Digital electronics and Logic Gates

Objectives

After going through this lesson, the learners will be able to :

- Identify the gates drawn and write their truth table
- Draw the output waveform for given input waveforms
- Appreciating the fact that NAND and NOR gates are universal gates the basic gates AND, OR and NOT gate can be obtained through suitable combinations of either of these two gates
- Find the output for the given inputs, for all types of gates
- Write the truth table for different combinations of given gates

Content Outline

- Unit Syllabus
- Module Wise Distribution of Unit Syllabus
- Words You Must Know
- Introduction
- Signals and Logic Gates
- OR Gate
- AND Gate
- NOT Gate
- NAND Gate
- NOR Gate

Unit Syllabus

Unit-09: Electronic Devices

Chapter-14: Semiconductor Electronic Material, Devices and Simple Circuits.

Energy bands in conductors, semiconductors and insulators (qualitative only) semiconductors intrinsic and extrinsic

Semiconductor diode -IV characteristics in forward and reverse bias, application of diode as a rectifier

Special purpose p-n diodes LED, photodiode, solar cell and Zener diode and their characteristics, Zener diode as a voltage regulator

Junction transistor, transistor action, characteristics of a transistor and transistor as amplifier common emitter configuration

Basic idea of analog and digital signal, logic gates OR, AND, NOR, NOT, NAND

Keeping the needs of state boards in mind we have not changed the content

Module Wise Distribution Of Unit Syllabus 10 Modules

Module 1	• Energy Bands in Solids • Forbidden Gap • Fermi Level • Energy Bands in Conductors, Semiconductors and Insulators
Module 2	• Uniqueness of Semiconductors • Charge Carriers in Semiconductors Electrons and Holes • Intrinsic Semiconductors • Extrinsic Semiconductors *p* and *n* Type • Why are *p* and *n* Type Semiconductors neutral?
Module 3	• *p-n* junction diode • Potential barrier • Depletion layer • Characteristics of *p-n* junction diode • Forward and reverse bias, knee voltage, magnitude of bias voltages • To draw the IV characteristics curve for a *p-n* junction in forward bias and reverse bias

Module 4	• Application of diode
	• Rectifier meaning and need of such a devise
	• half wave and full wave rectifier
	• rectifier in our homes
	• Special purpose diode
	    ○ LED
	    ○ Photodiode
	    ○ Solar cells

	• Solar panels and future of energy

Module 5	• To identify a diode, an LED, a resistor and a capacitor
	• use a multimeter to
	    ○ See the unidirectional flow of current in case of a diode and an LED
	    ○ Check whether a given diode is in working order

Module 6	• Zener diode • Characteristics of Zener diode • To draw the characteristic curve of a Zener diode and to determine its reverse breakdown voltage • How is a Zener diode different from other diodes? • Zener diode as a voltage regulator • Working of a Zener diode • Zener diodes in our homes

Module 7	• Junction transistor
	• Design of the transistor
	• *n-p-n* and *p-n-p*
	• Use a multimeter to
	    ○ identify base of transistor
	    ○ distinguish between *n-p-n* and *p-n-p* type transistor
	    ○ check whether a given electronic component (e.g. diode , transistor, or IC) is in working order
	• Transistor action
	• Characteristics of a transistor, *n-p-n* common emitter

Module 8	• Understanding transistor characteristics and its applications • To study the characteristics of a common emitter *n-p-n*, *p-n-p* transistor and to find the values of current and voltage gains.

	● Transistor as switch ● Transistor as amplifier
Module 9	● Transistor as an amplifier ● Circuit diagram and understanding bias ● Input and output waveforms ● phase change
Module 10	● Analog signals ● logic gates ● truth tables ○ OR gate ○ AND gate ○ NOT ○ NAND gate ○ NOR gate

Module 10

Words You Must Know

- **Conductors:** These are the materials which conduct electricity easily. They have a very large number of free electrons. conductors: material capable of carrying electric current, i.e. material which has "mobile charge carriers" and are therefore capable of electric current (e.g. electrons, ions) e.g. metals, liquids with ions (water, molten ionic compounds), plasma !
- **Insulators:** These are the materials which do not conduct electricity because they do not have free electrons. Quartz, most covalent and ionic solids, plastics
- **Semiconductors:** These are the materials for which electrical conductivity values less than conductors but more than that of insulators. The conductivities of semiconductors are highly temperature sensitive.
- **Semiconductor Materials:** germanium Ge, silicon Si, GaAs, GaP, InP have useful characteristic properties.
- **Superconductors:** certain materials have zero resistivity at very low temperature, but are quite like normal conductors at room temperature.

- **Energy Level:** As per Bohr's theory electrons revolve around the nucleus only in some specific orbits called stationary orbits. Energy of electrons in these orbits is constant and are termed as energy levels.
- **Energy Bands Theory:** In solid material, electron energy levels 'merge' to form bands of allowed energies. A band is a collection of a large number of close energies. The bands are separated by forbidden bands.
- **Valence Bands:** This band comprises energy of valence electrons.it is the outermost highest filled band with electrons of this band not contributing in conduction of electric current.
- **Conduction Band:** This is a higher band to valence band; it may be empty or partially filled. In metals or good conductors this band is filled.
- **Forbidden Energy Gap (E_g):** It is the minimum energy required to take an electron from valence band to conduction band. Insulators have highest E_g and conductors have least Eg.
- **Intrinsic Semiconductors:** these are pure semiconductors without any impurity. They show very small electrical conductivity at room temperature.
- The gap between the valence band and conduction band is relatively small. These are covalent bonded materials such as Si and Ge the forbidden gap width in Si is 1.1 eV and for Ge it is 0.7 eV
- Electrons moving to conduction band leave "hole" (covalent bond with missing electron) behind; under influence of applied electric field, neighboring electrons can jump into the hole, thus creating a new hole, etc.
- holes can move under the influence of an applied electric field, just like electrons; both contribute to conduction., in pure Si and Ge, there are equally many holes as there are conduction electrons
- **Doping:** It is the deliberate and controlled addition of impurities in intrinsic semiconductors to enhance their electrical conductivity in a controlled manner.
- **Extrinsic Semiconductors** initially pure semiconductor to which an appropriate /designed impurities is added to increase its conductivity are known as extrinsic semiconductors or impurity semiconductors
- **Dopant** two types of dopants used in doping the tetravalent Si or Ge element:
    i. Pentavalent dopants (valency 5); like Arsenic (As), Antimony (Sb), Phosphorous (P), etc.

ii. Trivalent dopants (valency 3); like Indium (In), Boron (B), Aluminium (Al), etc.

- ***p*-type Semiconductors**: These are formed by doping elements like Si and Ge with trivalent atoms. Like B, Al, Ga, In ,such that only 3 of the 4 covalent bonds get filled . A hole or vacancy is created because of the unfilled fourth covalent bond. There are more holes as compared to electrons in p type extrinsic semiconductor.
- ***n*-type Semiconductors**, these are formed by doping elements like Si and Ge with pentavalent atoms.. In this case impurity or dopant having 5 valence electrons like P, As, Sb is added to a sample of initially pure semiconductor.. of these 4 electrons get used by the covalent bond of the surrounding Si or Ge atoms The fifth electron is unpaired or left loosely bound .Hence only a small amount of energy is needed to lift it into the conduction band (0.5 eV for Si)*n* type semiconductors have more conduction electrons and fewer holes. Example; doping fraction of 1 in 10^8 Sb in Si yield about 5×10^{16} conduction electrons per cm^3 at room temperature which is a gain of 5×10^5 conduction electrons over intrinsic Si.
- Advantage of doped semiconductors is we can alter conductivity by choice of doping fraction and choose majority carriers.
- **p-n Junction:** A *p-n* junction is a boundary, or interface, between the two types of semiconductors, (*p*-type and *n*-type), inside a single crystal.
- **Diffusion Current:** Holes diffuse from p-side to *n*-side ($p \rightarrow n$) and electrons diffuse from *n*-side to *p*-side ($n \rightarrow p$). Diffusion means movement due to difference in concentration, from higher to lower concentration;
- **Potential Barrier** initially both the sides were electrically neutral. Now, because of diffusion of electrons and the holes, there are immobilized additional ions on both the sides.
- From the *n* side, electrons have diffused to the *p* side, so there are positive immobile ions on the *n* side, from the *p* side, holes have diffused to the n side, so there are negative immobile ions on the *p* side. These immobile ions near the junction create a potential difference across the junction.
- **Drift Current:** Due to the positive space-charge region on the *n*-side of the junction, and negative space charge region on the p-side of the junction, an electric field, directed from positive charge towards negative charge develops.

Due to this field, an electron on the p-side of the junction moves to the n-side and a hole on the n-side of the junction moves to p-side.

The motion of charge carriers due to the electric field is called drift.

A drift current, which is opposite in direction to the diffusion current, is set up.

- **Forward Bias:** When an external voltage V is applied across a semiconductor diode such that p-side is connected to the positive terminal of the battery and n-side to the negative terminal it is said to be forward biased.
- **Reverse Bias** The positive terminal of the battery is connected to the n-side of the semiconductor and negative terminal is connected to the p-side. This way of connecting a diode with a battery is called Reverse Biasing.
- **Characteristics of a *p-n* Junction Diode**

  When a bias is placed across a conductor, its characteristic curves show the dependence of current on voltage placed across the conductor
- **Knee Voltage** the special value of forward voltage beyond which the current increases with increase in the voltage is known as the knee Voltage.
- **Dynamic Resistance of a Junction Diode**
- The I-V characteristics of a p-n junction diode during forward /reverse biasing) is not a straight line. We therefore cannot have a unique (constant) value for the resistance of the diode. We can, however use the basic definition of resistance
- $resistance = \frac{change\ in\ potential\ difference}{corresponding\ change\ in\ current}$
- We can use it to define
- Dynamic resistance of a junction diode (for a particular value of the applied /current flowing) is defined as the ratio of small change in the applied potential across the diode to the corresponding small change in the junction current.
- $dynamic\ resistance = \frac{\Delta V}{\Delta I}$
- **Rectifier** is a device which converts an alternating current (AC) into a direct current (DC).
- **Filter Circuit:** The ripples in the DC can be reduced by allowing the output to pass through a **filter circuit.**
- **Photodiodes** used for detecting optical signals (photo detectors).
- **Light Emitting Diodes (LED)** which convert electrical energy into light.
- **Photovoltaic Devices** which convert optical radiation into electricity (solar cells)

- **Transistors -Bipolar Transistor** combination of two diodes that share the middle portion, called "base" of transistor; other two sections: "emitter" and "collector"; usually, base is very thin and lightly doped. Two kinds of bipolar transistors: *p-n-p* and *n-p-n* transistors
- **Transistor Action *p-n-p* Transistor:** If emitter-base junction is forward biased, "holes flow" from battery into emitter, move into base, some holes annihilated with electrons in *n*-type base, but because base thin and lightly doped, most holes make it through base into collector, holes move through collector into negative terminal of battery; i.e. "collector current" flows whose size depends on how many holes have been captured by electrons in the base. This depends on the number of *n*-type carriers in the base which can be controlled by the size of the base current, which is allowed to flow from the base to the emitter. The base current is usually very small. Small changes in base current can cause big differences in collector current.

  Since due to chosen biasing the emitter base junction has lower resistance as compared to base collector hence resistance increases so it is called transistor or transfer of resistance.
- **Common Emitter *n-p-n* Input Characteristics of a Transistor:** The variation of the base current I_B with the base-emitter voltage V_{BE} is called the input characteristic
- **Input Resistance:** This is dynamic (ac resistance) and as can be seen from the input characteristic, its value varies with the operating current in the transistor

$$r_i = \left(\frac{\Delta V_{BE}}{\Delta I_B}\right)_{V_{CE}}$$

  The value of r_i can be anything from a few hundreds to a few thousand ohms.
- **Output Characteristics of a Transistor:** The variation of the collector current I_C with the collector-emitter voltage V_{CE} is called the output characteristic
- **Output Resistance (r_o):** This is defined as the ratio of change in collector-emitter voltage (ΔV_{CE}) to the change in collector current (ΔI_C) at a constant base current I_B.

$$r_o = \left(\frac{\Delta V_{CE}}{\Delta I_C}\right)_{I_B}$$

- **Current Amplification Factor (β):** This is defined as the ratio of the change in collector current to the change in base current at a constant collector-emitter voltage (V_{CE}) when the transistor is in active state.

$$\beta_{ac} = \left(\frac{\Delta I_C}{\Delta I_B}\right)_{V_{CE}}$$

This is also known as small signal current gain and its value is very large.

If we simply find the ratio of I_C and I_B we get what is called β_{dc} of the transistor.

Hence

$$\beta_{dc} = \frac{I_C}{I_B}$$

Since I_C increases with I_B almost linearly and $I_C = 0$ when $I_B = 0$, the values of both β_{dc} and β_{ac} are nearly equal.

So, for most calculations β_{dc} can be used. Both βac and β_{dc} vary with V_{CE} and I_B (or I_C) slightly

- **Transfer Characteristics of a Transistor:** Plot transfer characteristics to show the variation of output voltage with input voltage called transfer as voltage is transferred from input to output.
- **Cutoff Region:** In the case of Si transistors, as long as input V_i is less than 0.6 V, the transistor will be in a cut off state and current I_C will be zero.
  Hence $V_o = V_{CC}$
- **Saturation State:** With increase of V_i, I_C increases almost linearly and so V_o decreases linearly till its value becomes less than about 1.0 V.
  Beyond this, the change becomes non-linear and the transistor goes into saturation state. With further increase in V_i the output voltage is found to decrease further towards zero though it may never become zero.
- **Active Region:** When V_i becomes greater than 0.6 V the transistor is in active state with some current I_C in the output path and the output V_o decreases
- **Switch and Amplifier:** When the transistor is used in the cut off or saturation state it acts as a switch. On the other hand, to use the transistor as an amplifier, it has to operate in the active region.
- **Analogue Signal:** It is the signal in which the current or the voltage varies continuously with time
- **Series Grouping of Resistors:** In series grouping of resistors the current through each resistor is the same.
- **Parallel Grouping of Resistors:** In Parallel grouping of resistors the potential difference across each resistor is the same and the current gets divided.

- **Binary Number System**: Binary number system uses only two digits that are 0 and 1.

Introduction

In this unit, we studied amplifiers and other electronic circuits which made use of analogue signals.

What is meant by analog /analogue?

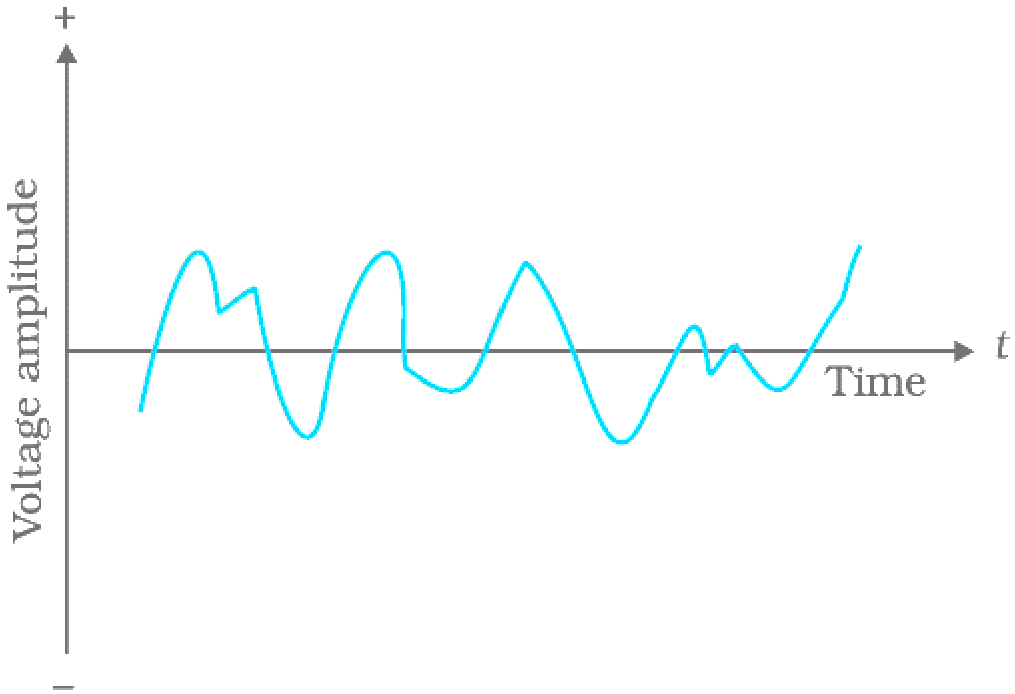
Analog, Also spelled analogue, describes a device or system that represents changing values as continuously variable physical quantities.

A typical analog device is a clock in which the hands move continuously around the face. Such a clock can indicate every possible time of day.

In contrast, a digital clock can represent only a finite number of times (every tenth of a second, for example).

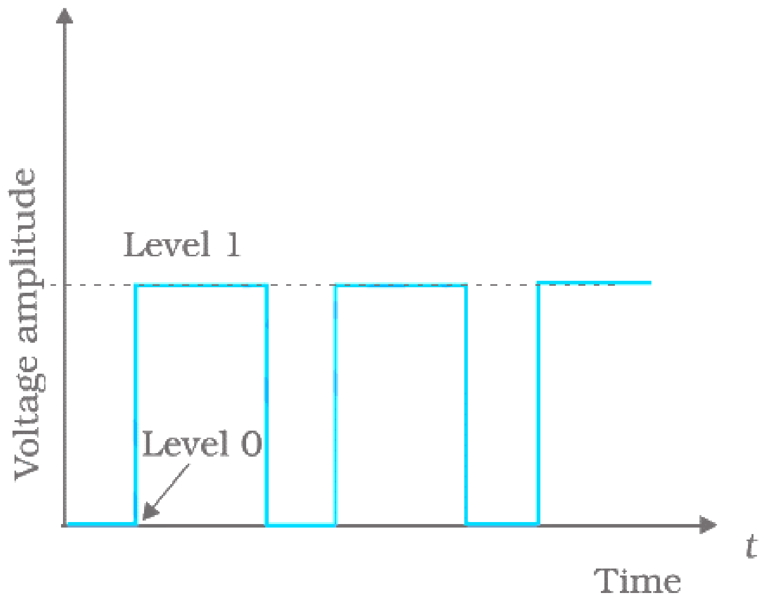
In these circuits the **voltage or currents varies continuously with time**.

A typical analog signal is shown in the figure (a) below.



(a)

The figure b shows a pulse waveform in which only discrete values of voltage are possible.



(b)

Here the voltage is either low (0) or maximum i.e. high. Here only two values of the voltage are possible.It is convenient to use binary numbers to represent these signals.

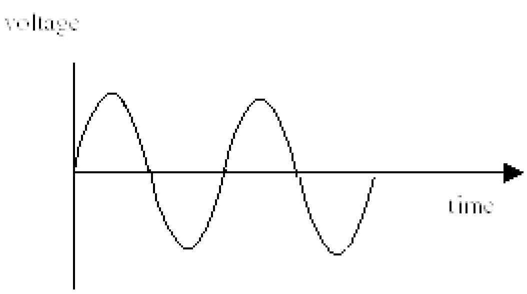
In digital electronics we use only these two levels of voltages i.e. high (1) or low (0).

So in digital circuits only two values (represented by 0 or 1) of the input and output voltage are permissible.

In this module we will study about some basic building blocks of digital electronics, called **Logic gates.**

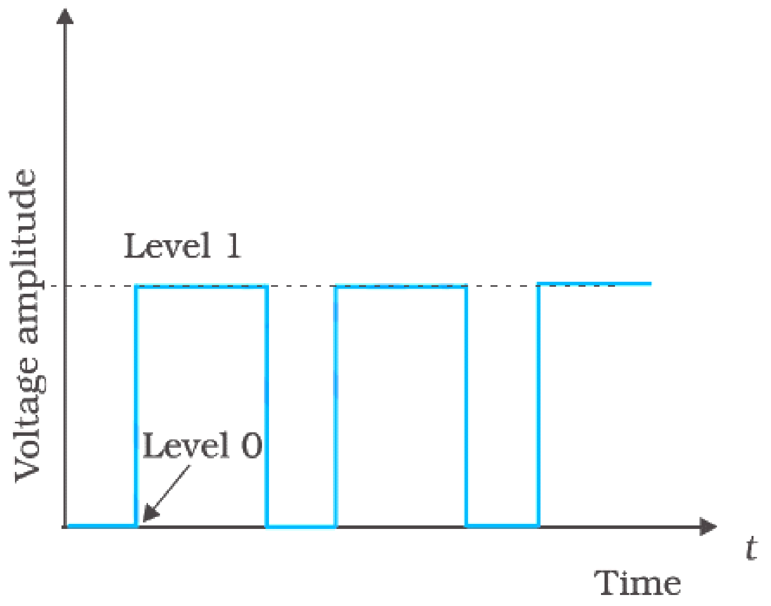
Signals and Logic Gates

In an analogue signal the current or the voltage changes continuously with time



Digital Signal:

- A signal, in which current (or voltage) can take only two discrete values, is called a digital signal.
- A digital signal takes only two values, the maximum and the minimum.
- The maximum value is represented by 1 and the minimum is represented by 0.
- The digital signals are in the form of pulses of equal level.
- A digital signal is represented by square waves.



Electronic circuits use diodes and transistors to create digital signals by keeping the circuit in on off on off condition periodically

Logic Gates

The logic gates are the building blocks of a digital circuit. Each logic gate follows a certain logical relationship between input and output voltage.

A digital circuit, which either allows a signal to pass through it or stops it, is called a **gate.**

Such gates generally allow the current to pass through them only when a given set of logical conditions are satisfied. They are therefore, referred to as **'logic gates'**

Each logic gate follows its own characteristic logical relationship between its output and input signals.Logic gates can have one or more input signals, but only one output signal.

Basic logic gates are of three types.

1) **OR gate**
2) **AND gate**
3) **NOT gate**

Each gate is represented by a symbol and its function can be described either by an algebraic expression called its (relevant) Boolean expression or by a table called its truth table.

Truth table: It shows all the possible combinations of its input signals and the outputs corresponding to each such combination.

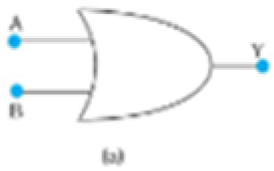
OR Gate

An OR gate has two (or more) inputs and gives one output. We generally use two inputs for an OR gate

In this gate the output is "true/ high" (represented by 1) if either, or both of its two inputs are "true/ high".

The output is "false /low", when both inputs are "false /low" (represented by 0)

Symbol

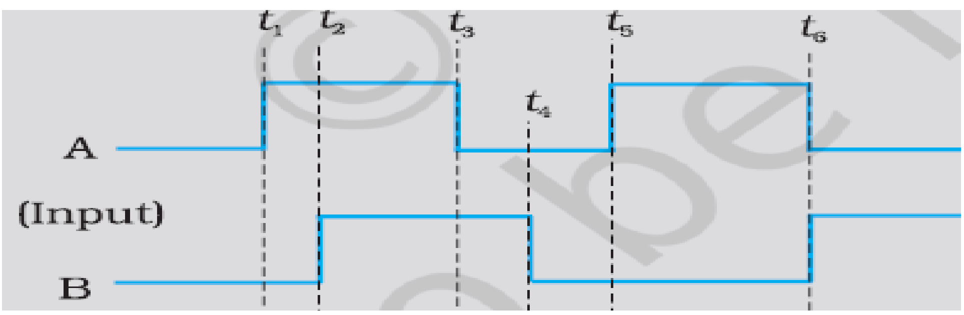


Boolean expression A+ B = Y

Truth table

Input		Output
A	B	Y
0	0	0
0	1	1
1	0	1
1	1	1

Example: Draw the output waveform (Y) of the OR gate for the following inputs A and B given in the figure below

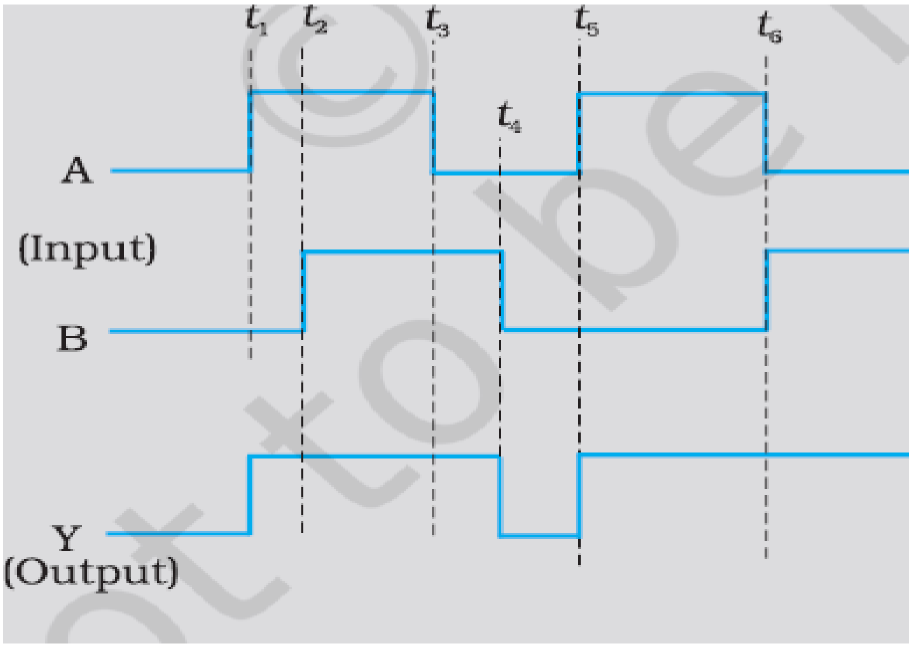


Solution

From the given figure we see that

- At $t < t_1$: A = 0, B = 0 Hence Y = 0
- For t_1 to t_2 A = 1, B = 0 Hence Y = 1
- For t_2 to t_3 A = 1, B = 1 Hence Y = 1
- For t_3 to t_4 A = 0, B = 1 Hence Y = 1
- For t_4 to t_5 A = 0, B = 0 Hence Y = 0
- For t_5 to t_6 A = 1, B = 0 Hence Y = 1
- For $t > t_6$ A = 0, B = 1 Hence Y = 1

Therefore the output waveform (Y) , will be



AND Gate

An **AND** gate has two (or more inputs) and gives one output. We generally use two inputs for an AND gate.

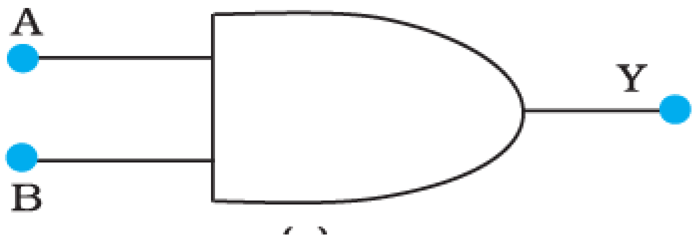
In this gate output is "true/ high", (represented by 1), only when both of its two inputs are "true/ high"

This implies that the output Y of AND gate is 1, only when both its inputs A and B are '1' each.

The output is "false /low", when either, or both, inputs are "false /low" (represented by 0)

Symbol

Symbol of AND gate is



Boolean Expression

Y= A.B (It is read as A and B equals Y)

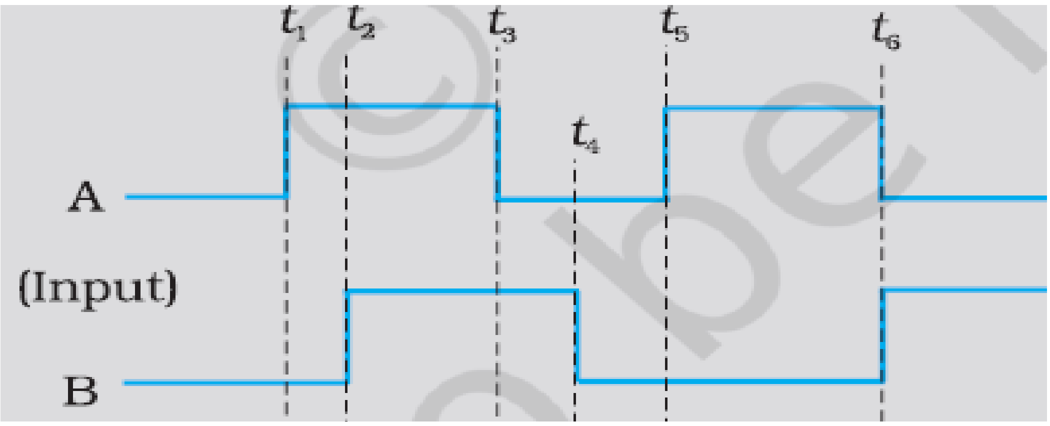
Truth Table

The truth table of an AND gate is

Input		Output
A	B	Y
0	0	0
0	1	0
1	0	0
1	1	1

Example:

Draw the output waveform (Y) of the AND gate for the following inputs A and B given in the figure below.

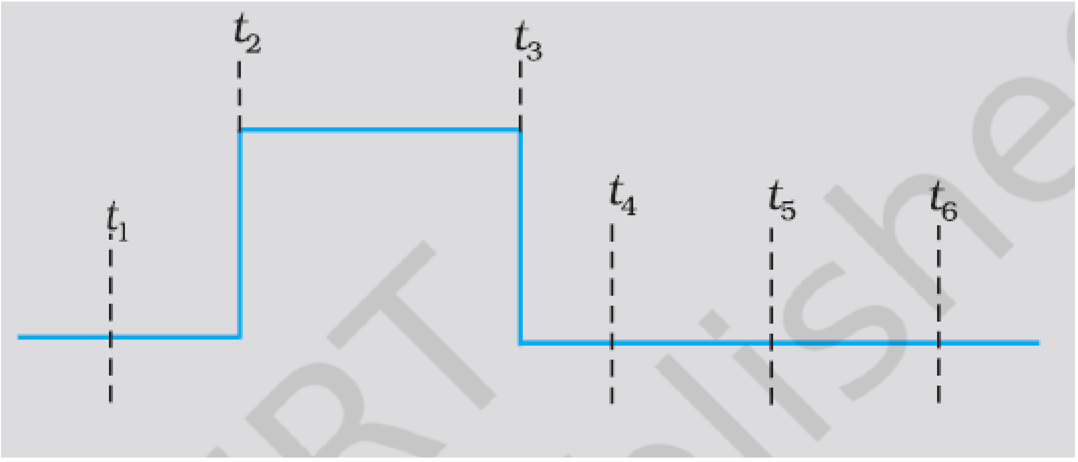


Solution: From the given figure we see that

- At t< t_1 : A = 0, B = 0 Hence Y = 0
- For t_1 to t_2 A = 1, B = 0 Hence Y = 0
- For t_2 to t_3 A = 1, B = 1 Hence Y = 1
- For t_3 to t_4 A = 0, B = 1 Hence Y = 0

- For t_4 to t_5 A = 0, B = 0 Hence Y = 0
- For t_5 to t_6 A = 1, B = 0 Hence Y = 0
- For $t > t_6$ A = 0, B = 1 Hence Y = 0

Therefore the output waveform (Y), will be



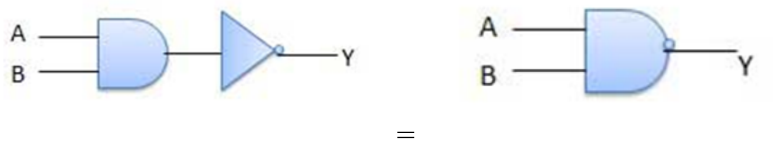
NAND Gate

NAND gate may be viewed as a combination of an AND gate followed by a NOT gate.

NAND gate has two inputs and gives one output.

If inputs A and B are both '1', its output Y is not '0' and not ' 1'.

The gate gets its name from this NOT (AND) behavior.



The gate formed by this combination is called NAND gate. The NAND gate is represented by the symbol

Boolean Expression

$Y = \overline{A.B}$

Truth Table

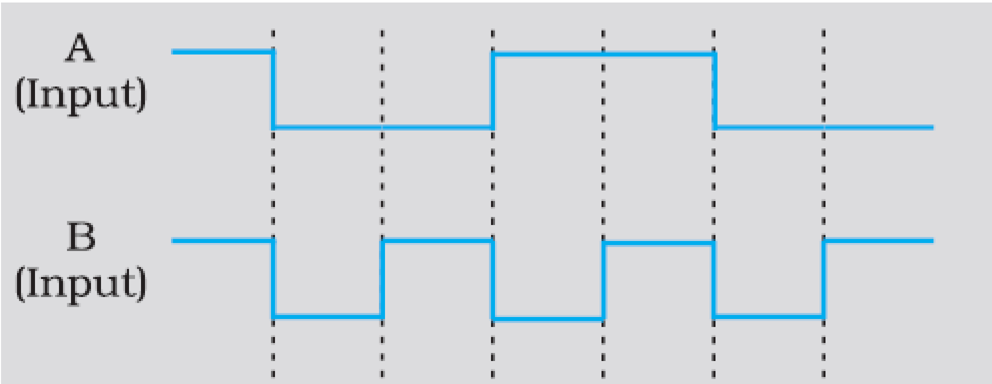
The truth table of the NAND gate is

Input		Output
A	B	Y
0	0	1
0	1	1
1	0	1
1	1	0

The output of a NAND gate is false i.e. '0', only if both of its inputs are true i.e. '1'.

Example:

Sketch the output waveform Y from a NAND gate having inputs A and B given below



Solution:

For $t < t_1$ A = 1, B = 1; Hence Y= 0

For t_1 to t_2; A = 0, B = 0; Hence Y = 1

For t_1 to t_2; A = 0, B = 0; Hence Y = 1

For t_2 to t_3; A = 0, B = 1; Hence Y = 0

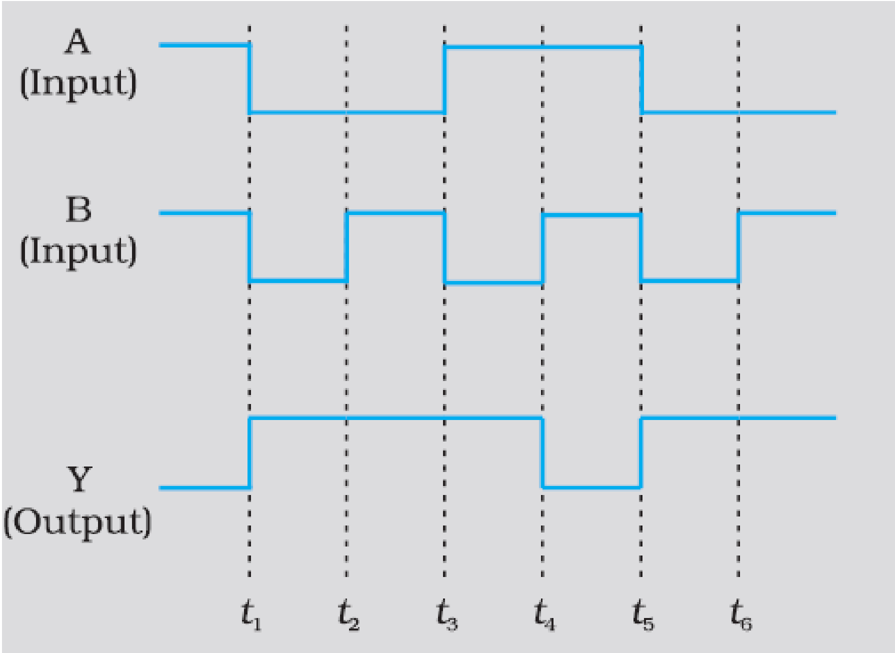
For t_3 to t_4; A = 1, B = 0; Hence Y = 1

For t_4 to t_5; A = 1, B = 1; Hence Y = 0

For t_5 to t_6; A = 0, B = 0; Hence Y = 1

For t_6 to t_7 A = 0, B = 1; Hence Y = 1

The output waveform will be

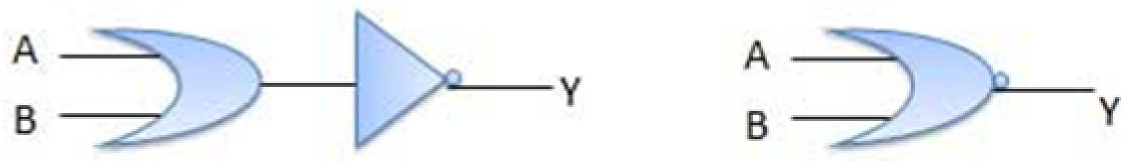


NAND gate is also called a 'universal gate' this is because we can obtain the three basic gates like AND, OR and NOT from an appropriate configuration of NAND gates.

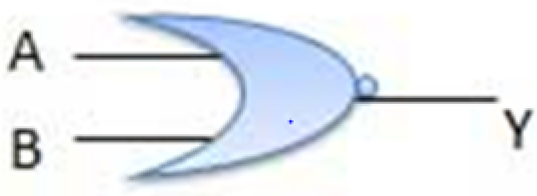
NOR Gate

NOR gate has two inputs and one output.

NOR gate may be viewed as a combination of an OR gate followed by a NOT gate.



Symbol for NOR gate is



Boolean Expression

The Boolean expression for NOR gate is

Y = $\overline{A + B}$

Truth table

Inputs		Output
A	B	$\overline{A+B}$
0	0	1
0	1	0
1	0	0
1	1	0

Note: The output of a NOR gate is ‘true’ i.e. ‘1’, if both its inputs are ‘false’ i.e. ‘0’.

Let us Summarize the main feature of these gates:-

- **AND- true only if A and B both are true**
- **OR- true if either or B or both are true**
- **NOT- Inverts value ‘true’ if input is ‘false,’ ;’false’ if input is ‘true’**
- **NAND-(AND followed by NOT) : ‘False’ only if A and B are both ‘true’**
- **NOR-(OR followed by NOT):’True’ only if A and B are both ‘false’**

Example:

Write the truth table for the gate shown below

Solution:

The given symbol neither corresponds to NOR gate .In this gate the inputs have been shorted, i.e. in this case both the inputs are simultaneously either 1 or 0.

The truth table of the given gate is

A	B	A+B	Y= $\overline{A + B}$
0	0	0	1
1	1	1	0

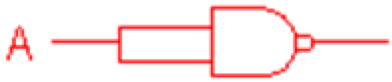
Here we see that if the input is 1, the output is zero, and if the input is 0, the output is 1.

This is the truth table of a NOT gate

It follows that a NOT gate can be obtained by 'shorting' the two inputs of a NOR gate.

Example:

Write the truth table for the gate shown below



Solution:

The given symbol corresponds to a NAND gate. In this gate the inputs have been shorted, i.e. in this case both the inputs are simultaneously either 1 or 0.

The truth table of the given gate is

A	B	A. B	Y= A. B
0	0	0	1
1	1	1	0

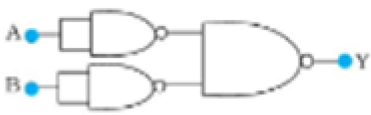
Here we see that if the input is 1, the output is zero, and if the input is 0, the output is 1.

This is the truth table of a NOT gate

It follows that a NOT gate can be obtained by shorting the two inputs of a NAND gate.

Example:

Identify the logic operation carried out by the gate shown below



Solution:

Let us write the truth table of the gates given in the figure

The signal A is effectively being fed to a NOT gate, so its output is $\overline{A}$ (NOT A).

The signal B is effectively being fed to a NOT gate, so its output is $\overline{B}$ (NOT B).

The signals NOT A and NOT B are the inputs fed to the NAND gate, the truth table is

A	B	$\overline{A}$	$\overline{B}$	$Y' = \overline{A}.\overline{B}$	Y= $\overline{Y'}$
0	0	1	1	1	0

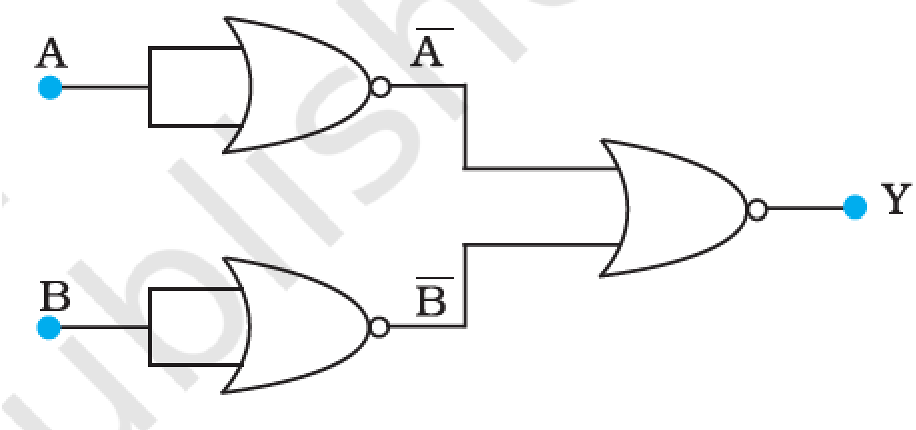
1	1	0	0	0	1
0	1	1	0	0	1
1	0	0	1	0	1

We see that the output is 0 only when both the inputs (A and B) are 0 each. This happens in the case of an OR gate.

The given combination of gates will therefore work as an OR gate.

Example:

Identify the logic operation carried out by the gate shown below



Solution:

Let us write the truth table for each of the given gates. We notice that the inputs for the third gate (a NOR) gate are the outputs of $\overline{A}$ and $\overline{B}$, if the first two gates which are effectively working as NOT gate

A	B	$\overline{A}$	$\overline{B}$	$Y' = \overline{A} + \overline{B}$	Y= Y'
0	0	1	1	1	0
1	1	0	0	0	1
0	1	1	0	1	0
1	0	0	1	1	0

We see that the output is 1 only when both the inputs A or B are 1 each. Hence this combination of gates will operate as an AND gate.