (A_2 + B_2) = G_2 + C_2 P_2 \\ &= G_2 + P_2 G_1 + P_2 P_1 G_0 + P_2 P_1 P_0 C_0 \end{aligned}$$

$$\begin{aligned} C_4 &= A_3 B_3 + C_3 (A_3 + B_3) = G_3 + C_3 P_3 \\ &= G_3 + P_3 G_2 + P_3 P_2 G_1 + P_3 P_2 P_1 G_0 + P_3 P_2 P_1 P_0 C_0 \end{aligned}$$

C_4 can, therefore, be generated independently of $C_1, C_2,$ and C_3 as P and G

functions can be generated from the A and B inputs directly. This is known as the carry look ahead feature. The circuitry within the unit 74LS283 incorporates this feature to minimise the associated delay. But it becomes necessary to have additional circuitry to incorporate carry look ahead feature when an adder has to be designed for numbers more than four. This can be done through generating *group carry generate* and *group carry propagate* signals. In the context of commercially available ICs, four bits constitute a group. The 74LS181 Arithmetic Logic Unit (ALU) generates both group carry generate and group carry propagate signals. These signals can be combined across stages in a manner similar to the relationships listed above. 74LS182, called Carry Look Ahead Generator, can accept these group-carry signals from the four ALUs to generate final carry bit in the case of 16-bit addition, as shown in the figure 7.

If 64-bit adder is to be built, a second level carry look ahead generator, taking the group carry signals from each group of 16 bits, will have to be used.

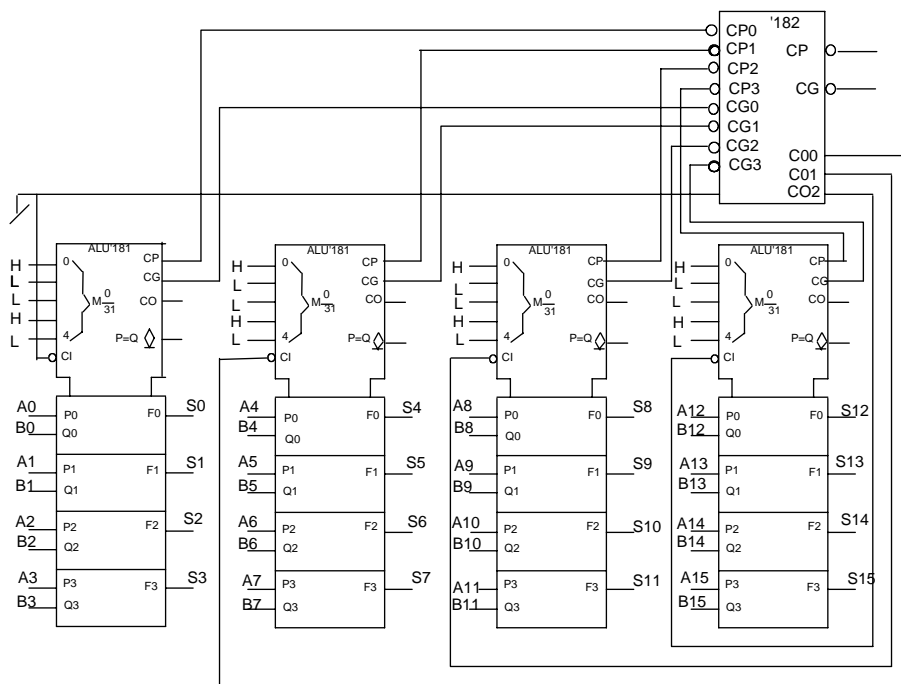


FIG. 7: 16-bit adder with carry look-ahead feature

Combined Addition and Subtraction

Normally subtraction is performed by changing the sign of subtrahend and adding it to the minuend. However, there are several ways of representing the signed

numbers. These include sign-magnitude, one's complement, two's complement forms and BCD representations. Here we consider addition and subtraction operations with numbers represented in two's complement form. The reader is urged to work out the hardware for other representations as exercises.

The algorithm for addition of two two's complement numbers is

“Add the two numbers and ignore the carry”

The algorithm for overflow is

“Overflow occurs when there is a carry into the sign-bit position and no carry out of the sign-bit position, and vice-versa”

The overflow may, therefore be realised by

$$OF = C_n \oplus C_{n-1}$$

The sign changing is done by complementing the subtrahend and adding a 1 in the least significant bit position. A mode signal, therefore, has to be created to instruct the arithmetic unit whether the addition or subtraction should take place. A 9-bit two's complement adder-subtractor is shown in the figure 8.

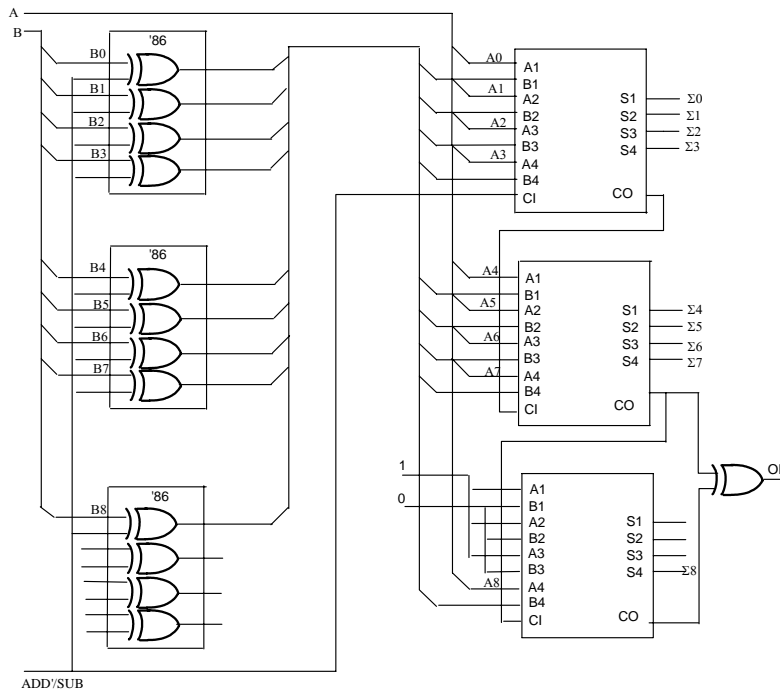


FIG.3: 9-bit two's complement adder-subtractor

APPENDIX: DEPENDENCY NOTATION

Introduction: Dependency Notation refers to the symbolic language developed as a part of the Standard ANSI/IEEE Std-91-1984. This notation was evolved to indicate the relationship of each input of a digital logic circuit to each output without explicitly showing the internal logic. However, this notation can only be used with regard to circuits of medium complexity and MSIs. When the MSIs are represented in this notation there would not be any need to constantly refer to the data sheet to understand the logical relationship between signals. This Appendix introduces the basics of Dependency Notation. Its use with regard to specific ICs will be elaborated in the related Modules. The material presented in the following should be sufficient to understand and to draw the logic diagrams needed for the design of digital systems of reasonable complexity.

General Definitions: IEEE Standard supports the notion of bubble-to-bubble logic design in with some important terms encountered are explained in the following.

Logic State: One of two possible abstract states that may be taken on by a logic (binary) variable.

0-State: The logic state represented by the binary number 0 and usually standing for Not Asserted state of a logic variable.

1-State: The logic state represented by the binary number 1 and usually standing for Asserted state of a logic variable.

External Logic State: A logic state assumed to exist outside symbol outline; (1) on an input line prior to any external qualifying symbol at the input or (2) on output line beyond any external qualifying symbol at that output.

Internal Logic State: A logic state assumed to exist inside a symbol outline at an input or an output.

Qualifying Symbol: It is graphics or text added to the basic outline of a device logic symbol to describe the physical or logical characteristics of the device. The "external qualifying symbol" mentioned above is typically an inversion bubble, which denotes a "negated" input or output, for which the external 0-state corresponds to the internal 1-state. "Internal 1-state" may be interpreted as the corresponding signal getting asserted. Similarly "internal 0-state" may be interpreted as the corresponding signal getting not-asserted.

A symbol for a digital circuit comprises of an outline or a combination of lines together with one or more qualifying symbols. Lines on the left hand side indicate inputs while the lines on the right hand side indicate outputs. This concept of composing the symbol is illustrated in the figure 1.

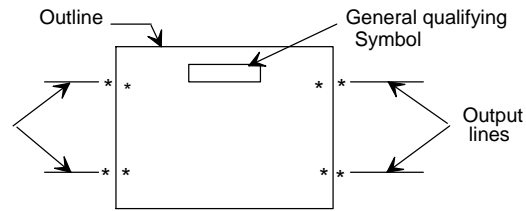










FIG. 1: Composition of a logic circuit symbol

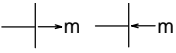
General additional information may be included in a symbol outline in the diagrams for digital circuits. A qualifying symbol is included at the top to indicate the general function performed by the logic circuit under consideration. Some of these qualifying symbols to indicate the device functions are listed in the following.

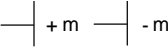
SYMBOL	DEVICE FUNCTION
\geq	OR
&	AND
=1	Exclusive OR
=	All inputs at the same state
2k	Even number of inputs Asserted
2k+1	Odd number of states Asserted
▷	Buffer
◻	Schmitt Trigger
X/Y	Code Converter
MUX	Multiplexer
DX	Demultiplexer
Σ	Adder
P - Q	Subtractor
CPG	Carry look-ahead generator
ALU	Arithmetic logic unit
COMP	Magnitude comparator


The input and output lines will have qualifying symbols inside the symbol outlines. These qualifying symbols are illustrated in the following.


SYMBOL	SIGNAL FUNCTION
—|	Asserted Low input (External 0 = Internal 1)
—|	Asserted Low output (Internal 1 = External 0)
—|	Asserted High input (External 1 = Internal 1)
—|	Asserted High output (Internal 1 = External 1)

-  Bithreshold input (Input with hysteresis)
-  Open-collector or open-drain output
-  Positive edge control input signal
-  Negative edge control input signal
-  3-State output
-  Postponed output (pulse triggered flip-flop)
-  Enable input, when at its internal 1-state, all outputs are enabled. When at its internal 0-state all outputs are at the internal 0-state
-  Data input to a storage element


 Shift right (left) inputs $m = 1, 2, 3$, etc.


 Counting up (down) inputs $m = 1, 2, 3$, etc.


 Binary Grouping. m is the highest power of 2.


 Content equals (e.g., 9)

 Internal connection

 Internal connection with negation

 Internal input (virtual input)

 Internal output (virtual output)

 Internal dynamic connection

When the logic circuit has one or more inputs that are common to more than one element of the circuit, the symbol is modified to include a common control block. The distinctive

shaped control block adopted by IEC is shown in the figure 2. Unless otherwise qualified specifically within the context of Dependency Notation the inputs to the control block are assumed to be common to all the elements within the circuit.

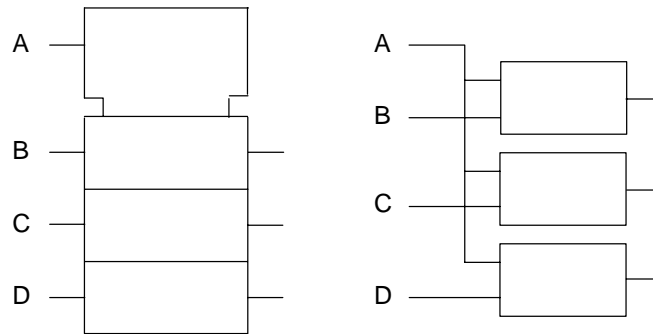


FIG 2: Symbol for common control block

If an output is dependent on all the elements of the circuit it is shown as a common output, and the common output element is distinctly shown by being separated from the other elements by a double line as shown in the figure 3. It may be noted that in drawing the symbols it is not permitted to represent the signals entering or leaving from the top or bottom section of the logic symbol.

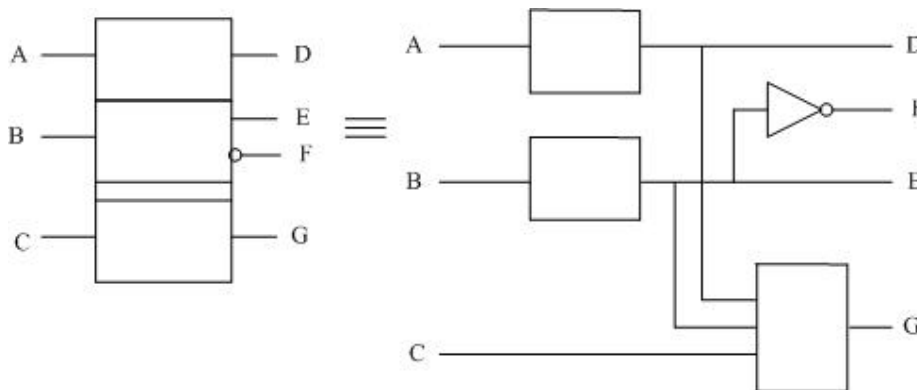


FIG 3: Symbol for common output block

Medium Scale Integrated (MSI) circuits available from many vendors are designed to perform well defined combinational or sequential functions. The commonly available MSIs include combinational circuits like multiplexers, demultiplexers, encoders, arithmetic units and comparators, and sequential circuits like registers, counters and display controllers. The aim of the Dependency Notation is to give a detailed description of the function of each input/output and the interrelationship between signals of the IC within the symbol itself, using simple codes. Such a notation will greatly help in designing with MSIs without constant dependence on the data sheets. While the dependency notation can be used to compose symbols for circuits that are composed of a few SSIs and MSIs, it is not always possible to create a symbol for every circuit. For example it is not feasible to compose a

symbol for an LSI chip like a microprocessor, using the dependency notation.

Dependency notation is a means of denoting the relationships, between inputs, outputs or inputs and outputs, without actually showing all the elements and interconnections involved. It should not be used to replace the symbols for combinational elements. It gives information that supplements that provided by the qualifying symbols for an element's function. The signals are classified as 'affecting' and 'affected'. An input as well as an output signal can be an affecting signal or affected signal. There are ten types of dependencies identified under this Standard. These are explained in the following.

AND Dependency (G Dependency): A common relationship between two signals is to have them ANDed together. This AND relationship in Dependency notation is shown as indicated in the figure 4. The input B is ANDed with input A and the complement of B is ANDed with C. the letter G has been chosen to indicate AND relationships and is placed at input B, inside the symbol. An arbitrary number (1 has been used here) is placed after the letter G and also at each affected input. Note the superscript slash after 1 at input C.

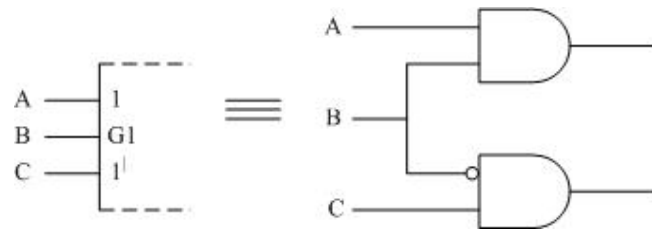


FIG. 4: G dependency between inputs

In figure 5 output B affects input A with an AND relationship. The lower example shows that it is the internal logic state of B, unaffected by the negation sign that is ANDed.

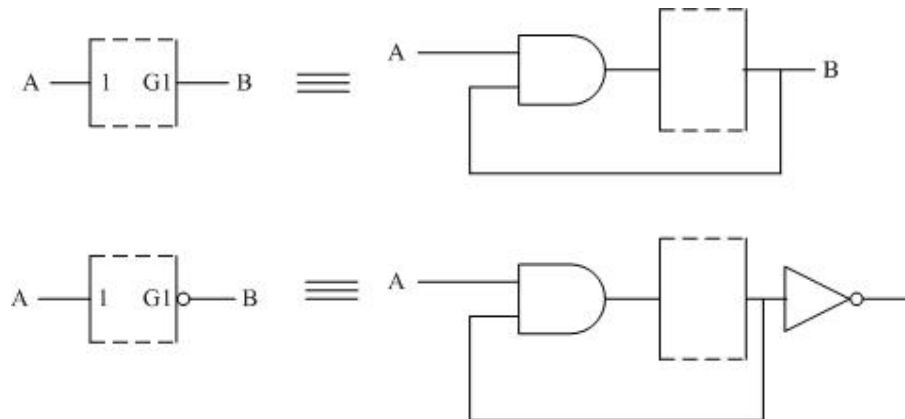


FIG. 5: G dependency between outputs and inputs

Figure 6 shows A to be ANDed with a dynamic input B.



FIG. 6: G dependency with a dynamic input

The rules for G-dependency can be summarised as:

When a G_m input or output (m is a number) stands at its internal 1-state (Asserted) all the inputs and outputs affected by this G_m stand at their normally defined internal logic states.

When G_m input or G_m output stands at its internal 0-state (Not Asserted) all the inputs and outputs affected by it stand at their 0-state (Not Asserted).

Conventions for the Application of Dependency Notation in General: The rules for applying dependency relationships in general follow the same pattern as was illustrated for G-dependency. Application of dependency notation is accomplished by:

Labelling the input (or output) affecting other inputs or outputs with a letter symbol indicating the relationship involved followed by an identifying number, arbitrarily chosen.

Labelling each input or output affected by that affecting input (or output) with that same number.

If it is the complement of the internal logic state of the affecting input or output that does the affecting, then a bar is placed over the identifying numbers at the affected inputs or outputs. If the affected input or output requires a label to denote its function this label will be prefixed by the identifying number of affecting input. If an input or output is affected by more than one affecting input, the identifying numbers of each of the affecting inputs will appear in the label of the affected one, separated by commas. The left-to-right sequence of these numbers is the same as the sequence of the affecting relationships.

If the labels denoting the functions of affected inputs or outputs must be numbers, the identifying numbers to be associated with both affecting inputs and affected inputs or outputs will be replaced by another character selected to avoid ambiguity

OR Dependency (V Dependency): The symbol denoting OR dependency is the letter V. Each input or output affected by a V_m input or V_m output stands in an OR relationship with this V_m input or output. When V_m input or output stands at its internal 1-state (Asserted) all inputs and outputs affected by this V_m input or V_m output stand at their internal 1-state (Asserted). When a V_m input or V_m output stands at its internal 0-state (Not Asserted), all inputs and outputs affected by this V_m input or V_m output stand at

their normally defined internal logic states. The nature of V dependency is illustrated in the figure 7.

Negate Dependency (N Dependency): The symbol denoting negate dependency is the letter N. Each input or output affected by an Nm input or Nm output stands in an Exclusive OR relationship with this Nm input or Nm output. When Nm input or Nm output stands at its internal 1-state (Asserted), the internal logic state of each input and each output affected by this Nm input or Nm output is the complement of the normally defined internal logic state of the input or output. When Nm input or Nm output stands at its internal 0-state, all inputs and outputs affected by this Nm input or Nm output stand at their normally defined internal logic states. This relationship is illustrated in the figure 8.

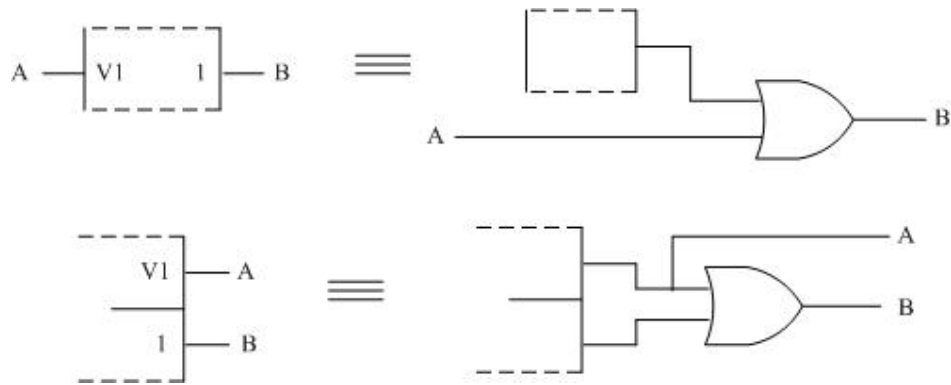


FIG. 7: V (OR) dependency

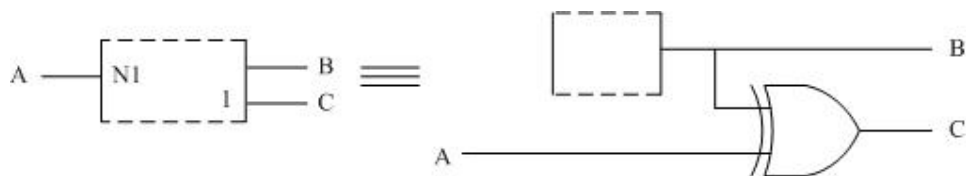


FIG 8: Illustration of N dependency

Interconnection Dependency (Z Dependency): The symbol denoting interconnection dependency is the letter Z. Interconnection dependency is used to indicate the existence of internal logic connections between inputs, outputs, internal inputs, and internal outputs, in any combination. When a Zm input or Zm output stands at its internal 1-state (Asserted), all inputs and outputs affected by this Zm input or Zm output stand at their internal 1-states (Asserted), unless modified by additional dependency notation. When a Zm input or Zm output stands at its internal 0-state Not Asserted, all inputs and outputs affected by this Zm input or Zm output stand at their internal 0 states (Not Asserted), unless modified by additional dependency notation. The nature of Z dependency is illustrated in the figure 9.

Control Dependency (C Dependency): The symbol denoting control dependency is the

letter C. Control dependency should only be used for sequential elements. It implies more than a simple AND relationship. It identifies an input that produces action, for example, the edge-triggered clock of a bistable circuit or the level-operated data enable of a transparent latch. When a Cm input or Cm output stands at its internal 1-state

(Asserted), the inputs affected by this Cm input or Cm output have their normally defined effect on the function of the element. When a Cm input or Cm output stands at its internal 0-state (Not asserted), the inputs affected by Cm are disabled and have no effect on the function of the element. This dependency is explained through examples in the figure 10.

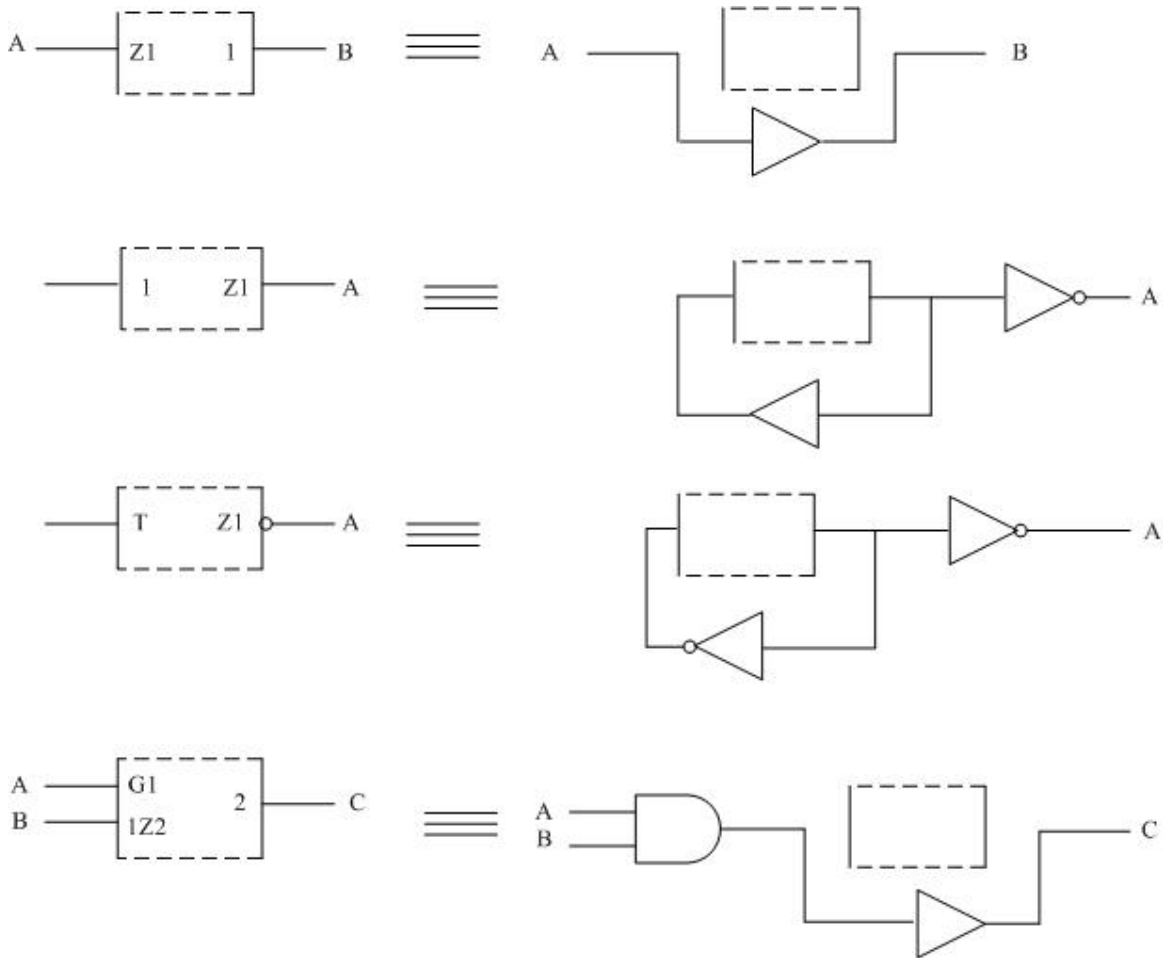


FIG. 9: Illustration of Z dependency

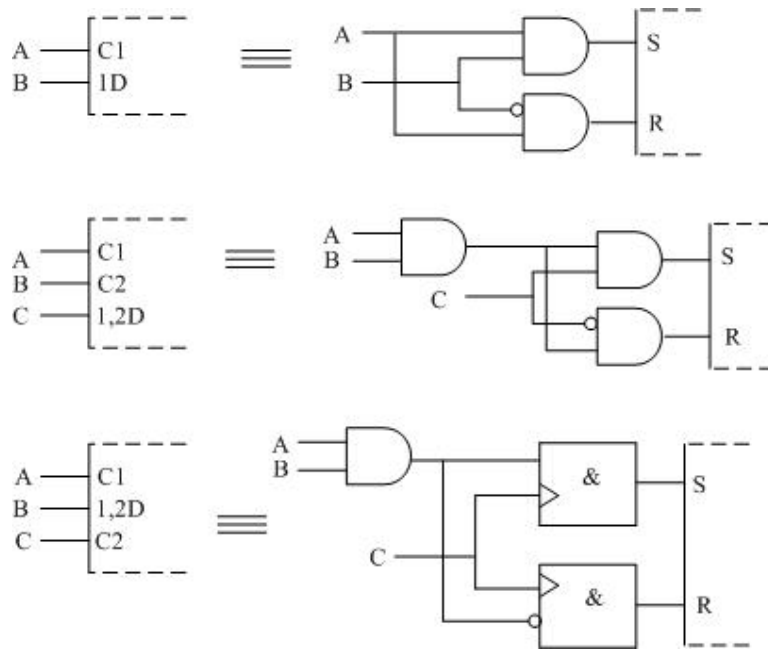


FIG. 10: Illustration of Control dependency

S (Set) and R (Reset) Dependencies: The symbol denoting the set dependency is S and the symbol denoting the reset dependency is R. Set and reset dependencies are used if it is necessary to specify the effect of the combination $R = S = 1$ on a bistable element. These dependencies should not be used if such specification is not necessary. When a S_m input stands at its internal 1-state (Asserted) the outputs affected by this S_m input will take on the internal logic states they normally would take on for the combination $S = 1, R = 0$, regardless of the state of any R input. When an S_m input stands at its internal 0-state (Not asserted) it has no effect.

When an R_m input stands at its internal 1-state (Asserted) the outputs affected by this R_m input will take on the internal logic states they normally would take on for the combination $S = 0, R = 1$ regardless of the state of the S input. When an R_m input stands at its internal 0-state it has no effect. The R and S dependencies are illustrated in the figure 11.

a	b	c	d
0	0	No change	
0	1	0	1
1	0	1	0
1	1	Not specified	

a	b	c	d
0	0	No change	
0	1	0	1
1	0	1	0
1	1	1	0

a	b	c	d
---	---	---	---

0 1 No change

0 1 0 1

1 0 1 0

1 1 0 1

a	b	c	d
0	1	No change	
0	1	0	1
1	0	1	0
1	1	1	1

0 1 0 1

1 0 1 0

1 1 1 1

a	b	c	d
0	1	No change	
0	1	0	1
1	0	1	0
1	1	0	0

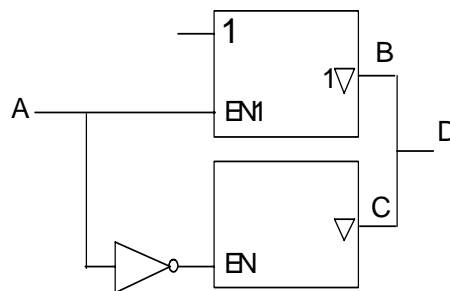
0 1 0 1

1 0 1 0

1 1 0 0

FIG 11: Illustration of R and S dependencies

Enable Dependency (EN Dependency): The symbol denoting enable dependency is EN. Enable dependency is used to indicate an Enable input that does not necessarily affect all outputs of an element. It can also be used when one or more inputs of an element are affected. When this input stands at its internal 1-state (Asserted), all the affected inputs and outputs stand at their normally defined internal logic states and have their normally defined effect on elements or distributed functions that may be connected to the outputs, provided no other inputs or outputs have an overriding and contradicting effect. When this input stands at its internal 0 state (Not Asserted), all the affected open-circuit outputs stand at their external high-impedance states, all 3-state outputs stand at their normally defined internal logic states and at their external high-impedance states, and other types of outputs stand at their internal 0-states. The nature of EN dependency is illustrated in the figure 12.



If A = 0, B disabled and D = C

If A = 1, C disabled and D = B

FIG 12: Illustration of the EN dependency

Mode Dependency (M Dependency): The symbol denoting mode dependency is the letter M. Mode dependency is used to indicate that the effects of particular inputs and

outputs of an element depend on the mode in which the element is operating. When an Mm input or Mm output stands at its internal 1-state (Asserted), the inputs affected by this Mm input or Mm output have their normally defined effect on the function of the element and the outputs affected by this Mm input or Mm output stand at their normally defined internal logic states, that is, the inputs and outputs are enabled. When an Mm input or Mm output stands at its internal 0-state, the inputs affected by this Mm input or Mm output have no effect on the function of the element and at each output affected by this Mm input or Mm output, any set of labels containing the identifying number of that Mm input or output has no effect and is to be ignored. When an affected input has several sets of labels separated by slashes, any set in which the identifying number of Mm input or Mm output appears has no effect and is to be ignored. This represents disabling of some of the functions of a multifunction input. When an output has several different sets of labels separated by slashes, only those sets in which the identifying number of this Mm input or Mm output appears are to be ignored. This represents disabling or selection of some of the function of a multifunction output, or the modification of some of the characteristics or dependent relationships of the output. These concepts are illustrated in the figure 13.

The circuit in the figure 13 has two inputs, B and C, that control which one of four modes (0, 1, 2, or 3) will exist at any time. Inputs D, E and F are D-inputs subject to dynamic control (clocking) by the A input. The numbers 1 and 2 are in the series chosen to indicate the modes of inputs E and F are only enabled in mode 1 (parallel loading) and input D is only enabled in mode 2 (for serial loading). Note that input A has three functions. It is the clock for entering data. In mode 2, it causes right shifting of data, which means a shift away from the control block. In mode 3, it causes the contents of the register to be incremented by one count.

M Dependency affecting Outputs : When an Mm input or Mm output stands at its internal 1 state, the affected outputs stand at their normally defined internal logic states, that is, the outputs are enabled.

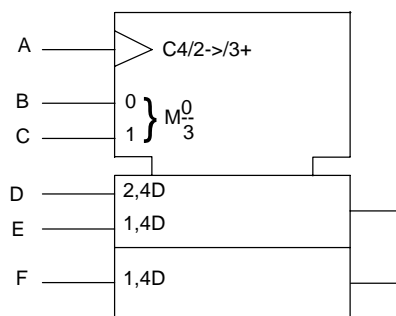


FIG.13: Illustration of M dependency.

When an Mm input or Mm output stands at its internal 0 state, at each affected output any set of labels containing the identifying number of that Mm input or Mm output has no effect and is to be ignored. When an output has several different sets of labels separated by slashes (e.g., C4/->/3+), only those sets in which the identifying number of this Mm input or Mm output appears are to be ignored. In the figure 5.14, mode 1 exists when the A input stands at its internal 1 state. The delayed output symbol is effective only in mode 1 (when input A = 1) in which case the device functions as a pulse-triggered flop-flop (Master-Slave flip-flop). When the input A = 0, the device is not in mode 1 so the delayed output symbol has no effect and the device functions as a transparent latch.

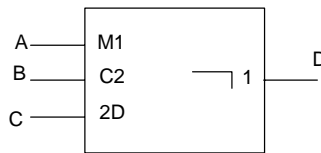


FIG. 14: Type of flip-flop determined by mode

If in figure 15, if the input A stands at its internal 1 state establishing mode 1, output B will stand at its internal 1 state when the content of the register equals 9. Since the output B is located in the common-control block with no defined function outside of mode 1, this output will stand at its internal 0 state when input a stands at its internal 0 state, regardless of the register content.

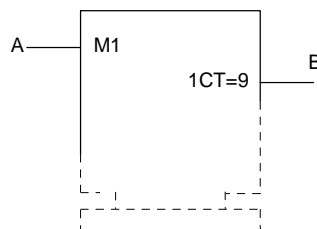


FIG. 15: Disabling an output of the common-control block

Address Dependency (A Dependency): The symbol denoting address dependency is the letter A. Address dependency provides a clear representation of those elements, particularly memories that use address control inputs to select specified sections of a multidimensional array. Address dependency allows a symbolic representation of only a single general case of the sections of the array, rather than requiring a symbolic representation of the entire array. When this input stands at its internal 1-state (ASSERTED), the inputs affected by this input (that is, the inputs of the section of the array selected by this input) have their normally defined effect on the elements of the selected section. Also, the internal logic states of the outputs affected by this input (that is, the outputs of the selected section) have their normal effect on the OR function (or the indicated functions) determining the internal logic states of the outputs of the array.

When the input stands at its internal 0-state (Not asserted), the inputs affected by this input (that is, the inputs of the section selected by this input) have no effect on the elements of this section. Also, the outputs affected by this input (that is, the outputs of the section selected by this input) have no effect on the outputs of the array. An affecting address input is labelled with the letter A followed by an identifying number that corresponds to the address of the particular section of the array selected by this input. The nature of address dependency is illustrated in the figure 16.

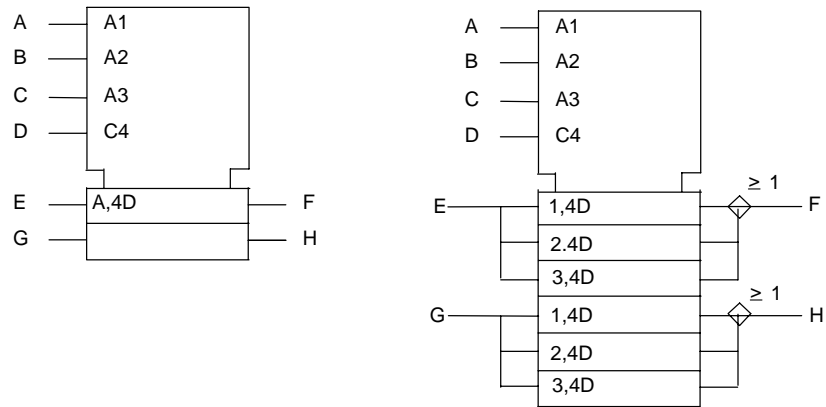


FIG 16: Illustration of address dependency.

Symbols based on the Dependency Notation, of some of the commonly encountered integrated circuits are given in the figure 17. The reader is advised to understand and interpret the function and operation of these integrated circuits using the dependency notation.

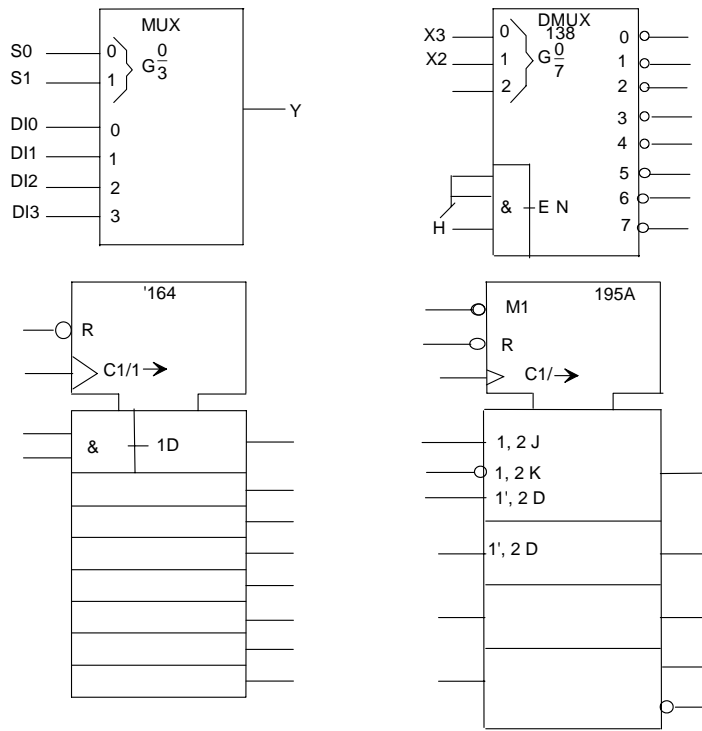


FIG. 17: Symbols of some common integrated circuits.

DRAWING DIGITAL CIRCUIT DIAGRAMS

The gate shown in the figure 18(a) is not commercially available. However, a minor modification will establish this correspondence. This is shown in the figure 18(b). Each one of the gates shown will correspond to the gates that are commercially available.

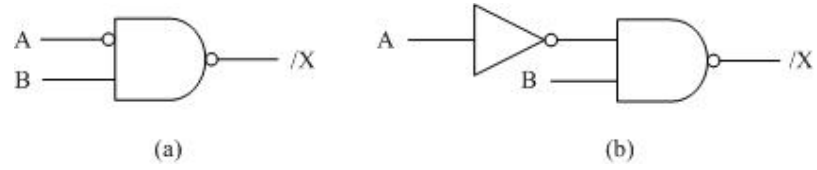


FIG. 18: Redrawing of a logic symbol to correspond to the actual gates used.

Documentation is an important aspect of any design exercise. Any such documentation must be consistent, use standard symbols and follow unambiguous procedures. Many varieties of documents need to be prepared to describe a given digital system exhaustively. It is necessary for any organisation concerned with the design and development and/or manufacturing and marketing of digital systems to evolve and implement a documentation standard for effective communication between individuals concerned with various aspects of the product. The basic rules to be followed in drawing the digital circuit diagrams will be presented in the following.

The basic rules are:

- All signals flow from left to right. In case of any deviation from this convention the direction must be indicated by an arrow. Such a need may arise when there is requirement to feed the output of a circuit module to the input of circuit module which is otherwise upstream from the signal flow point of view.
- External inputs should enter the left hand side of the diagram. Outputs from the circuit should be shown in the right hand side.
- Use polarised mnemonic notation and all the standard symbols thereof.
- Use dependency notation to represent any MSI and LSI circuits.
- All signals should have properly defined mnemonics with their assertion levels indicated.
- All gates represented in the circuit diagram must correspond to the actual hardware elements used. But the choice of operator symbol (NAND, NOR, OR, EXOR ETC.) for gates must be indicative of the function they perform.
- Each operator symbol should be given a number to correspond with the actual IC used. These are designated as U1, U2 etc. A particular number, say U2, may be given to more than one logic operator as an IC may have more than one functional element.
- The pin numbers corresponding to the specific IC used should be shown near the inputs or the outputs of the logic operator, or outside the symbol outline in the case of MSIs and LSIs.
- The specific ICs used along with their pin numbers for V_{CC} and GND (V_{BB}) should be shown at a convenient place on the circuit diagram.
- If the circuit diagram is large and is to be drawn on a large sheet, zonal co-ordinates should be incorporated.
- If a discontinuity is to be introduced in a signal line, its destination or source, if needed in terms of zonal coordinates, should be indicated at the discontinuity.

Consider the circuit diagram shown in the figure19. It is redrawn as per the rules stated above and shown in the figure 20.

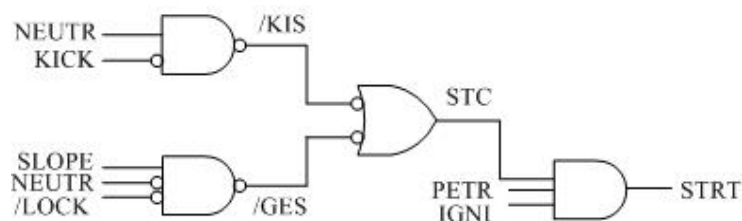


FIG. 19: Example of a combination circuit

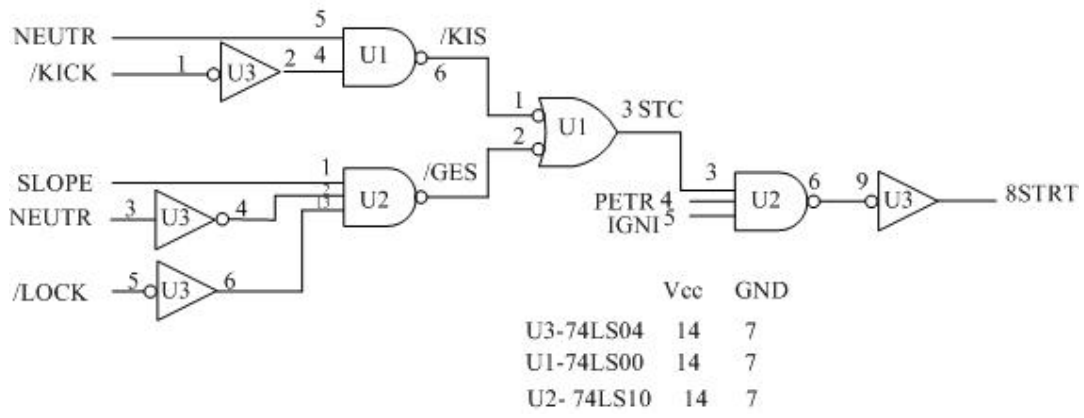


FIG. 20: Circuit diagram of figure 20 redrawn as per the rules of documentation standard