محاضرات في مقدمة الدوائر الالكترونية

الفرقة : الثالثة كلية العلوم (الترم الاول - لائحة جديدة)

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القائم بالتدريس
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IDENTIFICATION OF BASIC ELECTRONIC COMPONETS THEIR CHARACTERISTICS & TESTING

1.0.0 INTRODUCTION

An electronic circuit is composed of various types of components. Some of these components are termed as active components because they take part in the transformation of the energy while other components, which only dissipate or store energy, are called as passive elements. The vacuum tubes, rectifier, transistors are some of-the common active while the resistances, which dissipate the power and energy storing elements such as capacitances and inductances are known as passive elements. The transformers may be regarded as a matching device. The success of any electronic circuit depends not only on proper selection of the active elements but on the passive and matching elements too. The proper function, of an active device is decided by the proper values of these passive elements. Hence the selection of these elements such as resistances, inductances, capacitance, and transformers not only require the proper attention, but also decide the proper function of the active devices as well as the circuit as a whole.

Here we shall discuss about some important electronic components and their characteristics, particularly used in Biomedical instruments.

1.1.0 ELECTRONIC COMPONENTS :

These can be classified into

1.1.1 Passive Components : Components like resistance, capacitance inductance, and fall in this class.

1.1.2 Active Components : They can be further classified as
Semiconductor Devices : Semiconductor diode, zener diode, and varactor diode etc. Uni-junction transistor, Bipolar junction transistor (BJT), FET, silicon, Controlled rectifier etc.
Vacuum Tube Devices : Vacuum tube diode, triode, Tetrode, Pentode, Hexode, Heptode etc.
Gas Tube Devices : Gas diodes, Thyratons etc.
Photo Sensitivity Devices : Gas photodiodes, photo multiplier tubes, photodiodes, light emitting diode, photosensitive transistor etc.
Though there are devices, which are specific to particular frequency range and applications like microwave devices etc.

1.1.3 PASSIVE DEVICES:

1.1.4 RESISTANCES: Resistors can be made to control the flow of current, to work as Voltage dividers, to dissipate power and it can shape electrical waves when used in combination of other components. **Basic unit is ohms, (Ω)**

1.1.5 RESISTIVE ELEMENTS:

Metal alloys, carbon and graphite used with binders etc. are the, usual resistive materials. The alloys used as resistance wire usually have higher specific resistances than the base metals and have lower temperature coefficient of resistance. The three most common types of resistance wire used are nickel-copper, nickel. Chromium-aluminum and nickel-chromium. Carbon and graphite are used as the basic resistance materials when they are mixed and heated with proper variety of resin binders. These types of resistances are generally known as composition carbon type’s resistors. The resistive element may be either in the form of a film or a solid slug, which consists of a number of conducting particles held together by resin. In the film type the base materials may be glass, ceramic and plastics.
Resistors can be (i) fixed resistors with two ends, (ii) variable resistor or potentiometers. Resistors are specified by the value of resistance, in ohms maximum power dissipation in watts, and precision in %.
Types: Resistors can be designed in many ways by usage, shape, physical construction tolerances, resistances are of the following three types i.e.

1.1.6 FIXED RESISTORS:

1.1.7 SEMIVARIABLE RESISTORS:

1.1.8 VARIABLE RESISTORS:

The fixed resistances are those whose values cannot be changed. In case of semi variable types of resistances their values can be changed with help of a screwdriver. Semi variable types resistances are known as preset. In case of the variable resistances their values can be changed from zero to maximum with the help of a movable arm.

Types include : Metal oxide, non inductive, carbon composition, carbon film, metal film, deposited film, ceramic, chip fixed, variable, trimmer, carmet, miniature, PC Board SPST combination, wire wound fixed and variable units, dual potentiometers, power resistors, precision, conductive plastic, hybrid and surface mount.

Resistances in series	$R = R_1 + R_2 + R$
Resistances in parallel	$1/R = 1/R_1 + 1/R_2 + 1/R_3 + -$
Voltage drop	$V = I.R$ I is current,
Power dissipation	$P = I^2.R = V^2/R$

1.1.9 RHEOSTATE :

A wire wound pot that can dissipate 5 and more watts is often referred to as a rheostat. The resistance wire is wound on an open ring of ceramic which is covered with vitreous enable, except for the track of the wiper arm. Rheostats are used to control motor speeds, x-ray tube voltages, ovens and many other high power applications.

2.0.0 THERMISTORS:

A Thermistor is non-linear resistance made of semiconductor material that is extremely sensitive to change in temperature. For a small change in body temperature of a Thermistor, there is an appreciable change in its resistance, where as most conductors have a positive temperature coefficient, the thermistor can exhibits a positive or negative temperature coefficient, (NTC). The thermistor is mostly negative temperature coefficient resistances. The resistances of thermistor decreases rapidly for increased temperature.

The thermistor are used in wide variety of applications. They can be used in measurement and control of temperatures, time delay, temperature compensation and liquid level indicators. The thermistor is available in the form of a disk, bead, or bolted assembly packages.

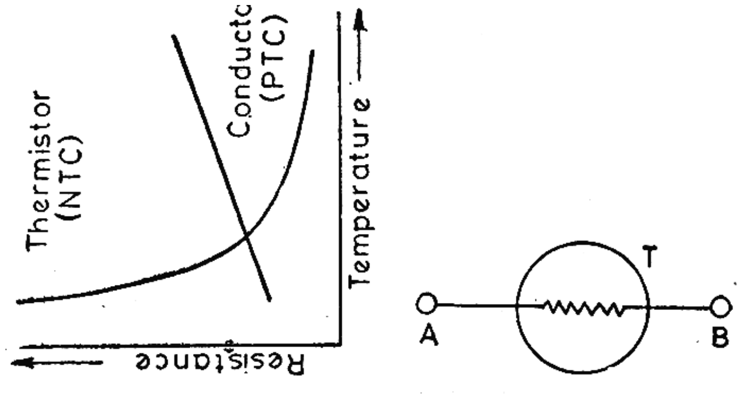


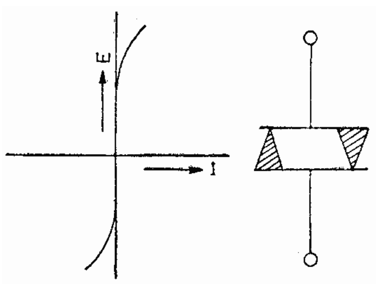
Fig.-1
shows the temperature-resistance characteristics of thermistor.

2.1.0 VARISTORS

These are voltage dependent resistances. They also fall under the category of non-linear resistors. According to the Ohm's Law the current is directly proportional to the impressed voltage but in case of varistors the current is proportional to the nth power of the impressed voltage i.e.

$$I \; \alpha \; Vn$$

where I is the current in Amperes and V is the impressed voltage on the Varistors. Figure-2 shows the V-I characteristics of the Varistors.



(Symbol)

Figure-2
V-I characteristic of varistors

Application of the Varistor include voltage surge and protective circuits and the generation of non-sinusoidal waveform. The varrstors are made out of silicon carbide and is available in:the form of disk, rod or washers.They can withstand and d.c.voltage upto 10 kV or so. . Fig.-3. Show the V-I characteristics of Varistors.

2.2.0 CAPACITORS :

It stores the charge across its two plates. Capacitor opposes the change of voltage across its plates; the electric field developed across the plate opposes the rapid change in voltages. It produces phase difference between voltage applied to it and the current, which passes through it. The current leads the voltage by 90º in the ideal capacitance with infinite resistance across the plates. (Fig. 3)

Design of capacitor is connected with relation of the proper electric material for particular type of application. The dielectric material used for capacitors may be grouped in the various classes. The dielectric coverage for different value of capacitor is shown in fig.-4.

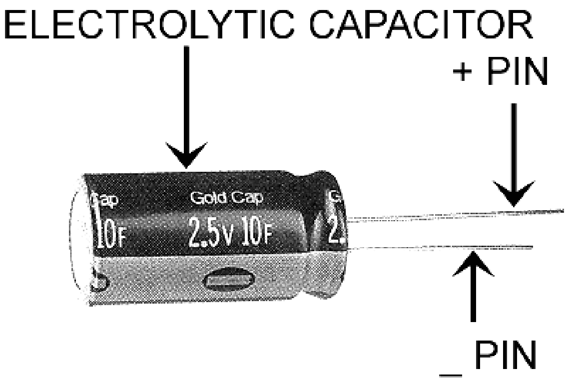


Figure –3

The value of capacitor never remains constant except under certain fixed conditions. It changes with temperature, frequency and ageing. The capacitance value marked on the capacitor strictly applies only at specified room temperature and at low frequencies. The behavior of capacitor at various frequencies may be grouped into the following seven classes.

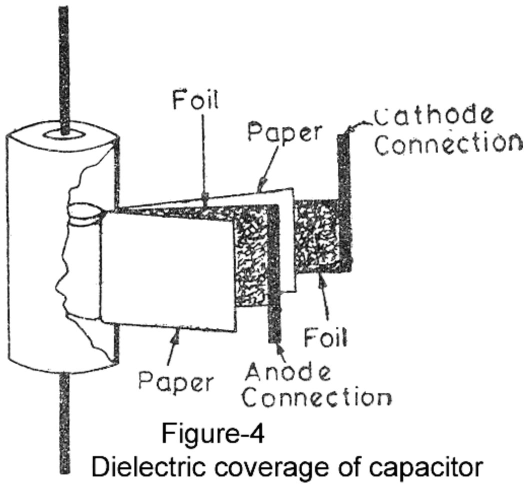


Figure-4
Dielectric coverage of capacitor

Mica, glass, air, and low loss ceramic capacitors are used from few kHz to few hundreds MHz.

Paper and metalized paper capacitor cover the frequency range from few Hz to few hundred kHz.

High dielectric constant ceramic capacitor can only be used between the frequency ranges from few kHz to few, hundred of kHz however, they can find use from very low frequency to 1000 kHz.

Aluminum electrolytic capacitor can find use at power frequency from 10Hz to 1000Hz but can be used up to 10 kHz.

Tantalum electrolytic capacitor may be used from dc to few hundred Hz.
Polyethylene, tere-phthalate (Mylar), cellulose acetate capacitor may find use from few hundred Hz to few MHz.

Polystyrene, polyethylene, poly-tetra-fluoro-ethylene (Teflon) capacitors are used from dc to 1000 MHz range. They are reported to give satisfactory performance even at higher frequencies.

The capacitance units in farads, µ F, pF, nF

Value of the capacitance is given by Its value and the max specify. Voltage which can be safely applied to its

When capacitor is put in parallel the over all capacitance C is

$$C = C_1 + C_2 + C_3 + \text{------}$$

and in series $\frac{1}{C} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3} + \cdots$

2.2.1 VARIABLE: Air variable capacitors are supplied as single or multi gauge type, and trimmers.

2.2.2 VARACTORS:

(voltage variable capacitors)
When a p-n diode is reversed biased the depletion, region becomes devoid of free electrons and holes. Thus in such a situation the depletion layer may be considered to be layer of dielectric while the p and n regions as the plates of capacitors.

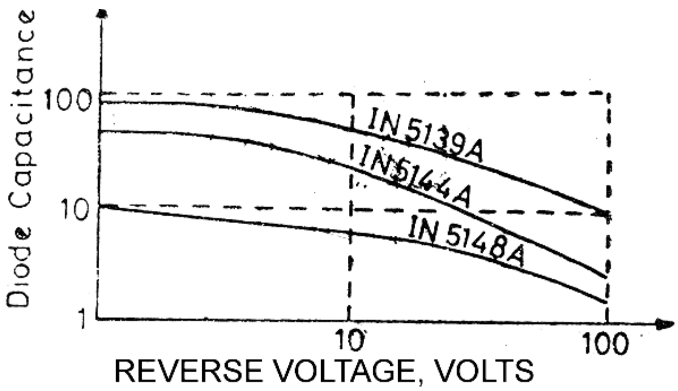


Figure-5

When the reversed biased increased the width of the depletion layer will increase, hence the capacitance will decrease. While with reduction of reverse bias the capacitance will increase as shown in figure-5.

Such types of diodes are also known as voltage variable capacitors or varactors. The symbol of the varactors diodes in shown in Fig.-6.

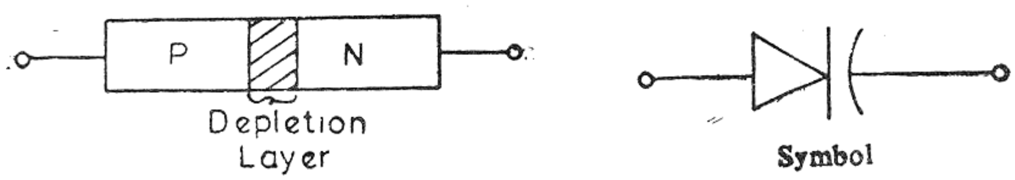


Figure 6
symbol of the varactors

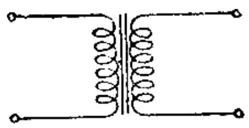
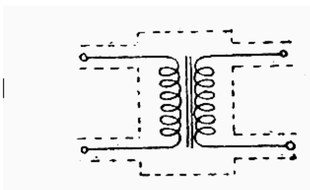
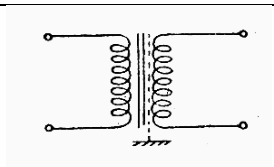
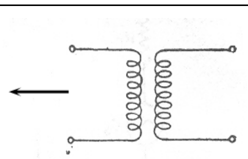
Capacitors are named in a number of ways : after the dielectric they use, or their application or some physical attribute.

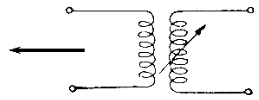
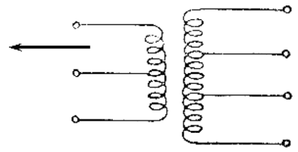
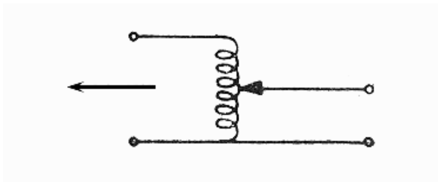
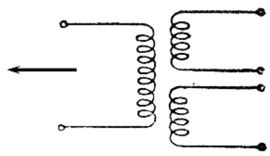
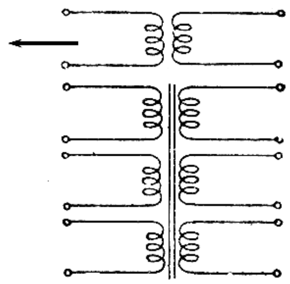
3.0.0 TRANSFORMERS :

The transformers used in electronic circuits may be classified into three classes depending on their application.

Power transformers used with power supplies.
Audio transformers cover the input and output transformers and isolation transformers.
Pulse transformers used in various types of pulse circuits.

Table given below shows various types of symbols of transformers.

S. No.	Type	Symbol
1	Transformer with magnetic core	
2	Shielded, transformer with magnetic core	
3	Magnetic core with a shield between windows	
4	Air corded transformer	

5	One winding transformer with adjustable inductance	
6	Transformer with tapings	
7	Autotransformer	
8	Single phase three winding transformer	
9	Three phase with 1-phase two winding transformer	

4.0.0 INDUCTORS: Like capacitors, inductors also store energy in one part of AC cycle and return it during the next part of the cycle.

Inductance is that property of a device that reacts against a change in current through the device. Inductors are components designed for use in circuits to resist changes in current and thus serve important control functions.

Inductor designed is based on the principle that a varying magnetic field induces a voltage in any conductor in that field. Thus, a practical inductor may simply be a coil wire. The current in each loop of the coil produces a magnetic field that passes through neighboring loops. If the current through the coil is constant the magnetic field is constant and no action takes place. A change in the current, however, produces a change in the magnetic field. The energy absorbed or released from the changing magnetic field reacts against the change in current, and this is exhibited as in induced voltage (electromotive force, emf), which is counter to the change in applied voltage. The inductor thus behaves as an impedance to ac current.

The counter emf is directly proportional to the rate of change of current through the coil (V_L=L[di/dt]). The proportionality constant is the inductance L, which has the unit of henrys (H) In an ac circuit, as shown in, the inductor offers reactance to alternating current. The inductive reactance XL has the units of ohms and is given by

$$X_L = wL = 2\pi fL$$

Total inductance

$$L = L_1 + L_2 + L_3 \text{ -----------}$$

Inductances in parallel :

$$1/L = 1/L_1 + 1/L_2 + 1/L_3$$

5.0.0 SEMICONDUCTORS DEVICES :

It is not easy to define a semiconductor if we want to take into account all its physical characteristics. However, a semiconductor is defined on the basis of electrical conductivity as under A semiconductor is a substance which has resistivity (10^{-4} to 0.5'Ω m) in between conductors and insulators e.g. germanium, silicon, carbon etc. When a semiconductor is neither a good conductor nor an insulator, then why not to classify it as a resistance material? The answer shall be readily available if we study the following table :

Sr. No.	Substance	Nature	Resistivity
1	Copper	Good conductor	1.7×10^{-8} Ω m
2	Germanium	Semiconductor	0.6 ‘Ω m
3	Glass	Insulator	9×10^{11} ' Ω □m
4	Nichrome	resistance material	10^{-4} Ω m

Comparing the resistivity of above materials, it is apparent that the resistivity of germanium (semiconductor) is quite high as compared to copper (conductor) but it is quite low when compared with glass (insulator). This shows that resistivity of a semiconductor lies in between conductor and insulators. However, it will be wrong to consider the semiconductor as a resistance material. For example, nichrome, which is one of the highest resistance material, has resistivity much lower than germanium. This shows that electrically germanium cannot be regarded as conductor or insulator or a resistance material. This gave a such substances like germanium the name of semiconductors.

It is interesting to note that it not the resistivity alone that decide whether a substances semiconductor or not. For example it is just possible to prepare an alloy whose resistivity falls within the range of semiconductors but the alloy cannot be regarded as a semiconductor. In fact, semiconductors have a number of peculiar properties which distinguish them from conductors, insulators and resistance materials.

5.1.0 PROPERTIES OF SEMICONDUCTORS:

The resistivity of semiconductor is less than an insulator but more than a conductor. The semiconductors have negative temperature coefficient of resistance i.e. the resistance of semiconductor decreases with the increase in temperature and vice-versa. For example germanium is actually an insulator at low temperatures but it becomes a good conductor at high temperatures.

When a suitable metallic impurity (e.g. arsenic, gallium etc.) is added to a semiconductor, its current conducting properties change appreciably. This property is most important.

5.1.1 Two type of semiconductor material known as P - type and N - type such as silicon and germanium.

p-type : Impurity Of lower group, it contain excess of holes or deficiency of electrons.
n-type : impurity of higher group, contains excess of electrons or deficiency of holes.

5.2.0 DIODES :
By forming a junction of n & p type material. Barrier potential is formed across the junction due to crossing of holes to n side and crossing of electron to p side.

This property of current flow in only one direction i.e. when the diode is forward biased is used in rectification. Though, theoretically the forward resistance of the diode is zero but practically it is not. The voltage drop in forward direction is v = i rd.

5.2.1 CHARACTERISTICS :

Where Rd is dynamic forward resistance. The junction drop is 0.3V in Germanium. And 0.7V in silicon diode.

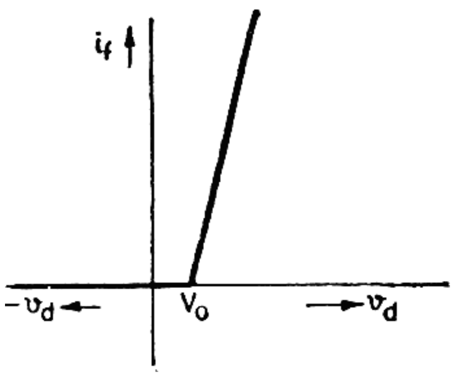


Figure-6
Characteristic of Diode

Diodes are specified by max reverse voltage, and forward voltage and maximum current capacity maximum frequency of operation.
Diodes are used in power supplies, for rectification, and in pulse shaping applications.

5.3.0 ZENER DIODE:

These diodes are operated in reverse bias mode, as the reverse bias is increased the resistance remains constant until a certain value known as avalanche point is reached due to avalanche effect the current suddenly increases and the voltage across it becomes almost constant.

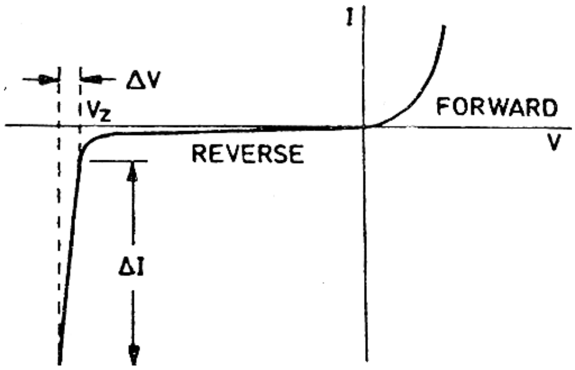


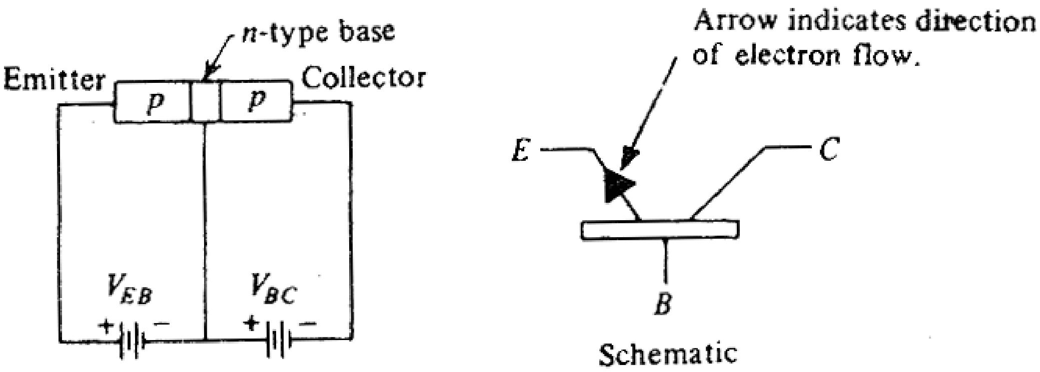
Figure - 7
Characteristic of Zenor Diode

Zener voltage may vary from as little as 3 volt to 150 volts depending on the way the Zener is manufactured used as the voltage regulator.

5.4.0 TRANSISTORS :

Bipolar junction Transistors (BJT) :

It is a three-layer device having two junctions npn and pnp transistors are possible.



(a) (b)

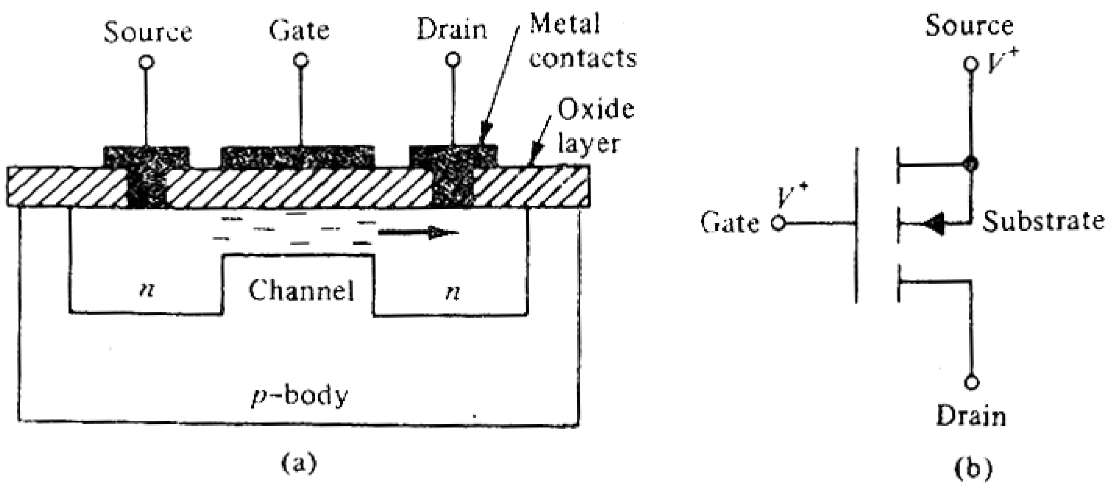


Figure - 8

Base of emitter junction is forward biased. Therefore having low resistance. Base to collector junction is reverse biased offering very high resistance. The order of collector current and emitter current is same but the collector circuit resistance is very high therefore resulting in voltage or power amplification. It works in three configurations

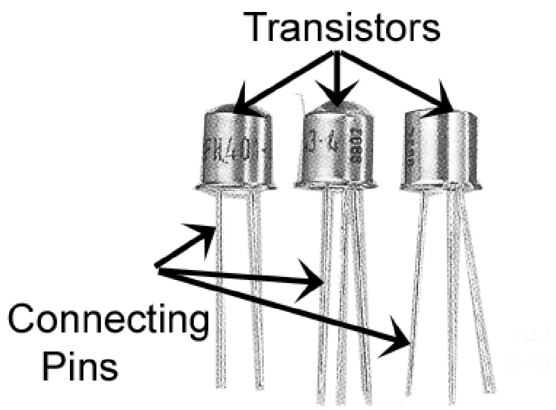


Figure-9

5.5.0 INTEGRATED CIRCUITS (I.C'S)

Transistors may be used as discrete units or as components of a microelectronic circuit. The advent of microelectronics has not affected the functions of the basic components-namely, transistors, resistors, and so on. The major difference is that all these components are available as an electrical functional unit fabricated on a single small IC chip. Many problems of circuit design are solved with the IC, thus simplifying the design, operation, and maintenance of instrumentation.

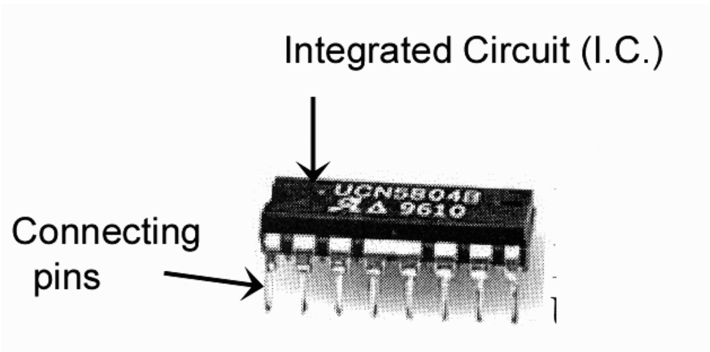


Figure 10
Integrated Circuit

ICs may function in a linear or nonlinear manner. The output of a linear IC is directly proportional to the input. Linear IC applications include many types of amplification, modulation, and voltage regulation. The operational amplifier is the most important type of linear IC. Nonlinear ICs include all digital ICs and other circuits where there is not a linear relationship between the input and output signals. Digital ICs, the most important type of a nonlinear ICs, usually use some form of bi-stable (on/off) operation. These ICs are common in computer circuits and in other digital applications such as counters, calculators, and digital data communication equipment.

ICs must be placed in a protective housing and have connections to the outside world. There are three methods of packaging ICs in containers (figure-11); the TO-5 glass metal can, the ceramic flat pack, and the dual-in-line ceramic or plastic flat packs known as dual-in-line packages (DIPs). The popular, less expensive plastic (DIP packages can have 14,16,18,24 or 40 connecting pins. A minimum of two pins is required for connecting the IC to the power supply. The remaining connections are available for use as terminals for input and output signals.

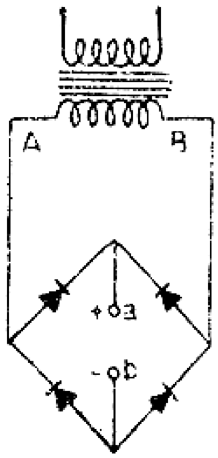


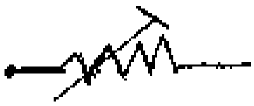
Figure-11 Full Wave Bridge Rectifier

6.0.0 ELECTRONICS COMPONENTS AND SYMBLOS

1. RESISTOR

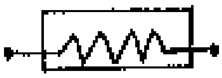
2. VARIABLE RESISTOR (POTENTIOMETER).

3. PRESET.

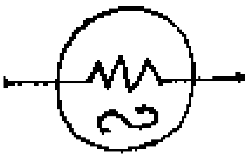


4. NTC RESISTOR (THERMISTOR)

5. PTC RESISTOR (POSISTOR)

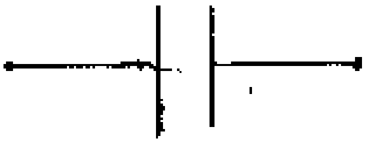


6. FUSIBLE RESISTOR

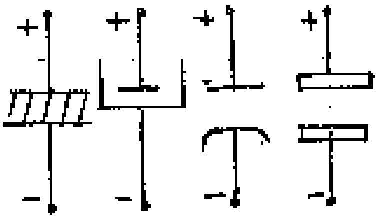


7. LDR (LIGHT DEPENDENT RESISTOR)

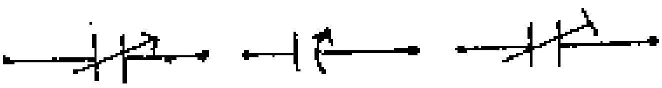
8. CAPACITOR. (NON-ELECTROLYTIC)



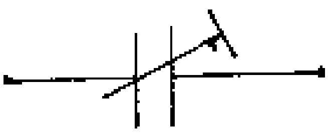
9. ELECTROLYTIC CAPICTOR.



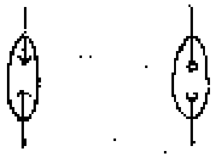
10. VARIABLE CAPACITOR.



11. TRIMMER CAPACITOR.

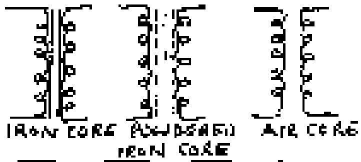


12. SPARK GAP CAPACITOR.

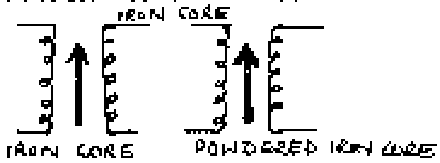


13. FUSE.

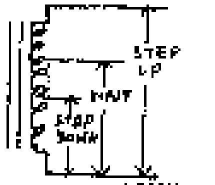
14. TRANSFORMER (ISOLATION.)



15. TUNING COILS

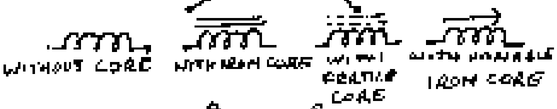


16. AUTO TRAMNSFORMER.

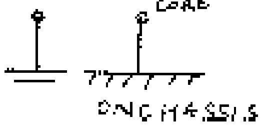


17. DEFLECTION COIL

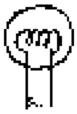
18. INDUCTOR



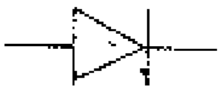
19. EARTH



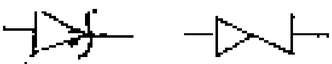
20. BULB.



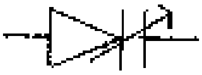
21. DIODE.



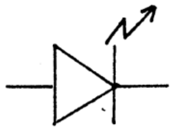
22. ZENER DIODE.



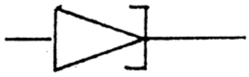
23. VARACTOR DIODE.



24. LED (LIGHT EMITTING DIODE)

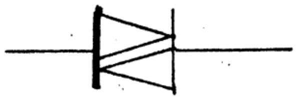


25. TUNNEL DIODE.

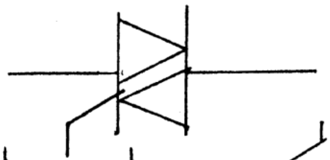


26. SCR (SILICON CONTROLLED RECTIFIER)

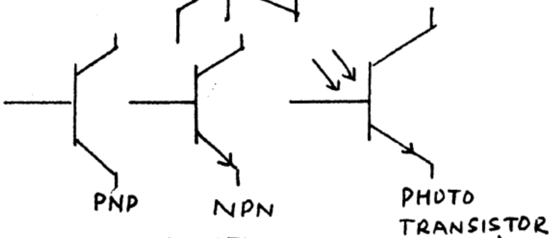
27. DIAC



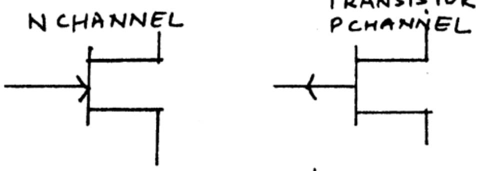
28. TRIAC.



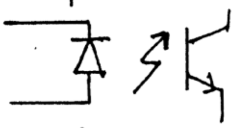
29. TRANSISTOR.



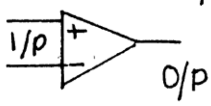
30. FIELD EFFECT TRANSISTOR (FET)



31. OPTGCUOUPLER.



32 .INTEGRATED CUIRCUIT (OP AMP.)

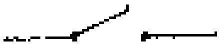


33 .CRT.

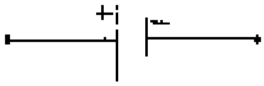
34. SPEAKER.

35. MICROPHONE.

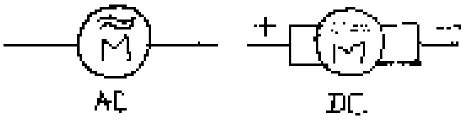
36. SWITCH.



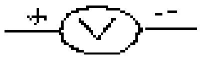
37. BATTERY.



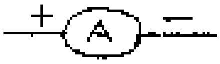
38. MOTOR.



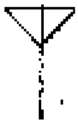
39VOL T METER



40. AMMETER.

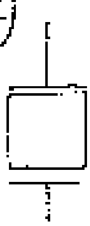


41. AERIAL (ANTENNA)

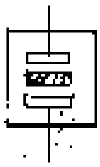


42. NEON LAMP.

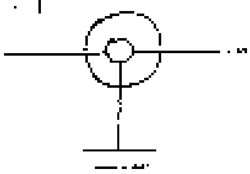
43. PEIZO ELECTRIC CRYSTAL



44. PEIZO BUZZER



45. SHIELDED CONNECTOR.



ON PCB

R - RESISTOR

L- INDUCTANCE

C-CAPACITANCE

D-DIODE

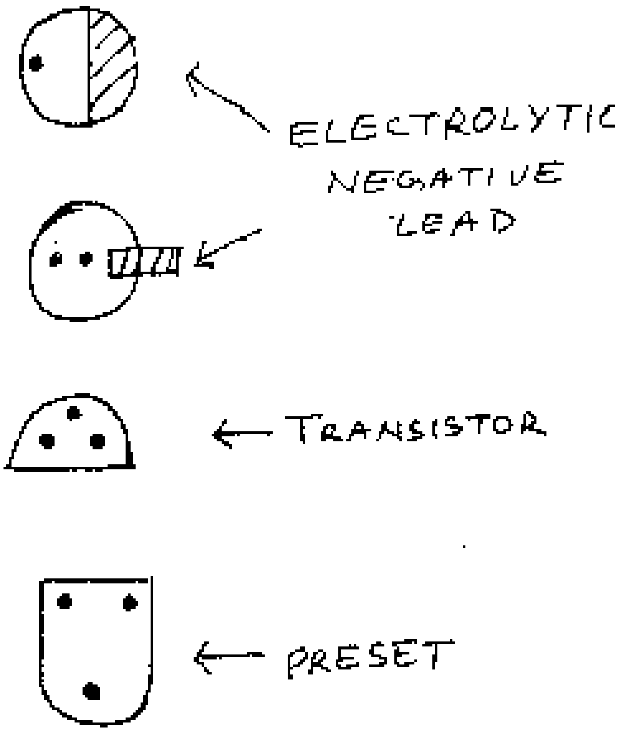
T-TRANSFORMER

F-FUSE

Q-TRANSISTOR

TP-TEST PIONTS

J-JUMBER



8.0.0 Colour code for Resistances

Colour	I Band	II Band	III Band	IV Band
	1st Digit	2nd Digit	Multiplier	Tolerance
Black	0	0	100	
Brown	I	I	10'	1%
Red	2	2	102	2%
Orange	3	3	103	
Yellow	4	4	104	
Green	5	5	10s	
Blue	6	6	106	
Violet	7	7	107	
Grey	8	8	108	
White	9	9	109	
Gold	--	--	10-1	5%
Silver	--	--	10-2	10%
No Colour	--	--	--	20%

***

Chapter 3
Special-Purpose Diodes

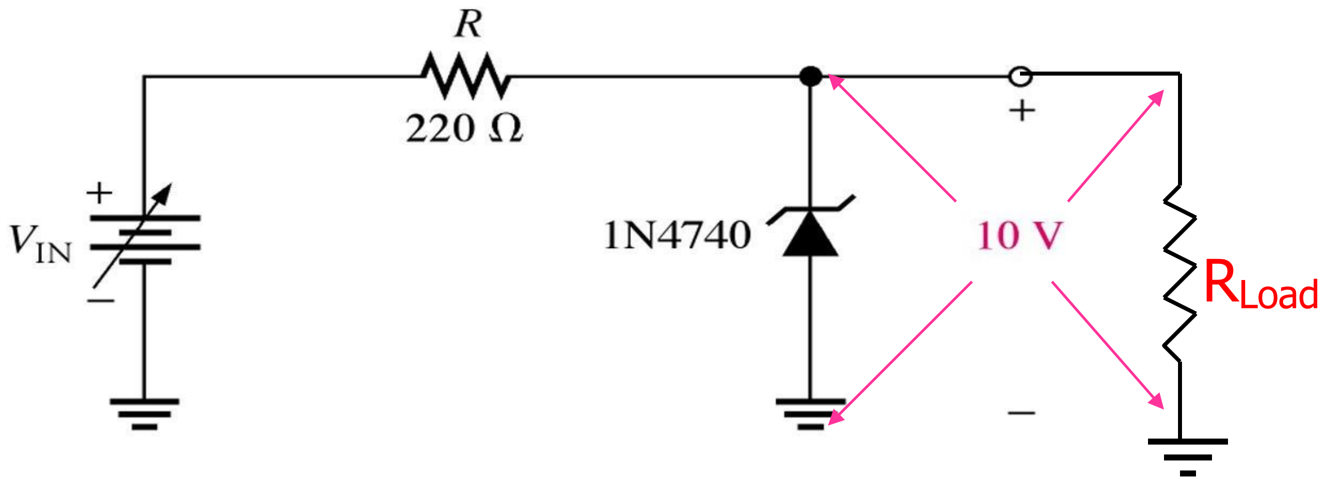
Objectives

- Describe the characteristics of a zener diode and analyze its operation
- Explain how a zener is used in voltage regulation and limiting
- Describe the varactor diode and its variable capacitance characteristics
- Discuss the operation and characteristics of LEDs and photodiodes
- Discuss the basic characteristics of the current regulator diode, the PIN diode, the step-recovery diode, the tunnel diode, and the laser diode.

Introduction

The basic function of **Zener diode** is to maintain a specific voltage across its terminals within given limits of line or load change.

Typically it is used for providing a stable reference voltage for use in power supplies and other equipments.

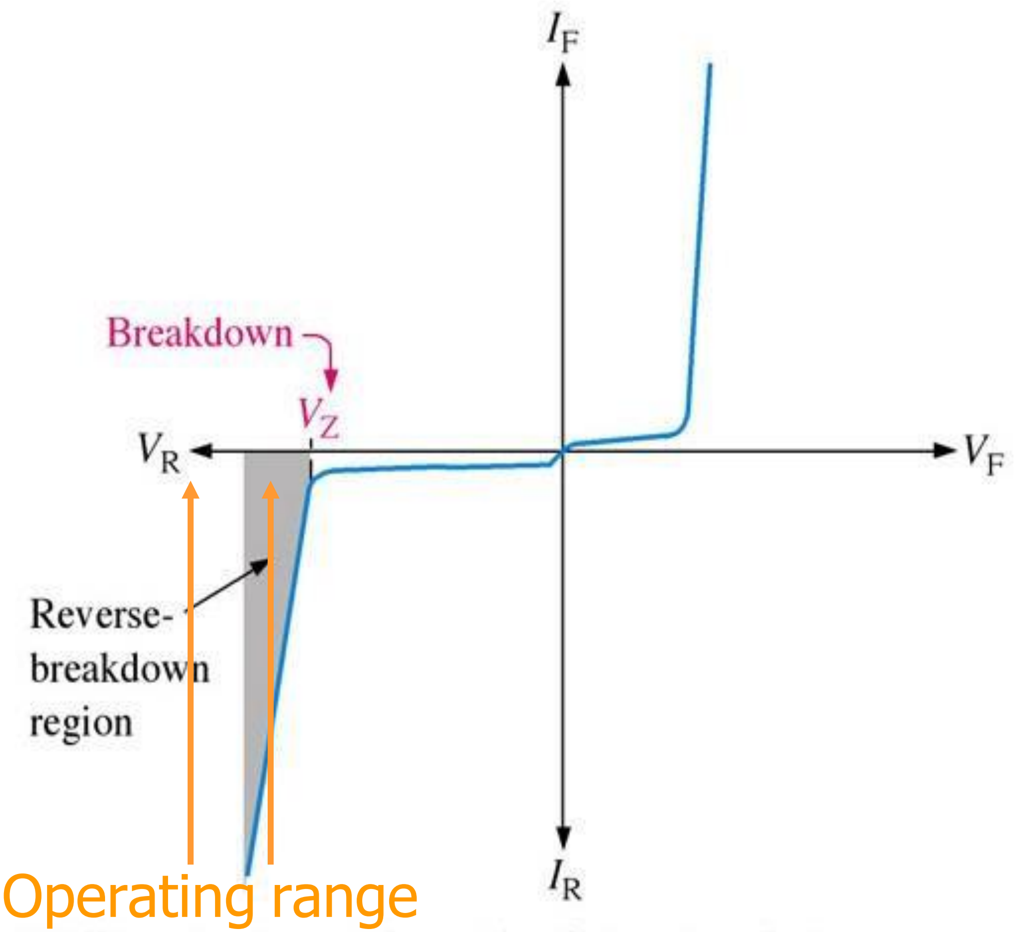


This particular Zener circuit will work to maintain 10volts across the load.

Zener Diode – Operating Range

A **Zener diode** is much like a normal diode (rectifier diode) when connected in forward bias, the exception being is that; it is placed in the circuit in **reverse bias** and **operates in reverse break-down region**.

This typical characteristic curve illustrates the operating range for a Zener diode. Note that its forward characteristics are same like a normal diode.



(b) The normal operating region for a zener diode is shaded.

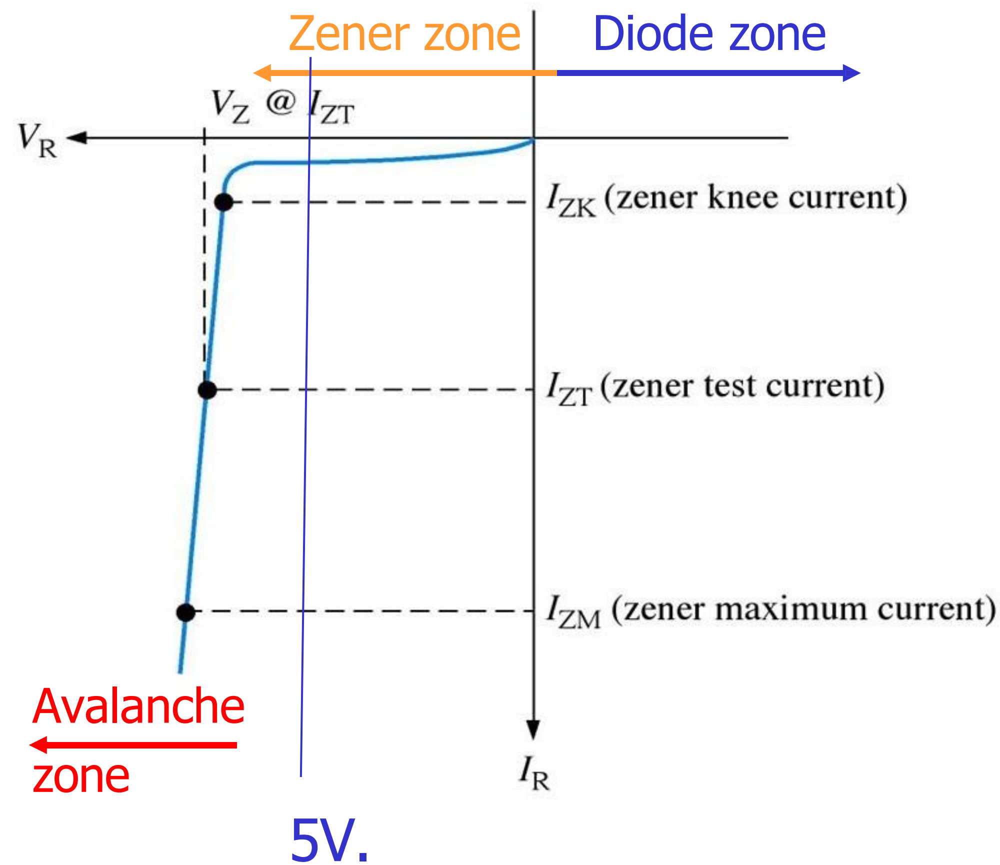
Zener Diodes – Regulation Ranges

The Zener diode's breakdown characteristics are determined by the doping process.

Low voltage Zeners (< 5V), operate in the Zener breakdown range.

Those diodes which are designed to operate (> 5V) operate mostly in avalanche breakdown range.

Zeners are available with voltage breakdowns of ***1.8V to 200V***.



This curve illustrates the minimum and maximum ranges of current operation that the Zener can effectively maintain its voltage.

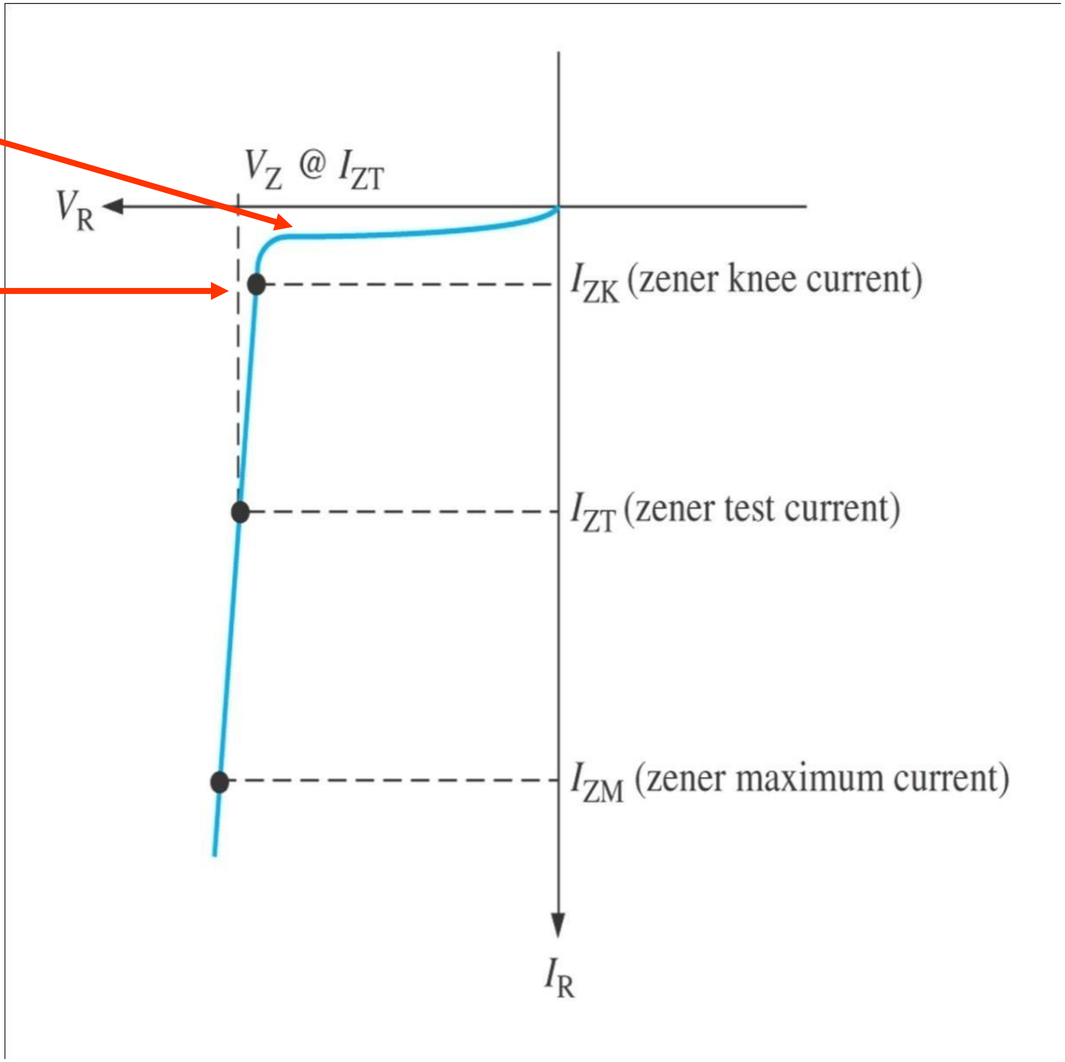
Zener Diode – Breakdown Characteristics

Note very small reverse current (before "knee").

Breakdown occurs @ knee.

Breakdown Characteristics:

- V_Z remains near constant
- V_Z provides:
  - Reference Voltage
  - Voltage Regulation
- I_Z increases rapidly
- I_{ZMAX} is achieved quickly
- Exceeding I_{ZMAX} is fatal



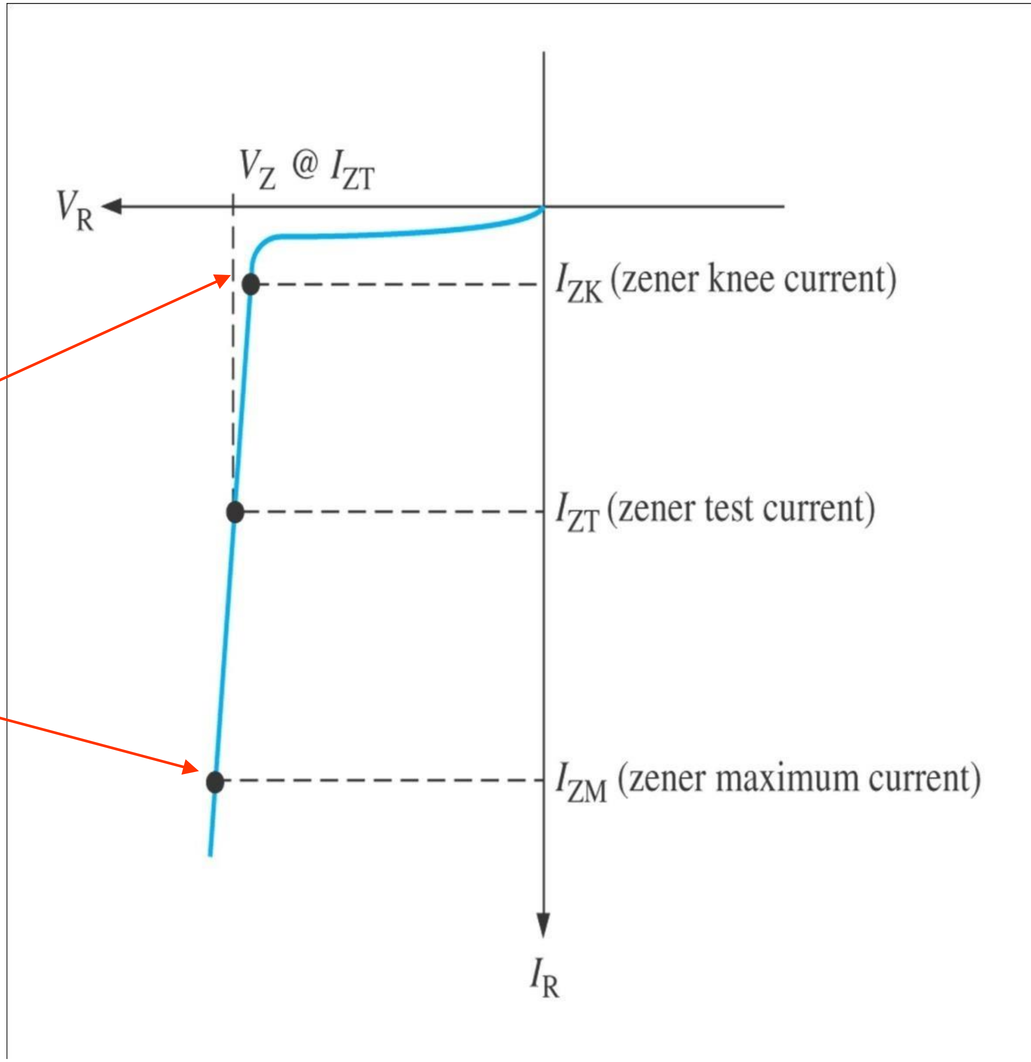
Zener Diodes – Voltage Regulation

Regulation occurs between:

V_{ZK} - knee voltage

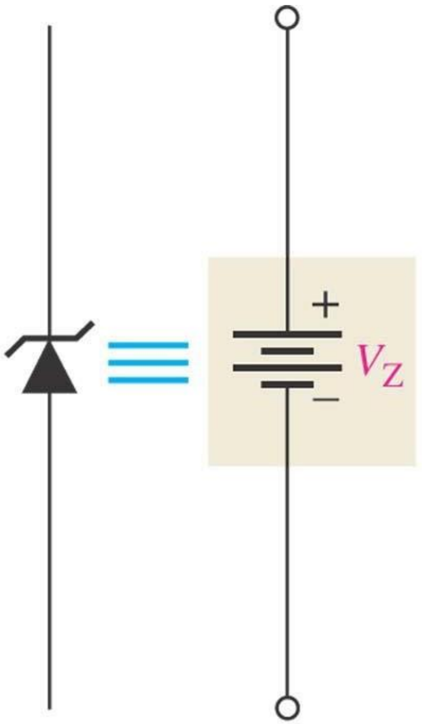
to

V_{ZM} - Imax



Zener Diode – Equivalent Circuit

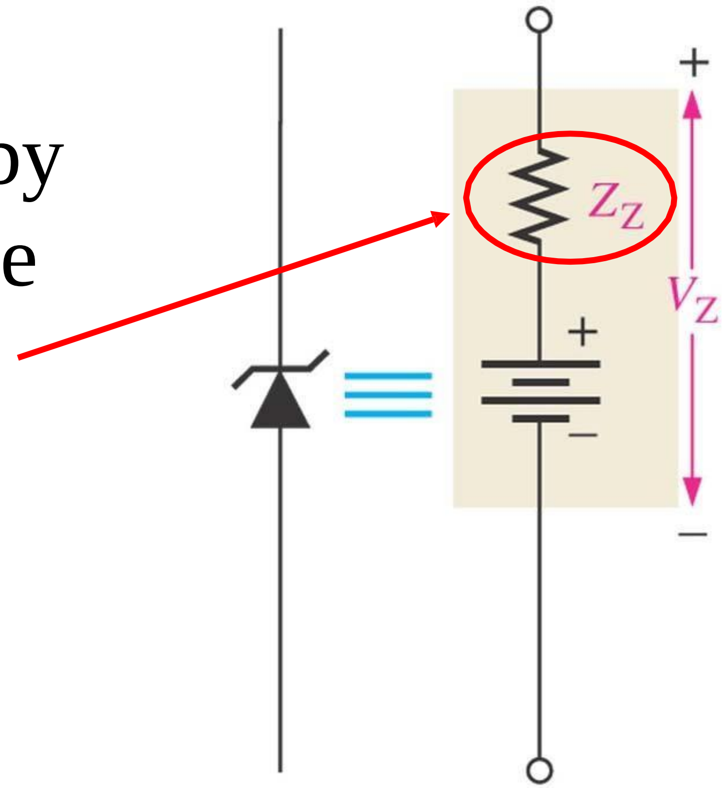
- Ideal Zener exhibits a **constant voltage**, regardless of current draw.
- Ideal Zener exhibits **No Resistance** characteristics.



(a) Ideal

Zener Diode – Equivalent Circuit

- Zener exhibits a near constant voltage, varied by current drawn through the series resistance Z_Z (z_r).
- As I_Z increases, V_Z also increases.

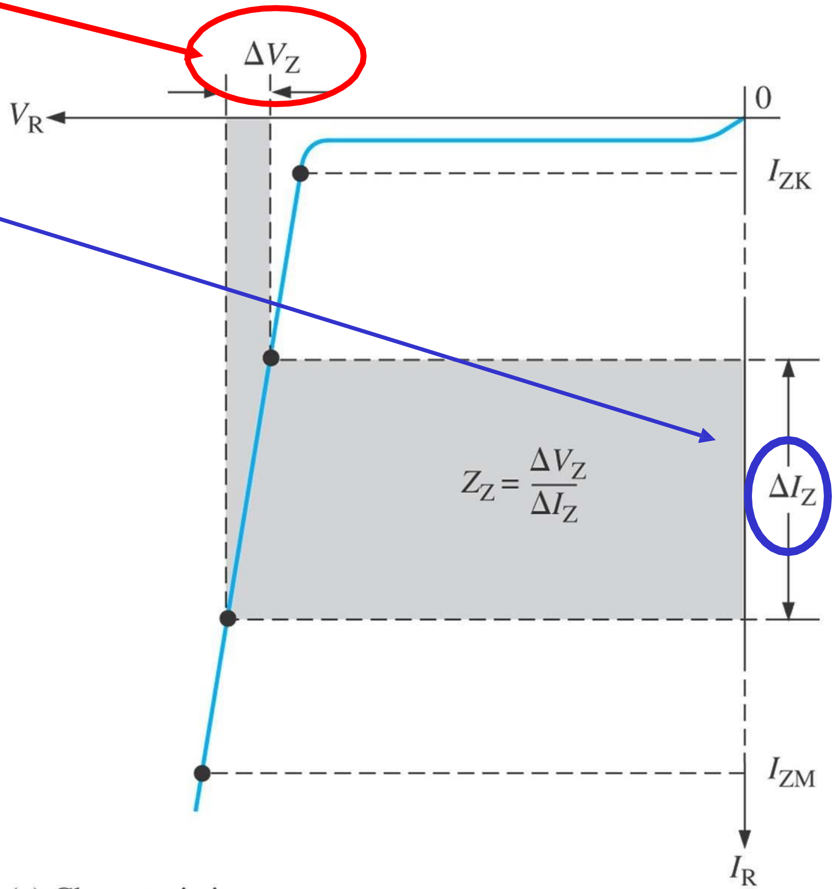


(b) Practical

Zener Diode – Characteristic Curve

- ΔV_Z results from ΔI_Z.
- ΔI_Z thru Z_Z produce this.

See Ex. 3-2



(c) Characteristic curve

Zener Diode

Zener diodes have given characteristics such as;

- Temperature Coefficients – describes the % ΔV_Z for ΔTemp (^{0}C)

  $\Delta V_Z = V_Z \times TC\ \Delta T \rightarrow$ %/^{o}C

  See Ex.3-3 (ΔVz)

- Power Ratings – the Zener incurs power dissipation based on I_Z and Z_Z $\rightarrow$ $P = I_Z^2 \times Z_Z$

  Power de-rating factor specifies the reduced power rating for device operating temperatures in excess of the "rated maximum temperature".

  $P_{D\,(de\text{-}rated)} = P_{D\,(max)} - (mW/^0C)\ \Delta T \rightarrow mW$

The data sheet provides this information. See Ex. 3-4 (%/^{o}C)

Zener Diode – Data Sheet

- Power ratings
- Temperature ratings
- Vz nominal
- Impedance
- Power derating curves
- Temperature coefficients
- ΔZz - Zener impedance

Maximum Ratings

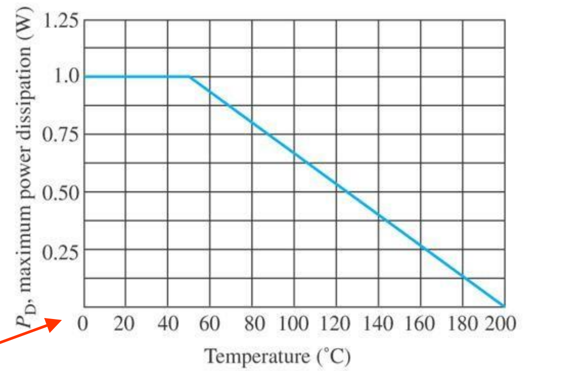
Rating	Symbol	Value	Unit
DC power dissipation @ $T_A = 50°C$ Derate above 50°C	P_D	1.0 6.67	Watt mW/°C
Operating and storage junction Temperature range	T_J, T_{stg}	−65 to +200	°C

Electrical Characteristics ($T_A = 25°C$ unless otherwise noted) $V_F = 1.2$ V max, $I_F = 200$ mA for all types.

JEDEC Type No. (Note 1)	Nominal Zener Voltage V_Z @ I_{ZT} Volts	Test Current I_{ZT} mA	Maximum Zener Impedance			Leakage Current	
			Z_{ZT} @ I_{ZT} Ohms	Z_{ZK} @ I_{ZK} Ohms	I_{ZK} mA	I_R μA Max	V_R Volts
1N4728	3.3	76	10	400	1.0	100	1.0
1N4729	3.6	69	10	400	1.0	100	1.0
1N4730	3.9	64	9.0	400	1.0	50	1.0
1N4731	4.3	58	9.0	400	1.0	10	1.0
1N4732	4.7	53	8.0	500	1.0	10	1.0
1N4733	5.1	49	7.0	550	1.0	10	1.0
1N4734	5.6	45	5.0	600	1.0	10	2.0
1N4735	6.2	41	2.0	700	1.0	10	3.0
1N4736	6.8	37	3.5	700	1.0	10	4.0
1N4737	7.5	34	4.0	700	0.5	10	5.0
1N4738	8.2	31	4.5	700	0.5	10	6.0
1N4739	9.1	28	5.0	700	0.5	10	7.0
1N4740	10	25	7.0	700	0.25	10	7.6
1N4741	11	23	8.0	700	0.25	5.0	8.4
1N4742	12	21	9.0	700	0.25	5.0	9.1
1N4743	13	19	10	700	0.25	5.0	9.9
1N4744	15	17	14	700	0.25	5.0	11.4
1N4745	16	15.5	16	700	0.25	5.0	12.2
1N4746	18	14	20	750	0.25	5.0	13.7
1N4747	20	12.5	22	750	0.25	5.0	15.2
1N4748	22	11.5	23	750	0.25	5.0	16.7
1N4749	24	10.5	25	750	0.25	5.0	18.2
1N4750	27	9.5	35	750	0.25	5.0	20.6
1N4751	30	8.5	40	1000	0.25	5.0	22.8
1N4752	33	7.5	45	1000	0.25	5.0	25.1
1N4753	36	7.0	50	1000	0.25	5.0	27.4
1N4754	39	6.5	60	1000	0.25	5.0	29.7
1N4755	43	6.0	70	1500	0.25	5.0	32.7
1N4756	47	5.5	80	1500	0.25	5.0	35.8
1N4757	51	5.0	95	1500	0.25	5.0	38.8
1N4758	56	4.5	110	2000	0.25	5.0	42.6
1N4759	62	4.0	125	2000	0.25	5.0	47.1
1N4760	68	3.7	150	2000	0.25	5.0	51.7
1N4761	75	3.3	175	2000	0.25	5.0	56.0
1N4762	82	3.0	200	3000	0.25	5.0	62.2
1N4763	91	2.8	250	3000	0.25	5.0	69.2
1N4764	100	2.5	350	3000	0.25	5.0	76.0

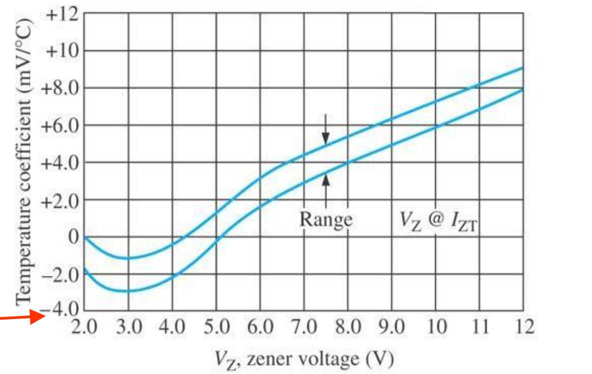
NOTE 1 — Tolerance and Type Number Designation. The JEDEC type numbers listed have a standard tolerance on the nominal zener voltage of ±10%. A standard tolerance of ±5% on individual units is also available and is indicated by suffixing "A" to the standard type number. C for ±2.0%, D for ±1.0%.

(a) Electrical characteristics

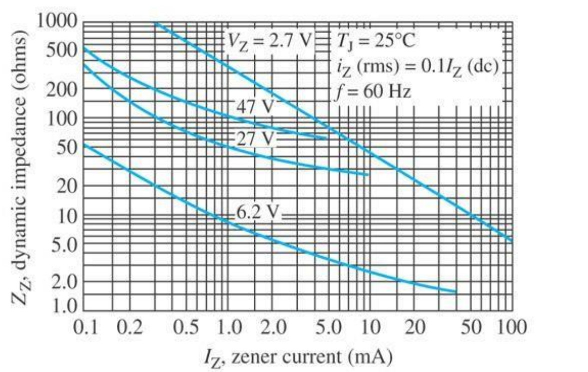


(b) Power derating

Range for Units to 12 Volts



(c) Temperature coefficient



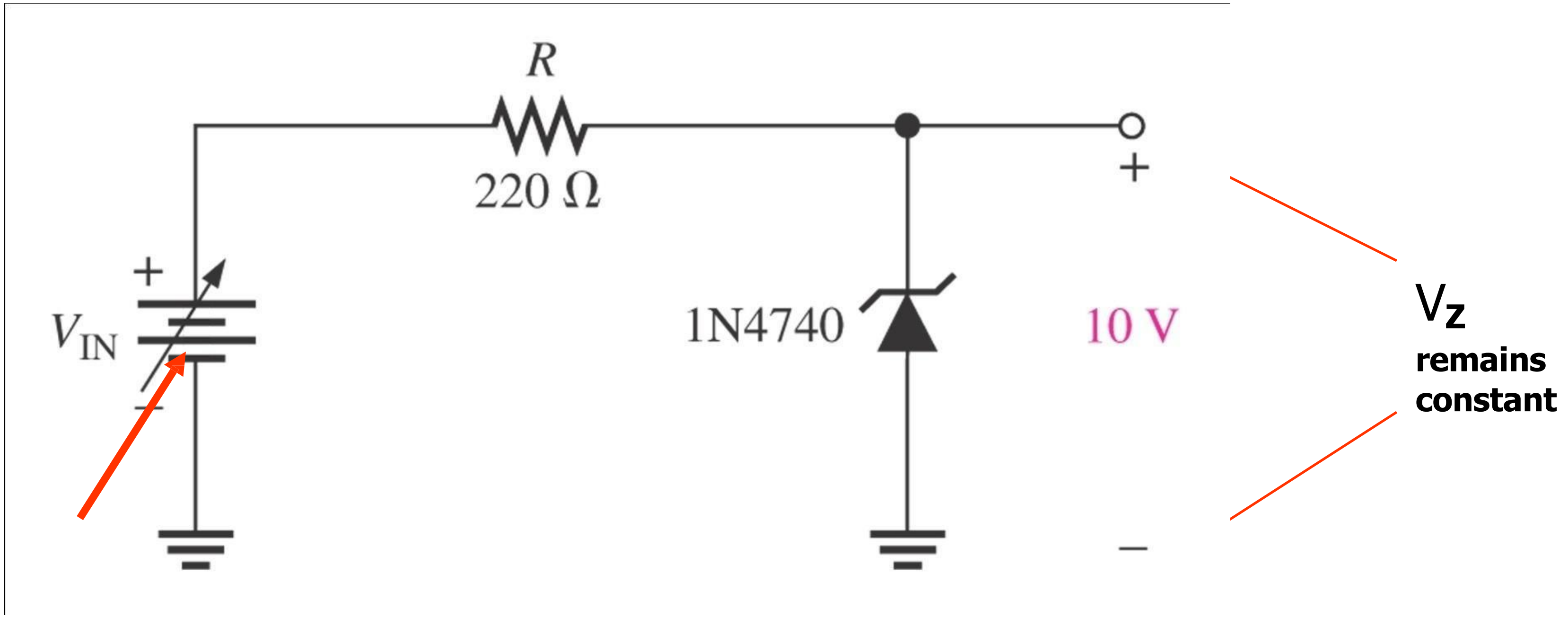
(d) Effect of zener current on zener impedance

Zener Diode - Applications

Voltage Regulation

In this simple illustration of zener regulation circuit, the zener diode will "adjust" its impedance based on varying input voltages. Zener current will increase or decrease directly with voltage input changes. The zener current, Iz, will vary to maintain a constant Vz.

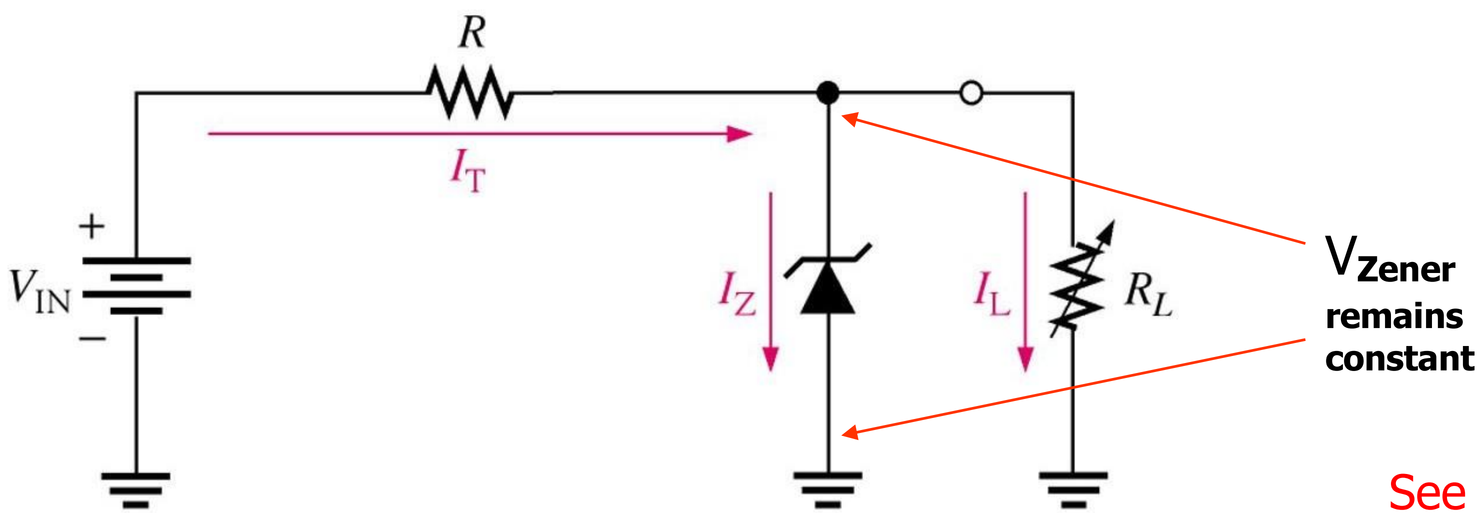
Note: The zener has a finite range of current operation.



Zener Diode - Applications

Load Regulation

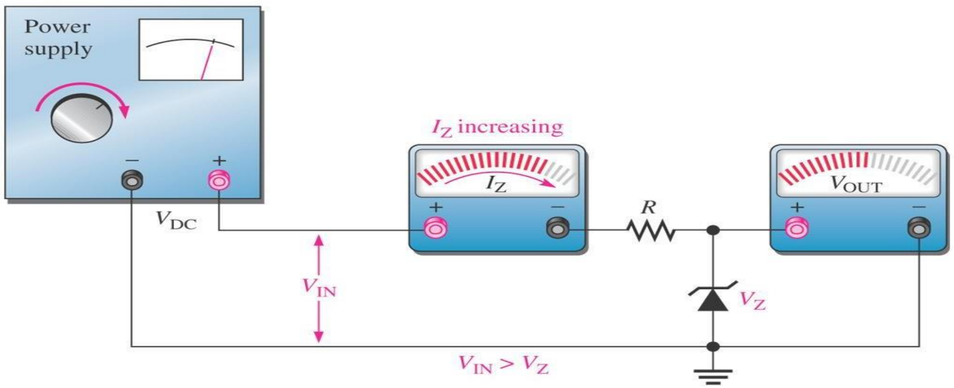
In this simple illustration of zener regulation circuit, the zener diode will “adjust” its impedance based on varying input voltages and loads (R_L) to be able to maintain its designated zener voltage. Zener current will increase or decrease directly with voltage input changes. The zener current will increase or decrease inversely with varying loads. Again, the zener has a finite range of operation.



See Ex. 3-5

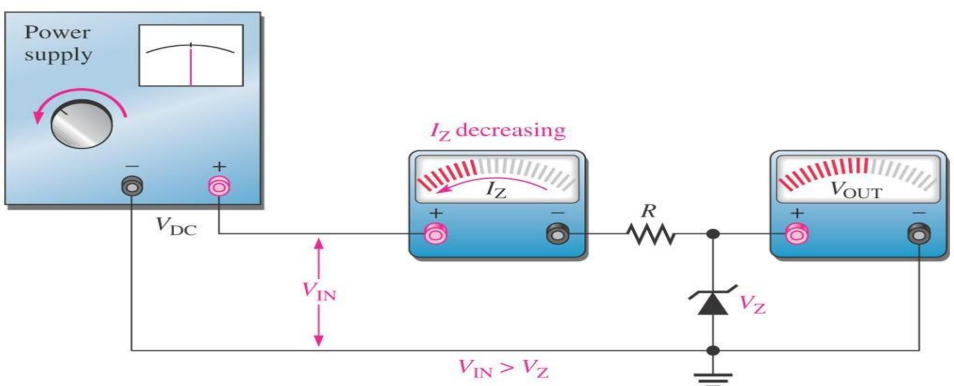
Acrobat Document

Zener Diode - Applications



(a) As the input voltage increases, the output voltage remains constant ($I_{ZK} < I_Z < I_{ZM}$).

Vin ↑ I_Z ↑ Vout →

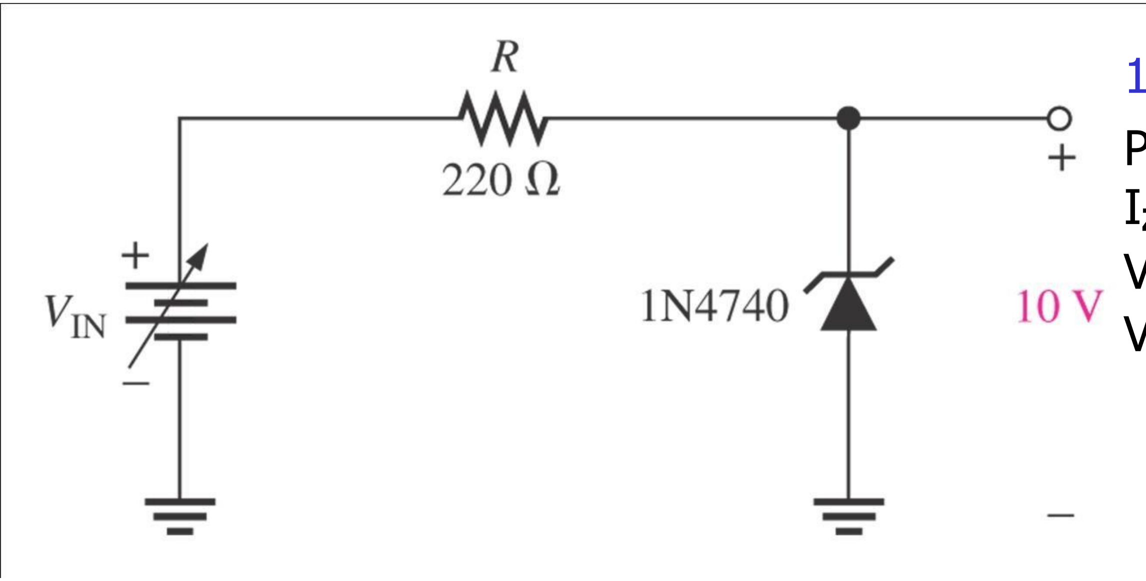


(b) As the input voltage decreases, the output voltage remains constant ($I_{ZK} < I_Z < I_{ZM}$).

Vin ↓ I_Z ↓ Vout →

**

Zener Diode - Applications



1N4740

P_{DMAX} = 1W. V_Z = 10V.

I_{ZK} = 0.25mA to I_{ZM} = 100mA

$V_{Rmin} = I_{ZK}R$= .25mA x 220 = 55mV

V_{Rmax} = I_{ZM} = 100mA x 220 = 22V.

Calculate $V_{ZRegulate}$: (pg.118)

$V_{inMIN} = V_R + V_Z$ = 55mV + 10V = 10.055V.

$V_R = I_Z R$ = (100mA)(220) = 22V.

$V_{in(max)}$ = 22V + 10V = 32V

$\therefore V_{Reg}$ is ≈10V to 32V.

Acrobat Document

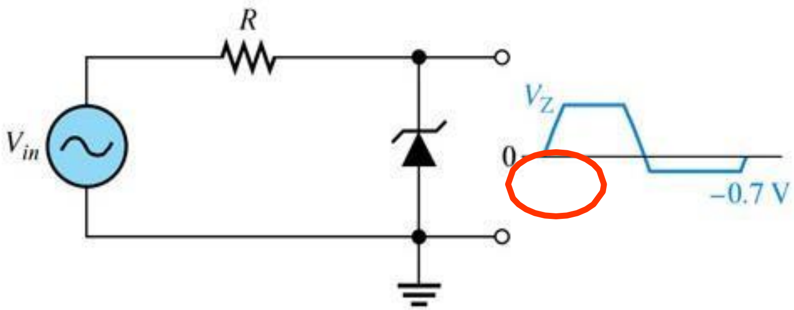
See Ex. 3-5

See Ex. 3-6

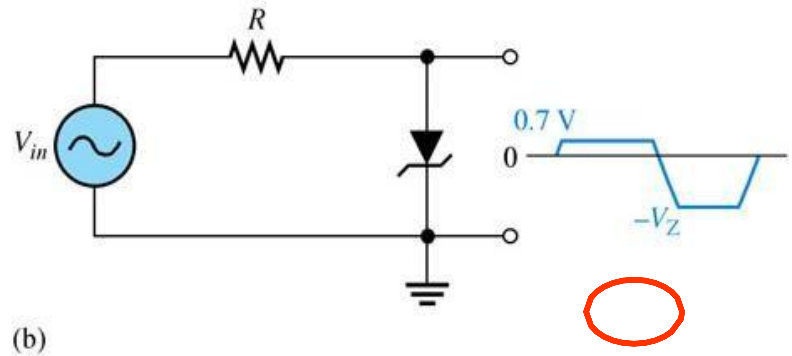
See Ex. 3-7

Zener Limiting

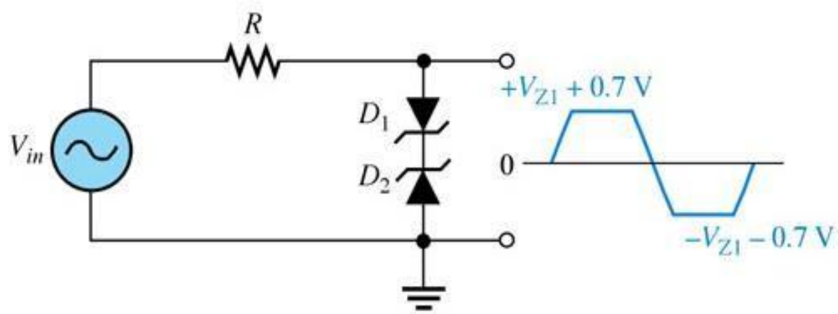
Zener diodes can used for limiting just as normal diodes. Recall in previous chapter studies about limiters. The difference to consider for a zener limiter is its zener breakdown characteristics.



(a)



(b)



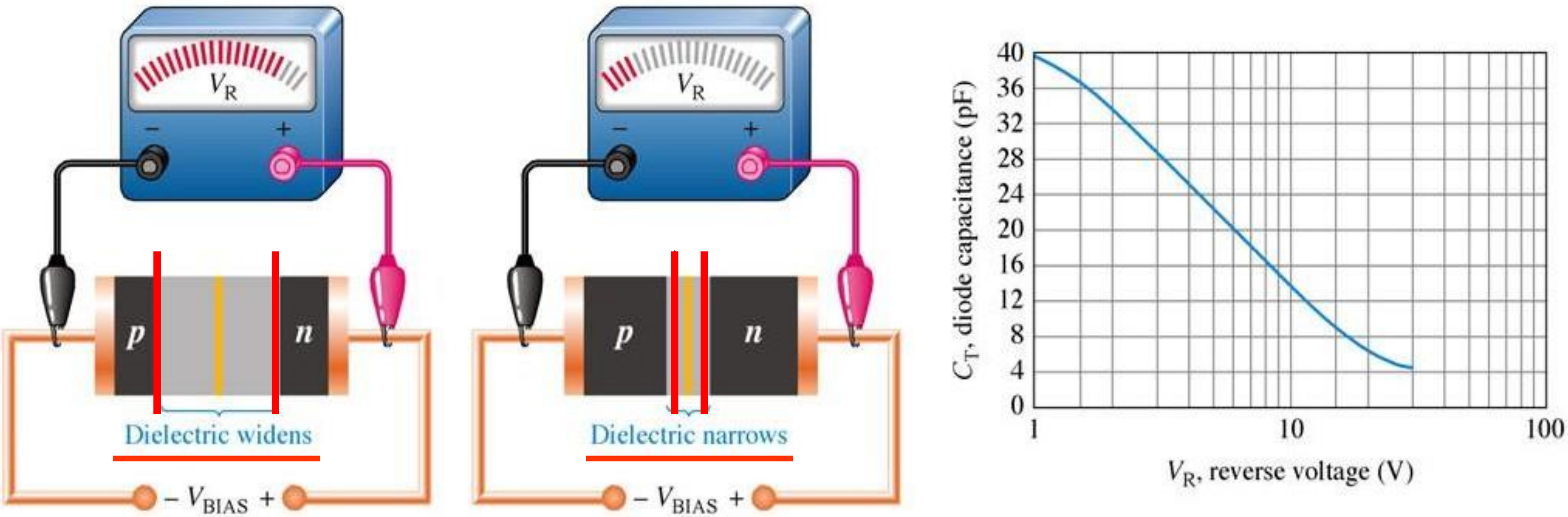
(c)

See Ex.3-8

Varactor Diodes

A **varactor diode** is best explained as a Variable Capacitor. Think of the depletion region as a variable dielectric.

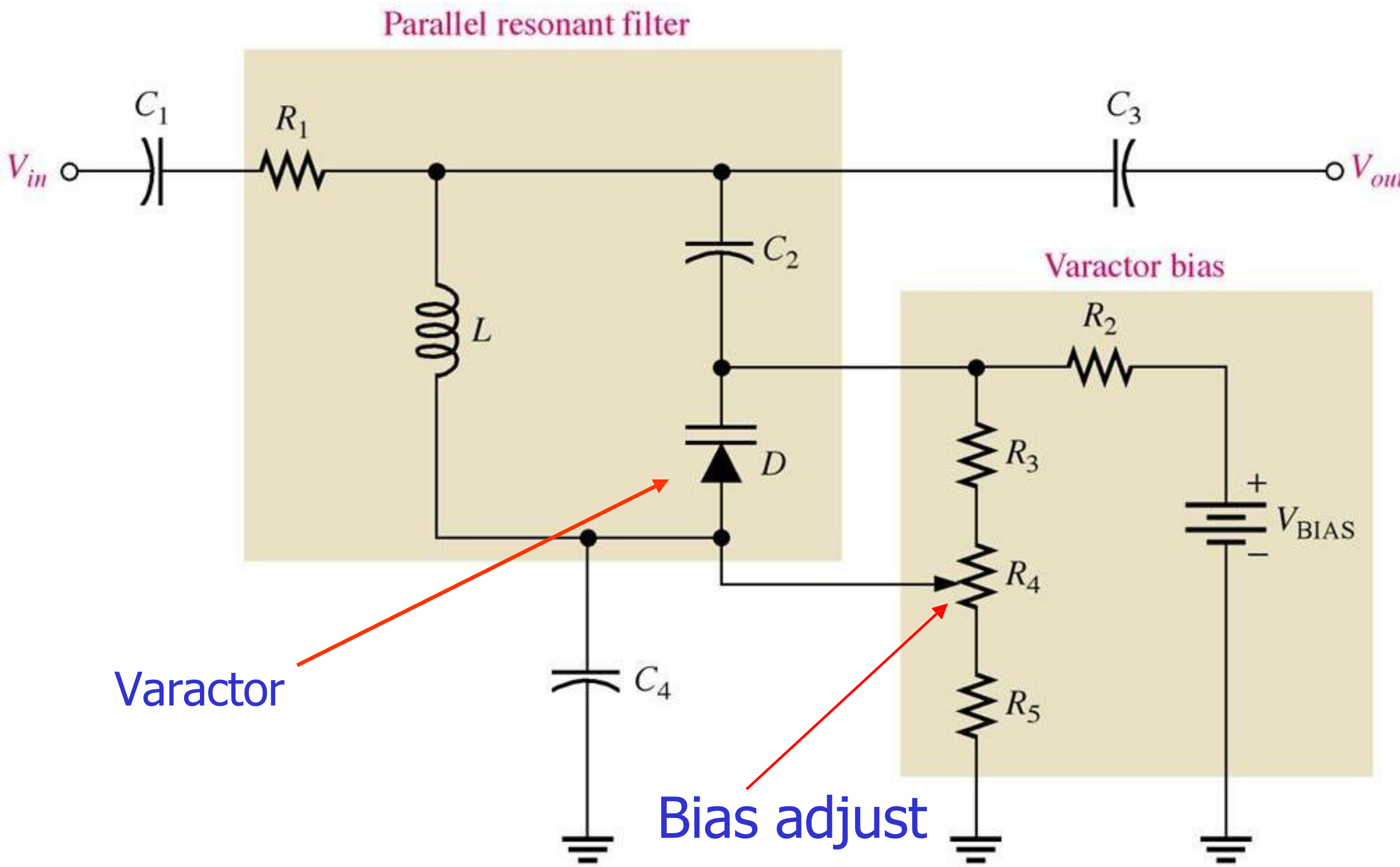
The diode is placed in reverse bias. The dielectric is "adjusted" by reverse bias voltage changes.



(a) Greater reverse bias, less capacitance (b) Less reverse bias, greater capacitance (c) Graph of diode capacitance versus reverse voltage

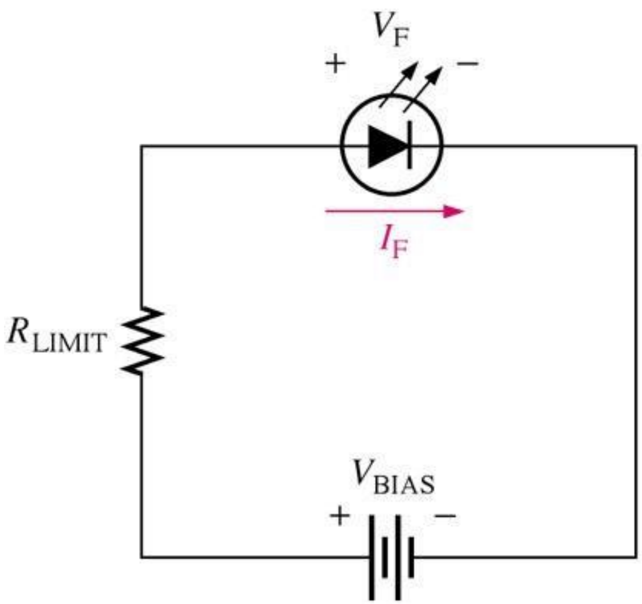
Varactor Diodes

The varactor diode can be useful in filter circuits as the adjustable component for resonance frequency selection.

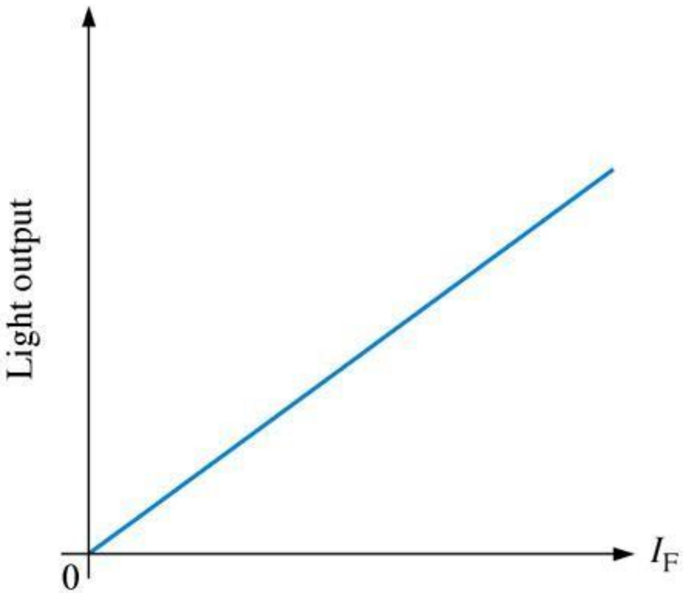


Optical Diodes

The **Light-Emitting Diode** (LED) emits photons as visible light. Its purpose is for indication and other intelligible displays. Various impurities are added during the doping process to vary the **color** output.



(a) Forward-biased operation



(b) General light output versus forward current

Optical Diodes

Electroluminescence, the process of emitting photons from a parent material (substrate), is the basis for LEDs.

Colors result from the choice of substrate material and the resulting wavelength;

Today's LEDs (green, red, yellow) are based on indium gallium aluminum phosphide

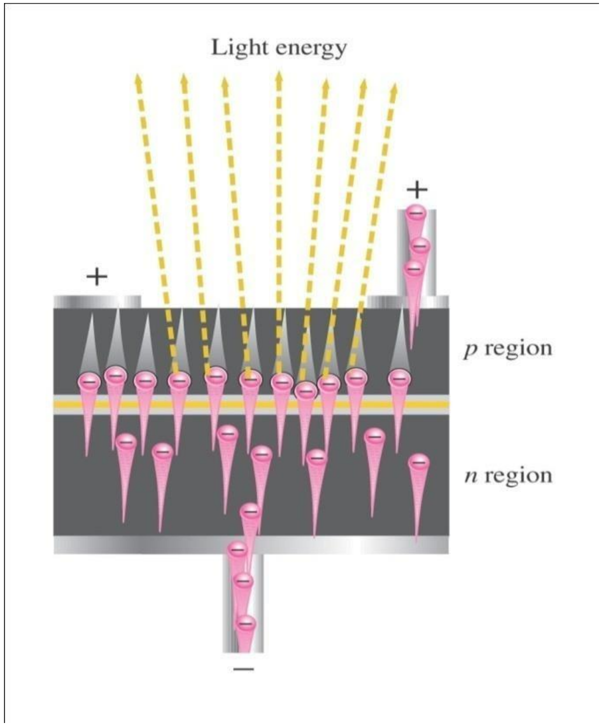
Blue uses silicon carbide or gallium nitride

IR (infrared) – GaAs (Gallium Arsenide)

LED Biasing: 1.2V to 3.2V is typical.

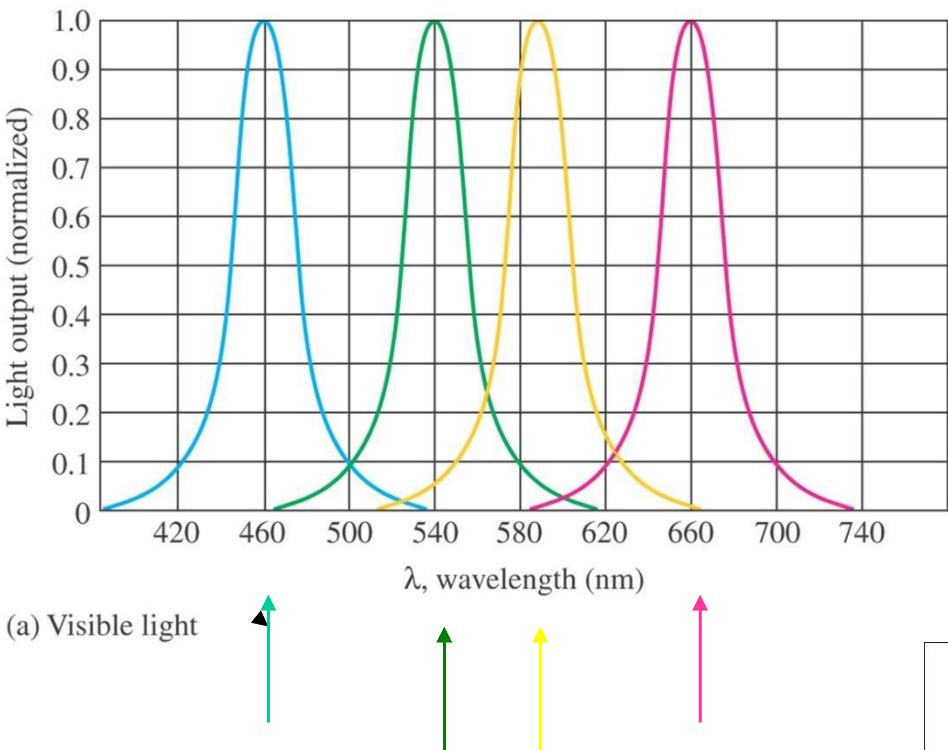
Note: Some newer LED's run at higher voltages and emit immense light energy.

Applications: Traffic Signals
Outdoor Video screens
Runway Markers

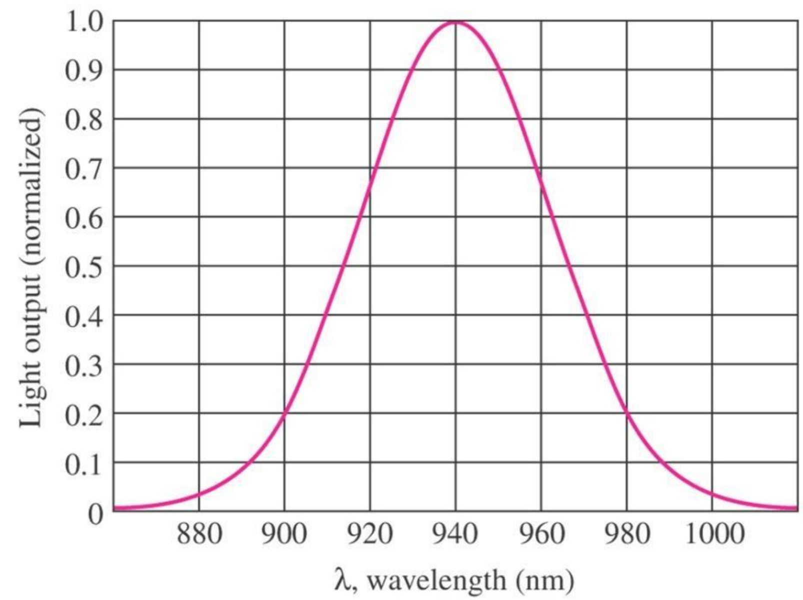


A strong +bias encourages conduction-band electrons in the N-material to jump the junction and recombine with available holes releasing light and heat.

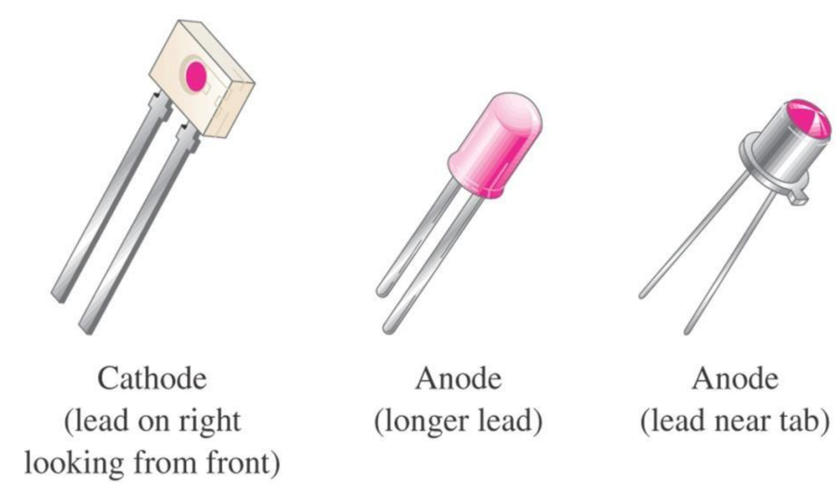
LED – Spectral Curves



(a) Visible light



(b) Infrared (IR)



Note the wavelengths of the various colors and infrared.

Note lead designations to the right.

LED Datasheet – MLED81 Infrared LED

Maximum Ratings

Rating	Symbol	Value	Unit
Reverse voltage	V_R	5	Volts
Forward current — continuous	I_F	100	mA
Forward current — peak pulse	I_F	1	A
Total power dissipation @ $T_A = 25°C$ Derate above 25°C	P_D	100 2.2	mW mW/°C
Ambient operating temperature range	T_A	–30 to +70	°C
Storage temperature	T_{stg}	–30 to +80	°C
Lead soldering temperature, 5 seconds max, 1/16 inch from case	—	260	°C

Electrical Characteristics ($T_A = 25°C$ unless otherwise noted)

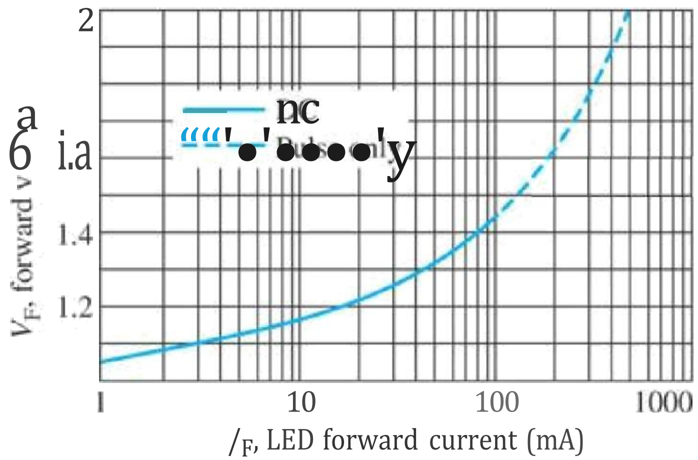
Characteristic	Symbol	Min	Typ	Max	Unit
Reverse leakage current ($V_R = 3$ V)	I_R	—	10	—	nA
Reverse leakage current ($V_R = 5$ V)	I_R	—	1	10	μA
Forward voltage ($I_F = 100$ mA)	V_F	—	1.35	1.7	V
Temperature coefficient of forward voltage	ΔV_F	—	– 1.6	—	mV/K
Capacitance ($f = 1$ MHz)	C	—	25	—	pF

Optical Characteristics ($T_A = 25°C$ unless otherwise noted)

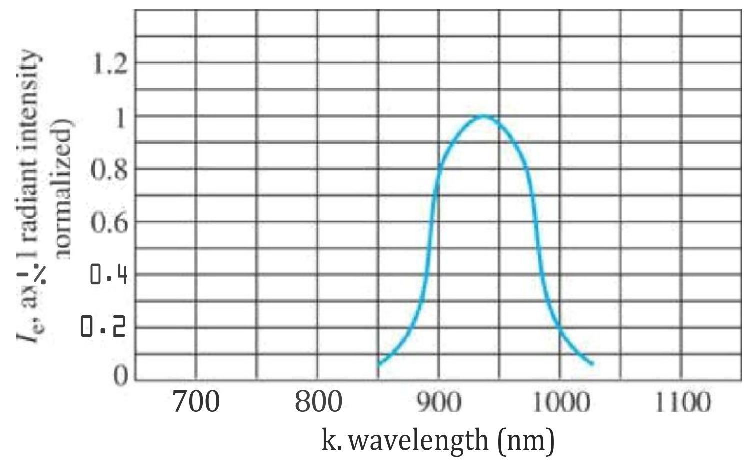
Characteristic	Symbol	Min	Typ	Max	Unit
Peak wavelength ($I_F = 100$ mA)	λp	—	940	—	nm
Spectral half-power bandwidth	$\Delta\lambda$	—	50	—	nm
Total power output ($I_F = 100$ mA)	ϕe	—	16	—	mW
Temperature coefficient of total power output	$\Delta\phi e$	—	– 0.25	—	%/K
Axial radiant intensity ($I_F = 100$ mA)	I_e	10	15	—	mW/sr
Temperature coefficient of axial radiant intensity	ΔI_e	—	– 0.25	—	%/K
Power half-angle	φ	—	±30	—	°

(a) Ratings and characteristics

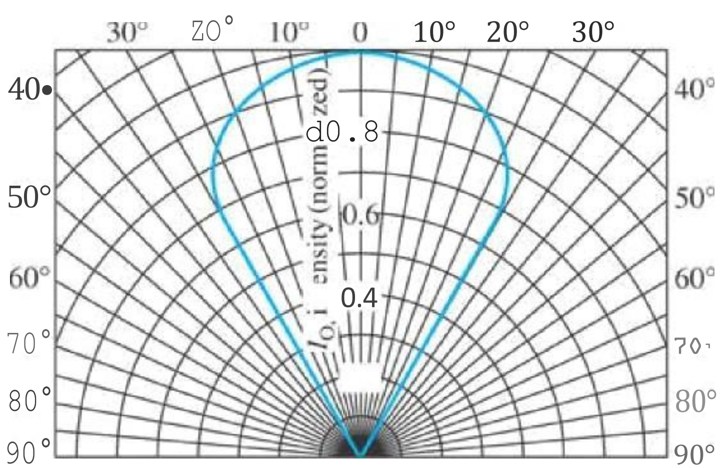
LED Datasheet – MLED81



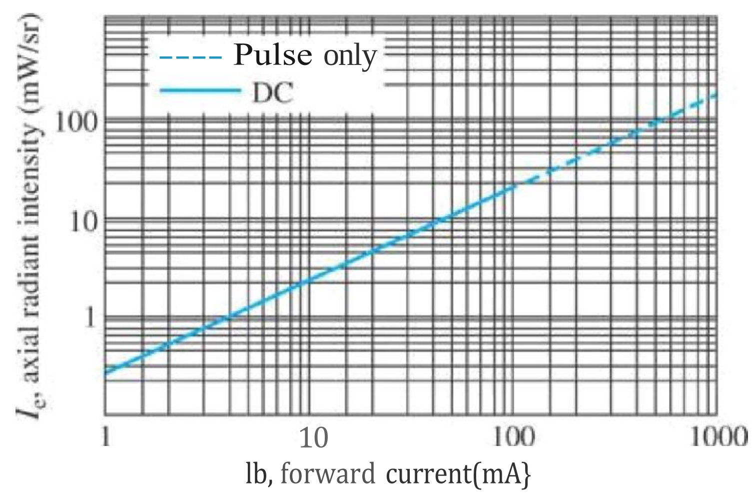
(b) LED forward voltage versus forward current



(c) Relative spectral emission



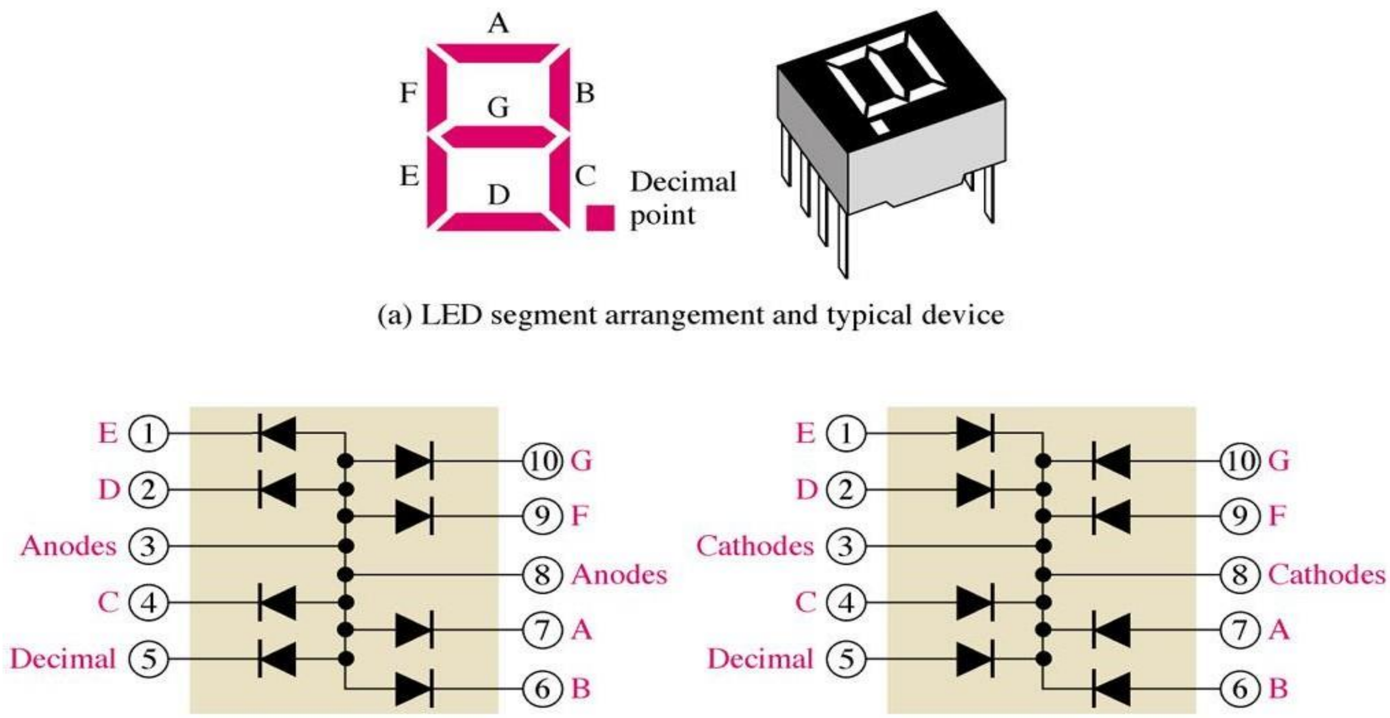
(d) Spatial radiation pattern



(e) Intensity versus forward current

Optical Diodes

The Seven Segment display is an example of LEDs applications for display of decimal digits.



(a) LED segment arrangement and typical device

(b) Common anode

(c) Common cathode

See "Light Emitting Diodes.pdf"

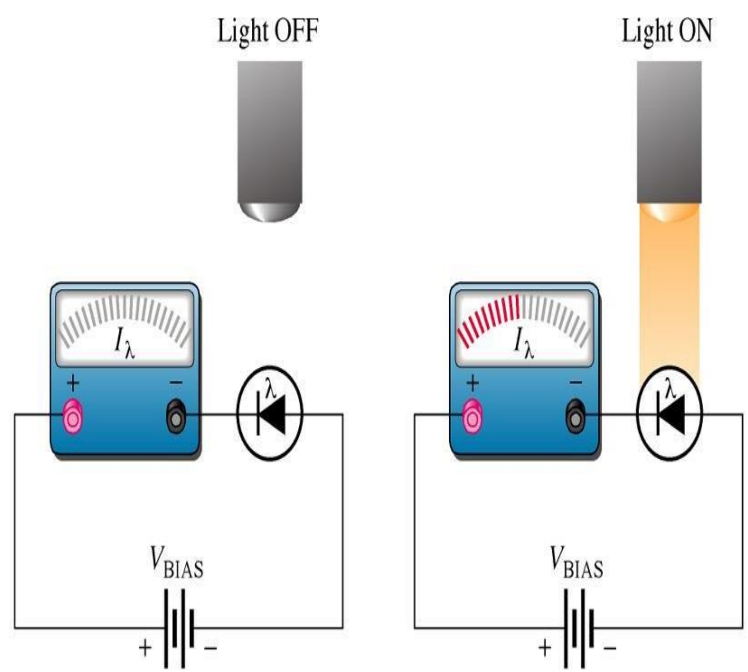
Acrobat Document

Photodiodes

Unlike LED's, photodiodes receive light rather than produce light. The **Photodiode** varies it's current in response to the amount of light that strikes it. It is placed in the circuit in ***Reverse Bias***. As with most diodes, no current flows when in reverse bias, but when light strikes the exposed junction through a tiny window, reverse current increases proportional to light intensity (irradiance).

Note:

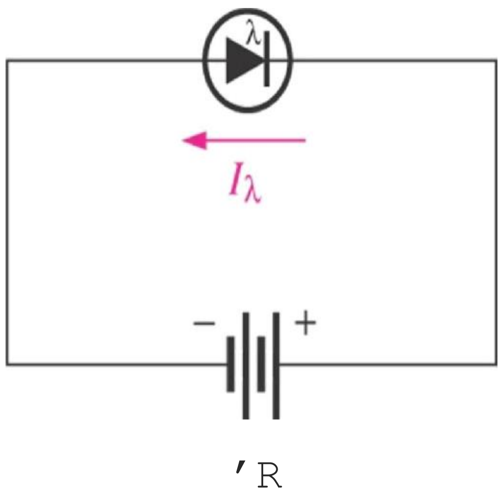
Photodiodes all exhibit a "reverse leakage current" which appears as an inverse variable resistance. Irradiance causes the device to exhibit a reduction in the variable resistance characteristic.



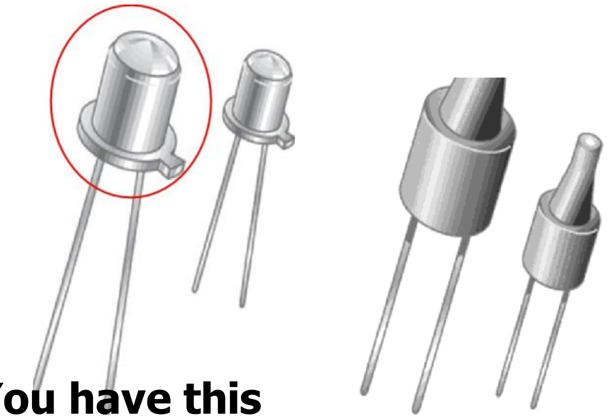
(a) No light, no current except negligible dark current

(b) Where there is incident light, resistance decreases and there is reverse current.

Photodiodes



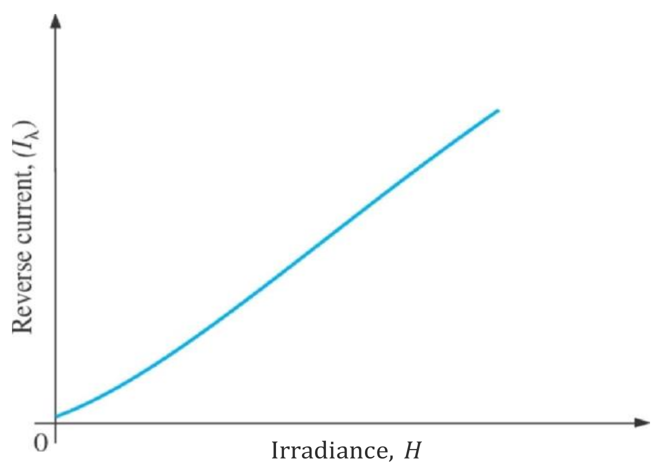
(a) Reverse-bias operation



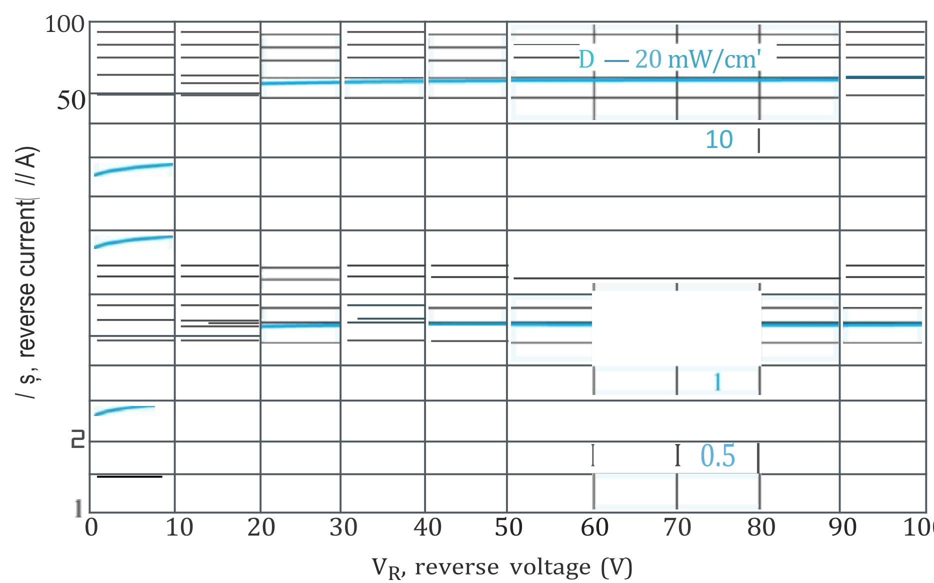
You have this one in your kit.

(b) Typical devices

(c) Alternate symbol



(a) General graph of reverse current versus irradiance



(b) Example of a graph of reverse current versus reverse voltage for several values of irradiance

Photodiodes – MRD821

Maximum Ratings

Rating	Symbol	Value	u»ñt
Reverse outrage	˥R	35	Volts
Forward current — continuous	˥F	i00	mA
Total power dissipation @ $T_A = 25°C$ Dernie abnve 25°C	P_D	150 3.3	mW *mwtx:*
Amhient operating temperature range	T_A	−30 o+70	°C
Storage temperature	T_{stg}	-40to+80	'
had so]doring wmpurarure. 3 sccDnds max. 1/16 tnch from case		260	°C

Mlectricat Characteristics (Fg Z5°C unievs otherwise nnted}

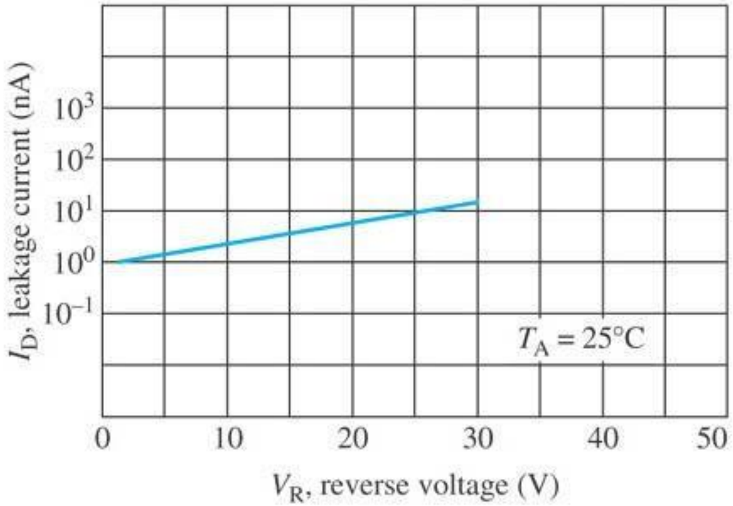
Cbaractezdstic	Symbol	him		I\dax	Unit
Dark current {P_R = IO V)	ip		3	3D	nA
Capacitance(/= I NtHz, V= 0j	C,	—	I75	—	pr

Optical Characteristics ($T_A = 25°C$ unless otherwise noted)

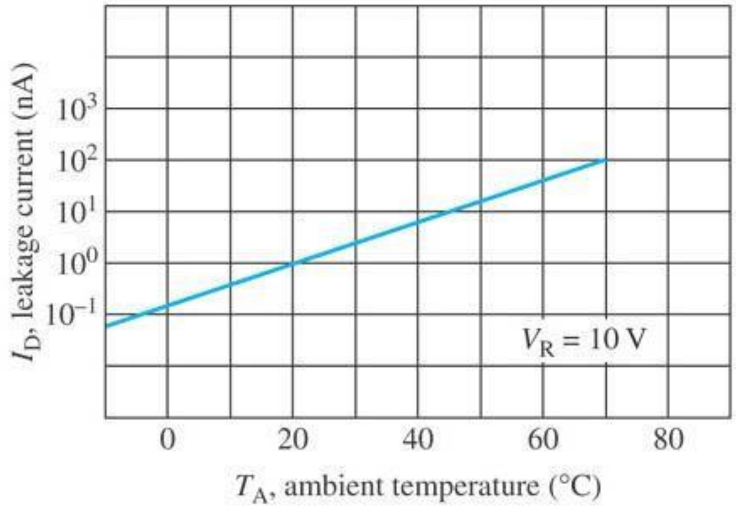
Characteristic	Symbol	NSTn		Max	Unit
Wavelcngth o£maximum.sensitivity	Qmax	—	940	—	nm
Spec\ralrangc	At	—	l10		nm
Sensirivity {k =• 940 nm. O_R 20 V)	S	—	30	—	,uA/mW/cm-
Temperature coefFcien‹ of sensitivity	*as*		0.18		U/K
Acceptance halF-angle	gi	—	170		
Short circuit current (Ev = I O0D lux)	/	—	SD		, sA
Open circuit volmge (Ev — IOfKl tux)	Up	—	O.3	—	V

(a) RaGngszndcharzcmrBGcs

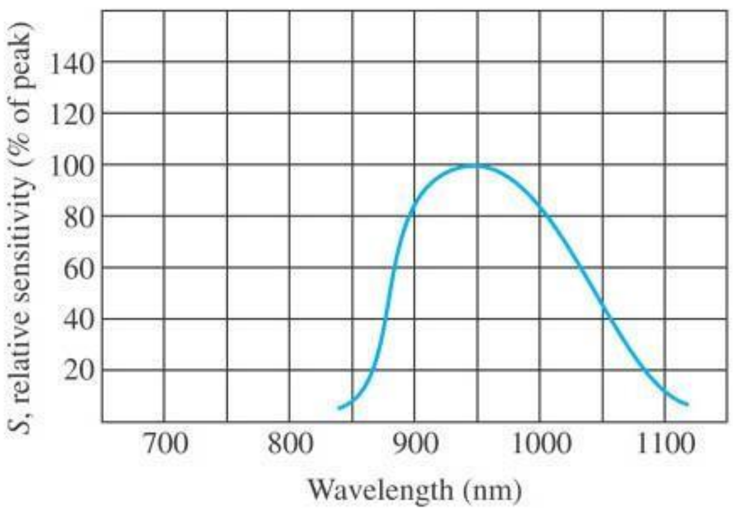
Photodiodes – MRD821



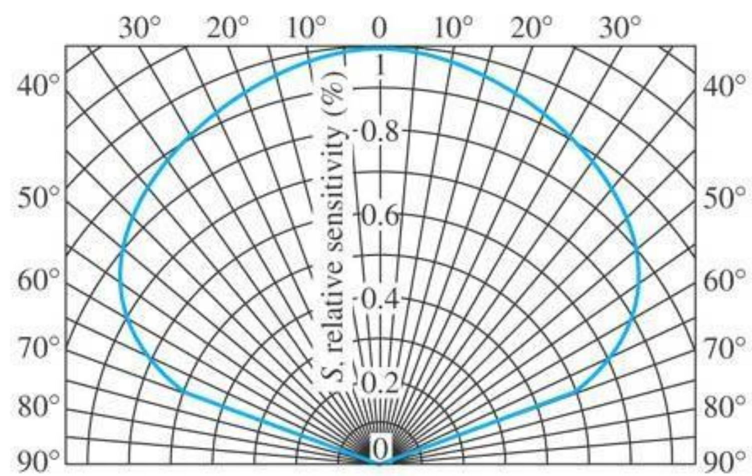
(b) Dark current versus reverse voltage



(c) Dark current versus temperature



(d) Relative spectral sensitivity



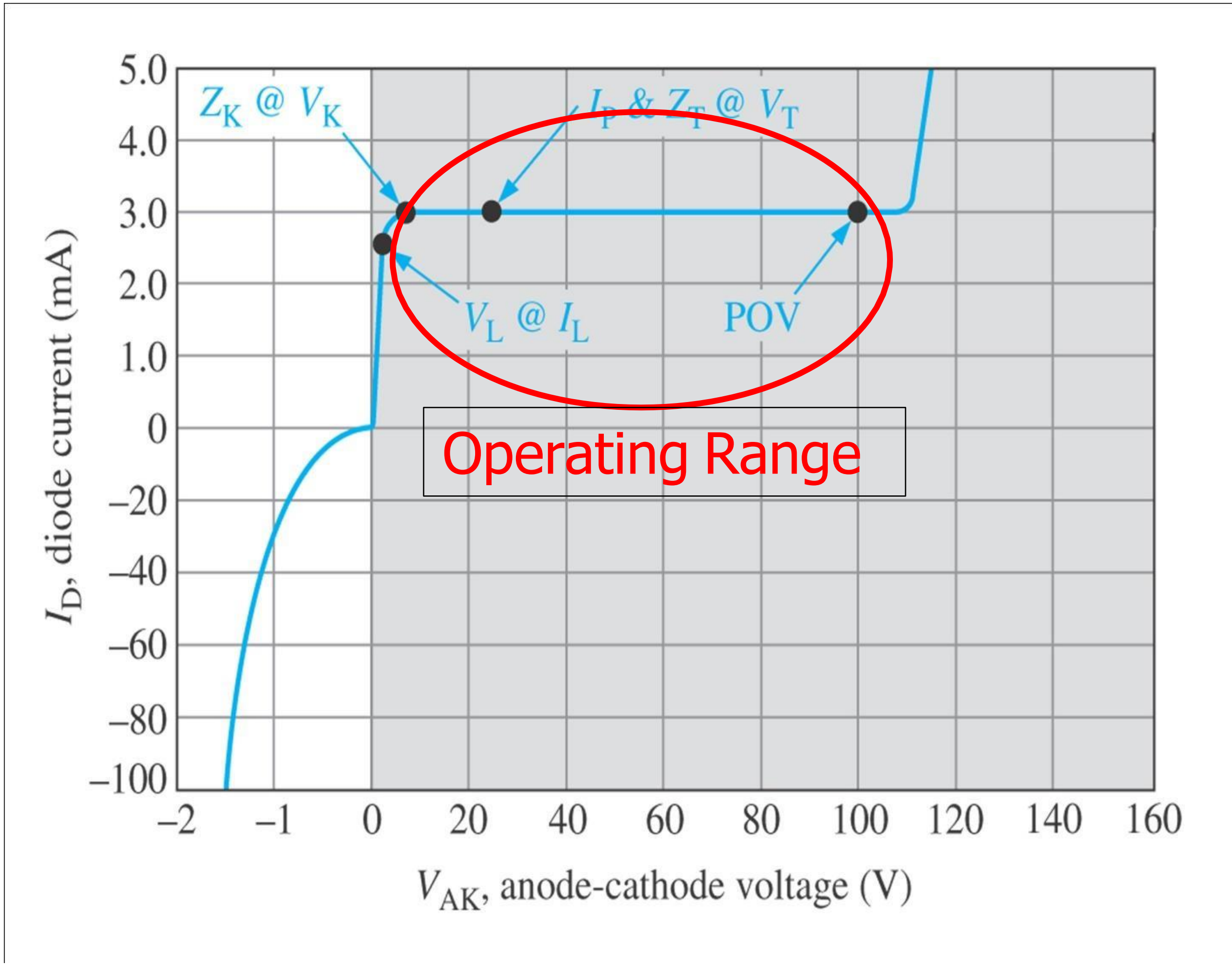
(e) Angular response

Other Diode Types

Current Regulator Diodes:

(constant current diodes) keep a constant current value over a specified range of forward bias voltages ranging from about 1.5 V to 6 V.

This device exhibits very high impedances.

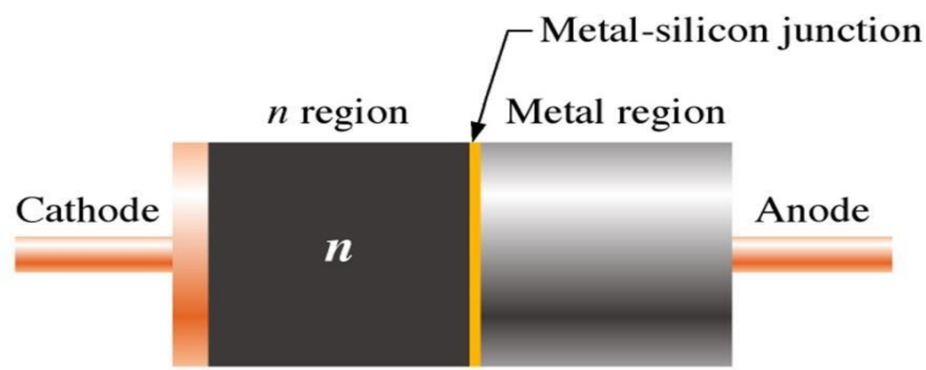


Other Diode Types

The **Schottky Diode's** (Hot-Carrier diodes)

Significant characteristic is its fast switching speed. This is useful for high frequencies and digital applications. It is not a typical diode in that it does not have a p-n junction. Instead, it consists of a lightly-doped n-material and heavily-doped (conduction-band electrons) metal bounded together.

Response is very quick…high speed digital communications.

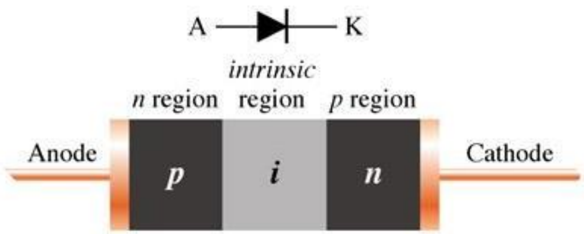


Lightly doped

Heavily doped (conduction-band electrons)

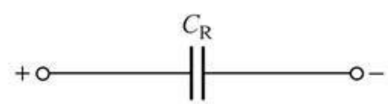
Other Diode Types

The ***PIN-diode*** is also used in mostly microwave frequency applications. Its variable forward series resistance characteristic is used for attenuation, modulation, and switching. In reverse bias it exhibits a nearly constant capacitance. Also used in attenuators.



(a) Construction

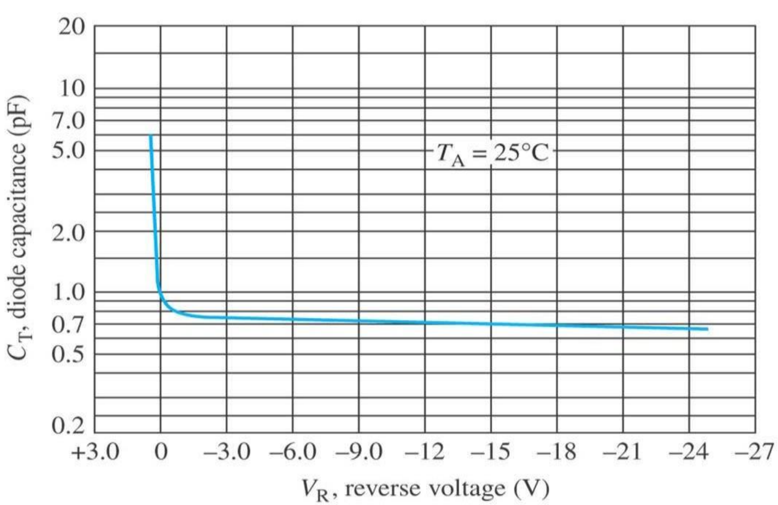
Fixed Capacitance

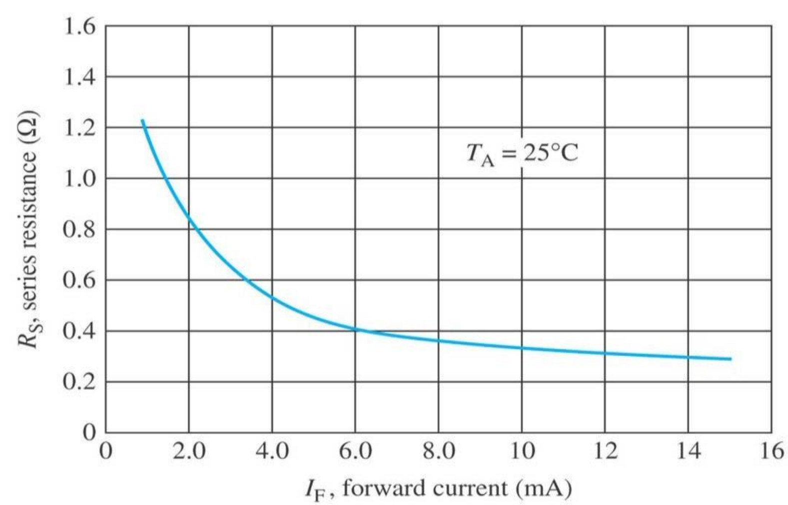


(b) Reverse-biased

Current-controlled Resistance

(c) Forward-biased





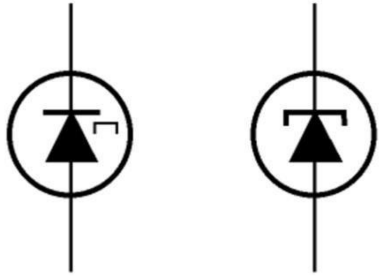
Other Diode Types

The **step-recovery diode** is also used for fast switching applications. This is achieved by reduced doping near the junction. The diode recovers very quickly, making it useful in high-frequency (VHF) applications.

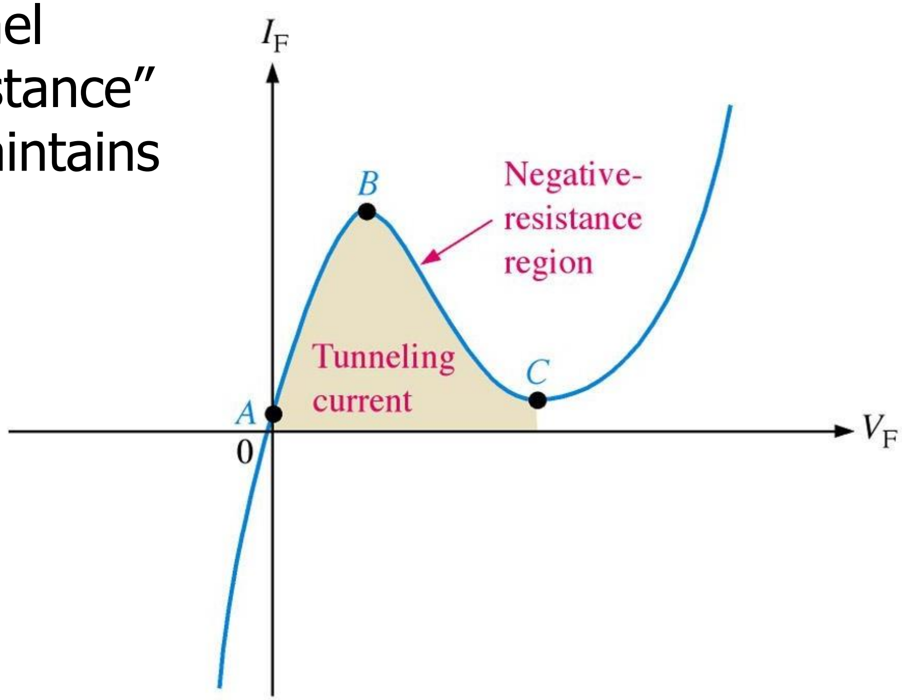
Other Diode Types

The **tunnel diode** exhibits **negative resistance**. It will actually conduct well with low forward bias. With further increases in bias it reaches the negative resistance range where current will actually go down. This is achieved by heavily-doped p and n materials that create a very thin depletion region which permits electrons to "tunnel" thru the barrier region.

Tank circuits oscillate but "die out" due to the internal resistance. A tunnel diode will provide "negative resistance" that overcomes the loses and maintains the oscillations.

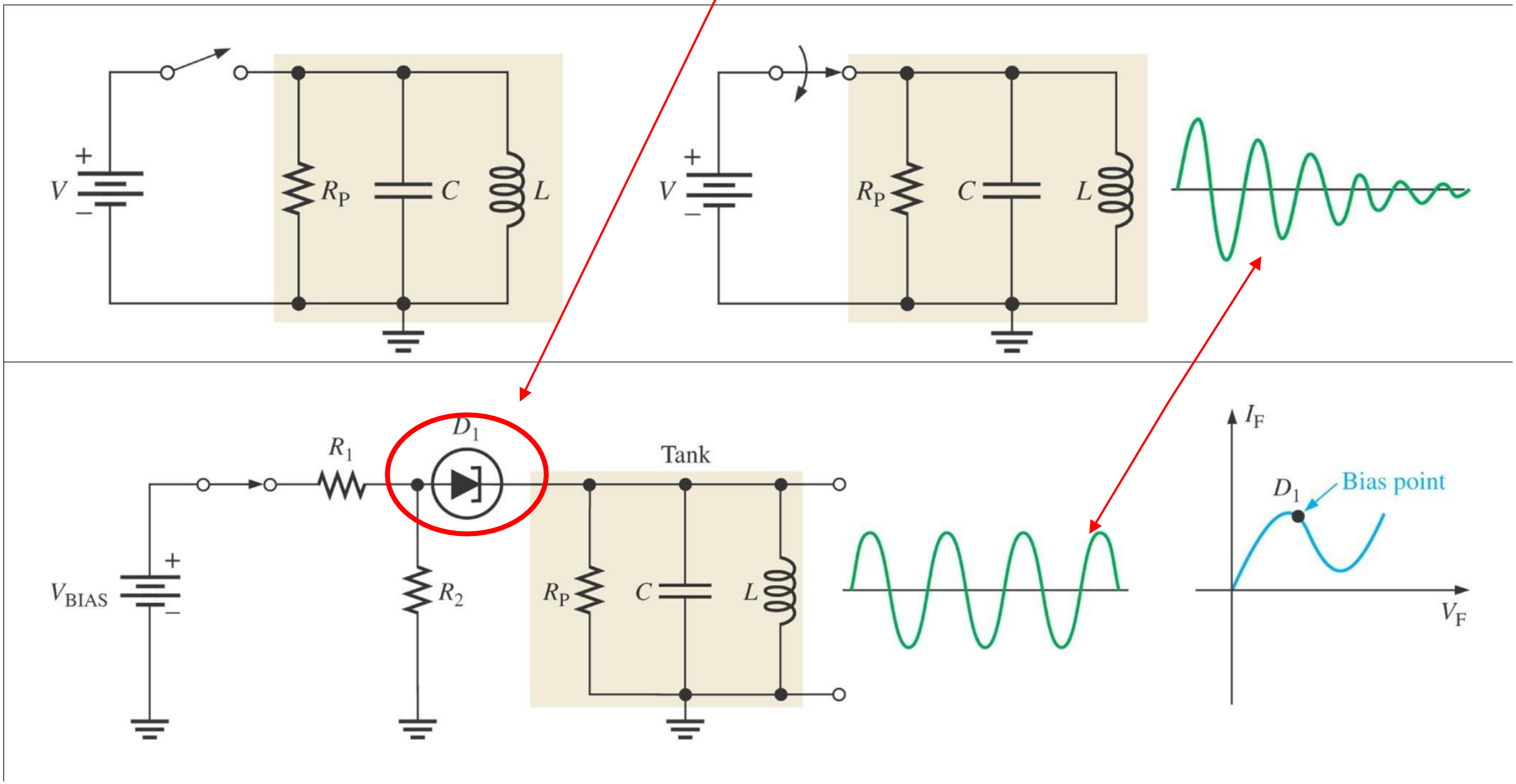


Germanium or Gallium



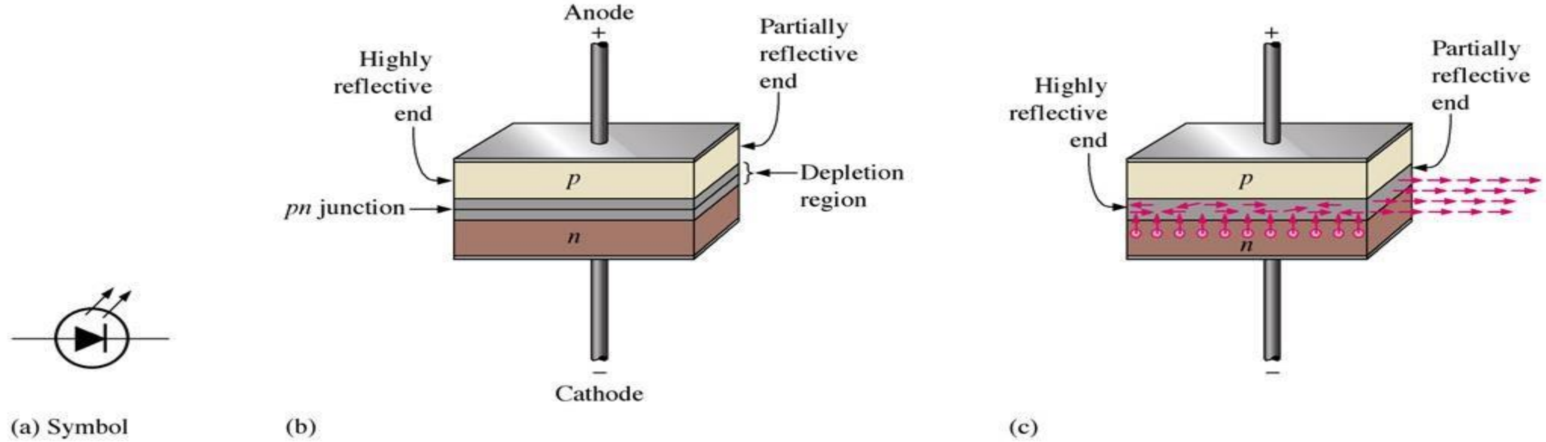
Tunnel Diodes

Tank circuits oscillate but “die out” due to the internal resistance. A tunnel diode will provide “negative resistance” that overcomes the loses and maintains the oscillations.



Other Diode Types

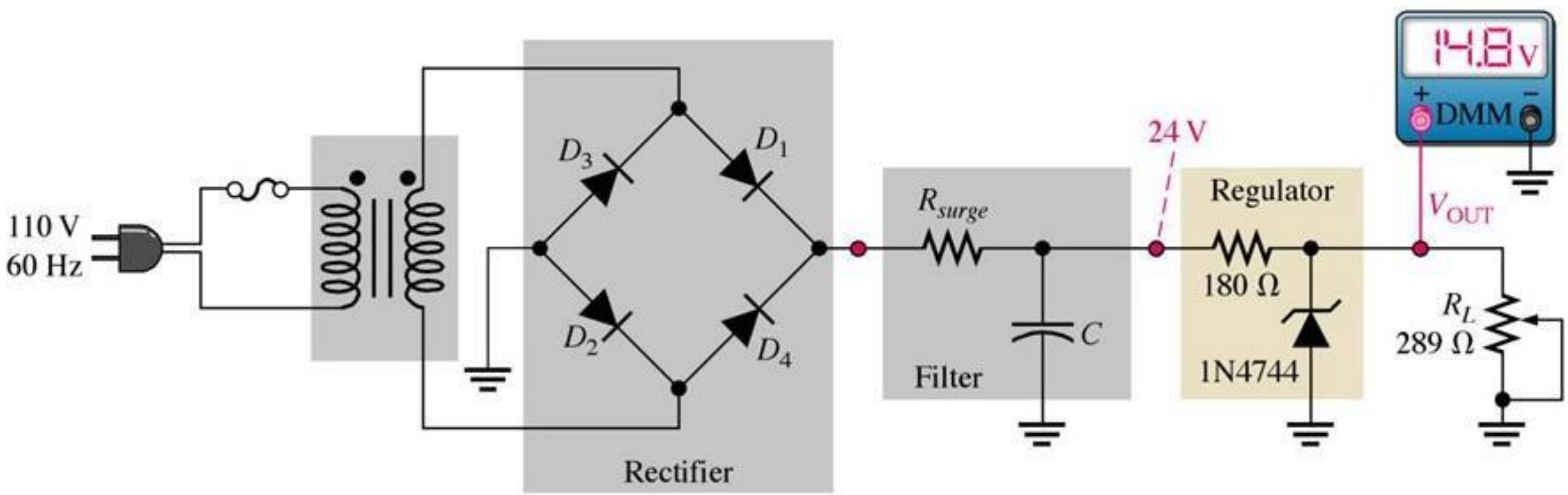
The **LASER diode:**
(**L**ight **A**mplification by **S**timulated **E**mission of **R**adiation) produces a monochromatic (single color) “coherent” light. Laser diodes in conjunction with photodiodes are used to retrieve data from compact discs.



Forward bias the diode and electrons move thru the junction, recombination occurs (as ordinary). Recombinations result in photon release, causing a chain reaction of releases and avalanching photons which form an intense laser beam.

Troubleshooting

Although precise power supplies typically use IC type regulators, zener diodes can be used alone as a voltage regulator. As with all troubleshooting techniques we must know what is normal.

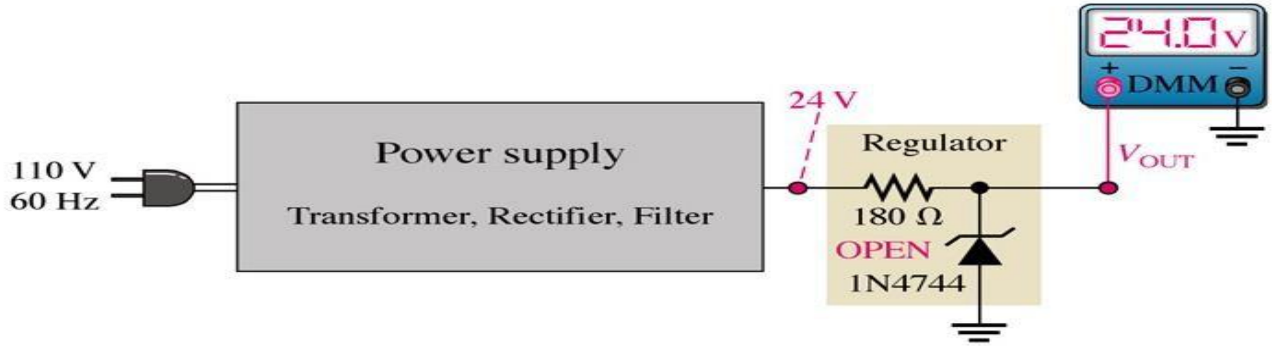


(b) Correct output voltage with full load

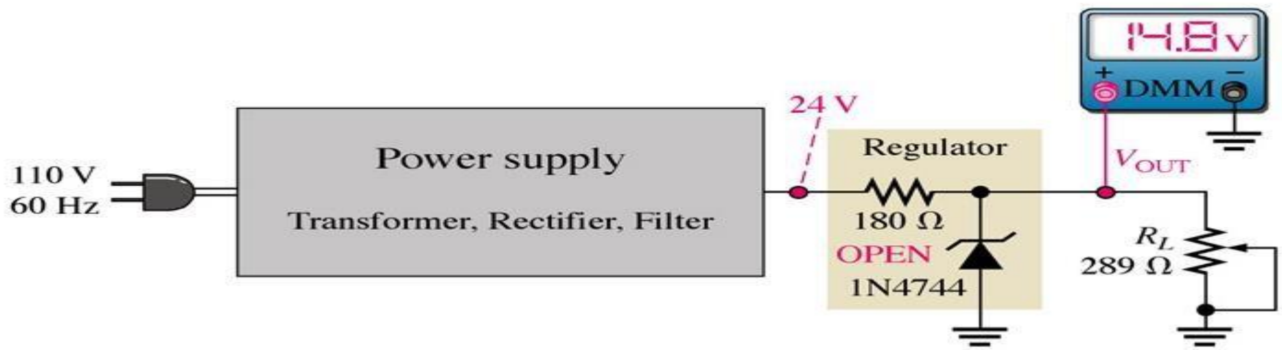
A properly functioning zener will work to maintain the output voltage within certain limits despite changes in load.

Troubleshooting

With an open zener diode, the full unregulated voltage will be present at the output without a load. In some cases with full or partial loading an open zener could remain undetected.



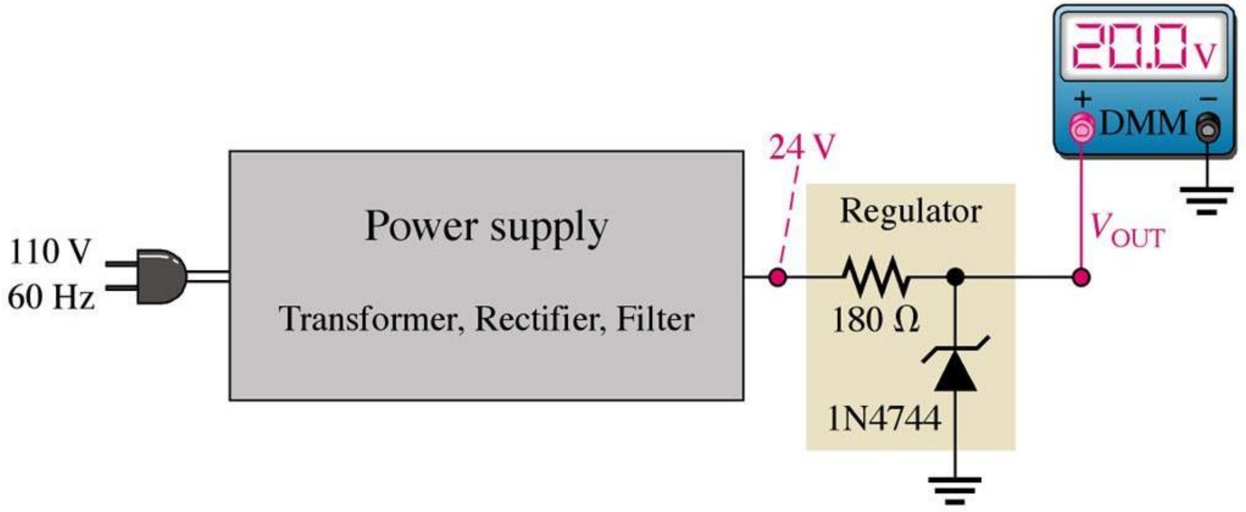
(a) Open zener diode with no load



(b) Open zener diode cannot be detected by full-load measurement in this case.

Troubleshooting

With excessive zener impedance the voltage would be higher than normal but less than the full unregulated output.



Summary

- The zener diode operates in reverse breakdown.
- A zener diode maintains a nearly constant voltage across its terminals over a specified range of currents.
- Line regulation is the maintenance of a specific voltage with changing input voltages.
- Load regulation is the maintenance of a specific voltage for different loads.
- There are other diode types used for specific RF purposes such as varactor diodes (variable capacitance), Schottky diodes (high speed switching), and PIN diodes (microwave attenuation and switching).

Summary

- Light emitting diodes (LED) emit either infrared or visible light when forward-biased.
- Photodiodes exhibit an increase in reverse current with light intensity.
- The laser diode emits a monochromatic light

Thevenin Equivalent Circuits

Introduction

In each of these problems, we are shown a circuit and its Thevenin or Norton equivalent circuit. The Thevenin and Norton equivalent circuits are described using three parameters: V_{oc}, the open circuit voltage of the circuit, I_{sc}, the short circuit of the circuit and R_{th}, the Thevenin resistance of the circuit. Each problem, asks us to determine the value of asked to determine the value of V_{oc}, I_{sc} or R_{th}.

Thevenin equivalent circuits are discussed in Section 5.5 of *Introduction to Electric Circuits* by R.C. Dorf and J.A Svoboda. Norton equivalent circuits are discussed in Section 5.6.

Worked Examples

Example 1:
The circuit shown in Figure 1b is the Thevenin equivalent circuit of the circuit shown in Figure 1a. Find the value of the open circuit voltage, V_{oc} and Thevenin resistance, R_{th}.

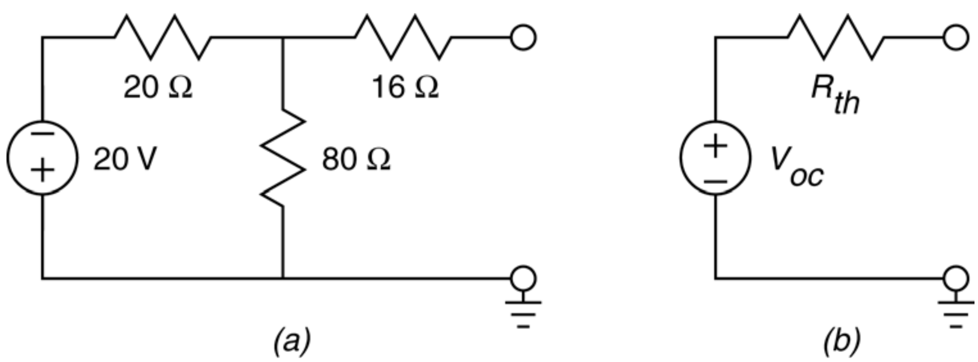


Figure 1 The circuit considered in Example 1.

Solution: The circuit from Figure 1a can be reduced to its Thevenin equivalent circuit in four steps shown in Figure 2a, b, c and d.

A source transformation transforms the series voltage source and 20 Ω resistor in Figure 1a into the parallel current source and 20 Ω resistor in Figure 2a. The current source current is calculated from the voltage source voltage and resistance as $\frac{20\text{ V}}{20\ \Omega} = 1\text{ A}$. After the source transformation, the 20 Ω resistor is parallel to the 80 Ω resistor. Replacing these parallel resistors with the equivalent 16 Ω resistor produces the circuit shown in Figure 2b.

A second source transformation transforms the parallel current source and 16 Ω resistor in Figure 2b into the series voltage source and 16 Ω resistor in Figure 2c. The voltage source voltage is calculated from the current source current and resistance as $(1\text{ A})(16\ \Omega) = 16\text{ V}$. After the source transformation, the two16 Ω resistors are in series. Replacing these series resistors with the equivalent 32 Ω resistor produces the circuit shown in Figure 2d.

Comparing Figure 2d to Figure 1b shows that the Thevenin resistance is R_{th} = 32 Ω and the open circuit voltage, V_{oc} = -16 V.

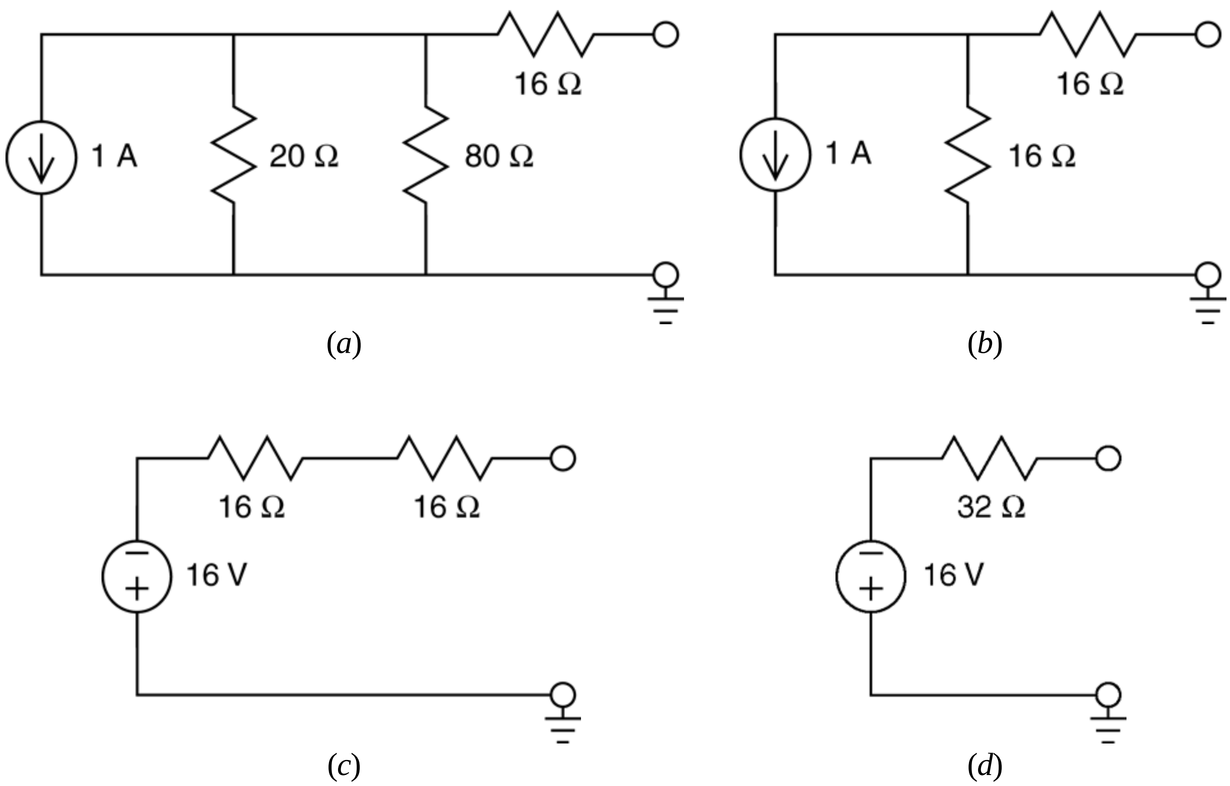


Figure 2 The circuit from Figure 1a can be reduced to its Thevenin equivalent circuit in four steps shown here as (*a*), (*b*), (*c*), and (*d*).

Example 2:
The circuit shown in Figure 3b is the Thevenin equivalent circuit of the circuit shown in Figure 1a. Find the value of the open circuit voltage, V_{oc} and Thevenin resistance, R_{th}.

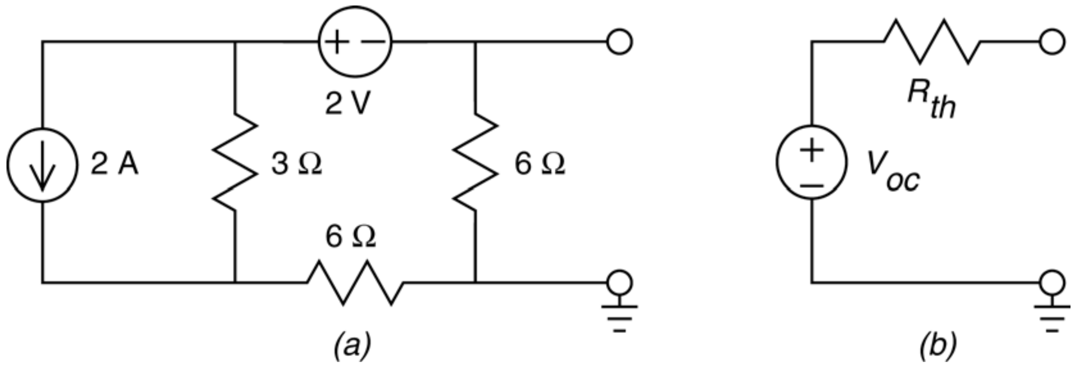


Figure 3 The circuit considered in Example 2.

Solution: The circuit from Figure 3a can be reduced to its Thevenin equivalent circuit in five steps shown in Figure 4a, b, c, d and e.

A source transformation transforms the parallel current source and 3 Ω resistor in Figure 3a into the series voltage source and 3 Ω resistor in Figure 4a. The voltage source voltage is calculated from the current source current and resistance as $(2\ \text{A})(3\ \Omega) = 6\ \text{V}$. After the source transformation, the 3 Ω and 6 Ω resistors are in series. Also, the 6V and 3 V voltage sources are in series. Replacing the series resistors with the equivalent 9 Ω resistor and the series voltage sources with the equivalent 8 V source produces the circuit shown in Figure 4b.

A second source transformation transforms the series 8 V voltage source and 9 Ω resistor in Figure 4b into the parallel current source and 9 Ω resistor in Figure 4c. The current source current is calculated from the voltage source voltage and resistance as $\frac{8\ \text{V}}{9\ \Omega} = 0.89\ \text{A}$. After the source transformation, the 9 Ω resistor is parallel to the 6 Ω resistor. Replacing these parallel resistors with the equivalent 3.6 Ω resistor produces the circuit shown in Figure 4d.

A third source transformation transforms the parallel 0.89 A current source and 3.6 Ω resistor in Figure 4d into the series voltage source and 3.6 Ω resistor in Figure 4e. The voltage source voltage is calculated from the current source current and resistance as $(0.89\ \text{A})(3.6\ \Omega) = 3.2\ \text{V}$.

Comparing Figure 4e to Figure 3b shows that Thevenin resistance is $R_{th} = 3.6\ \Omega$ and that the open circuit voltage, V_{oc} = -3.2 V.

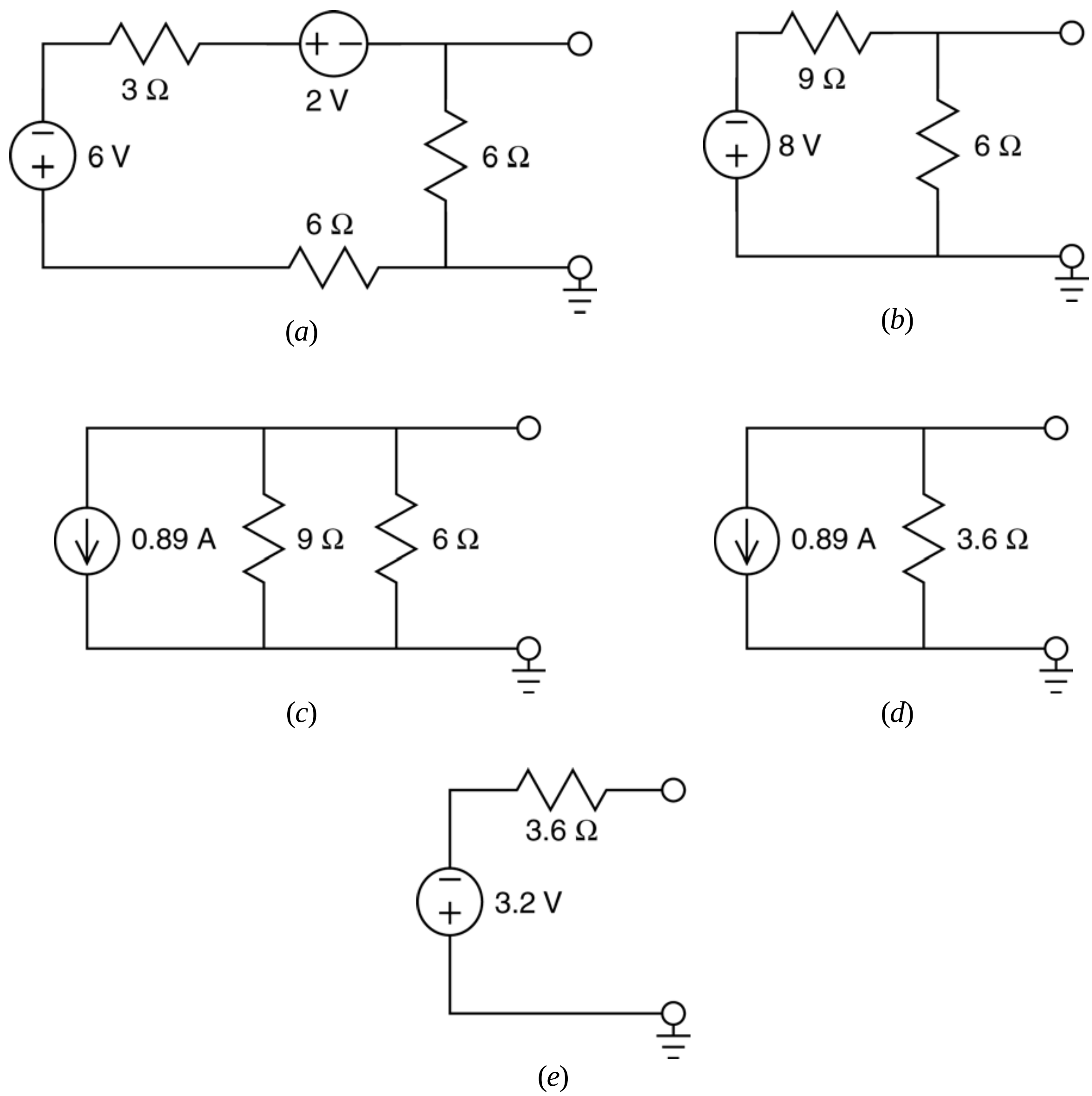


Figure 4 The circuit from Figure 3a can be reduced to its Thevenin equivalent circuit in five steps shown here as (*a*), (*b*), (*c*), (*d*) and (*e*).

Example 3:

The circuit shown in Figure 5b is the Thevenin equivalent circuit of the circuit shown in Figure 5a. Find the value of the open circuit voltage, V_{oc} and Thevenin resistance, R_{th}.

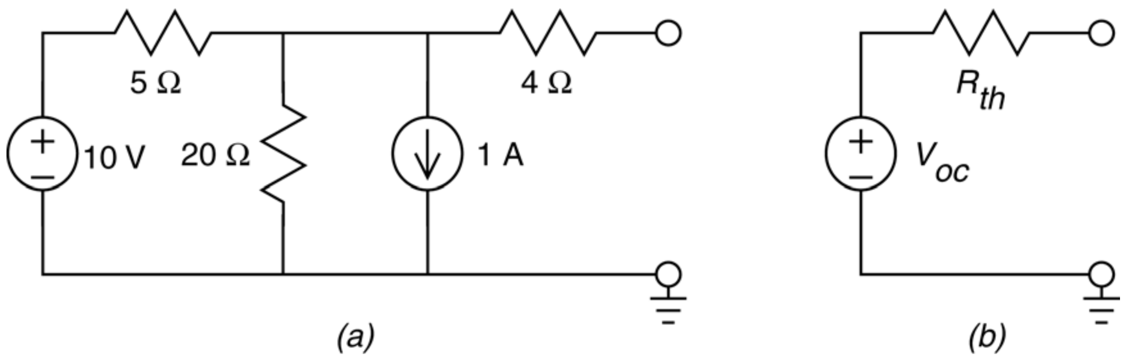


Figure 5 The circuit considered in Example 3.

Solution: The circuit from Figure 5a can be reduced to its Thevenin equivalent circuit in four steps shown in Figure 6a, b, c and d.

A source transformation transforms the series 10 V voltage source and 5 Ω resistor in Figure 5a into the parallel current source and 5 Ω resistor in Figure 6a. The current source current is calculated from the voltage source voltage and resistance as $\frac{10\text{ V}}{5\ \Omega} = 2\text{ A}$. After the source transformation, the 5 Ω resistor is parallel to the 20 Ω resistor. Also, the 2 A current source is parallel to the 1 A current source. Replacing these parallel resistors with the equivalent 4 Ω resistor and replacing the parallel current sources with the equivalent 1 A current source produces the circuit shown in Figure 6b.

A second source transformation transforms the parallel 1 A current source and 4 Ω resistor in Figure 6b into the series voltage source and 4 Ω resistor in Figure 6c. The voltage source voltage is calculated from the current source current and resistance as $(1\text{ A})(4\ \Omega) = 4\text{ V}$. After the source transformation, the two 4 Ω resistors are in series. Replacing the series resistors with the equivalent 8 Ω produces the circuit shown in Figure 6d.

Comparing Figure 6d to Figure 5b shows that Thevenin resistance is R_{th} = 8 Ω and that the open circuit voltage, V_{oc} = 4 V.

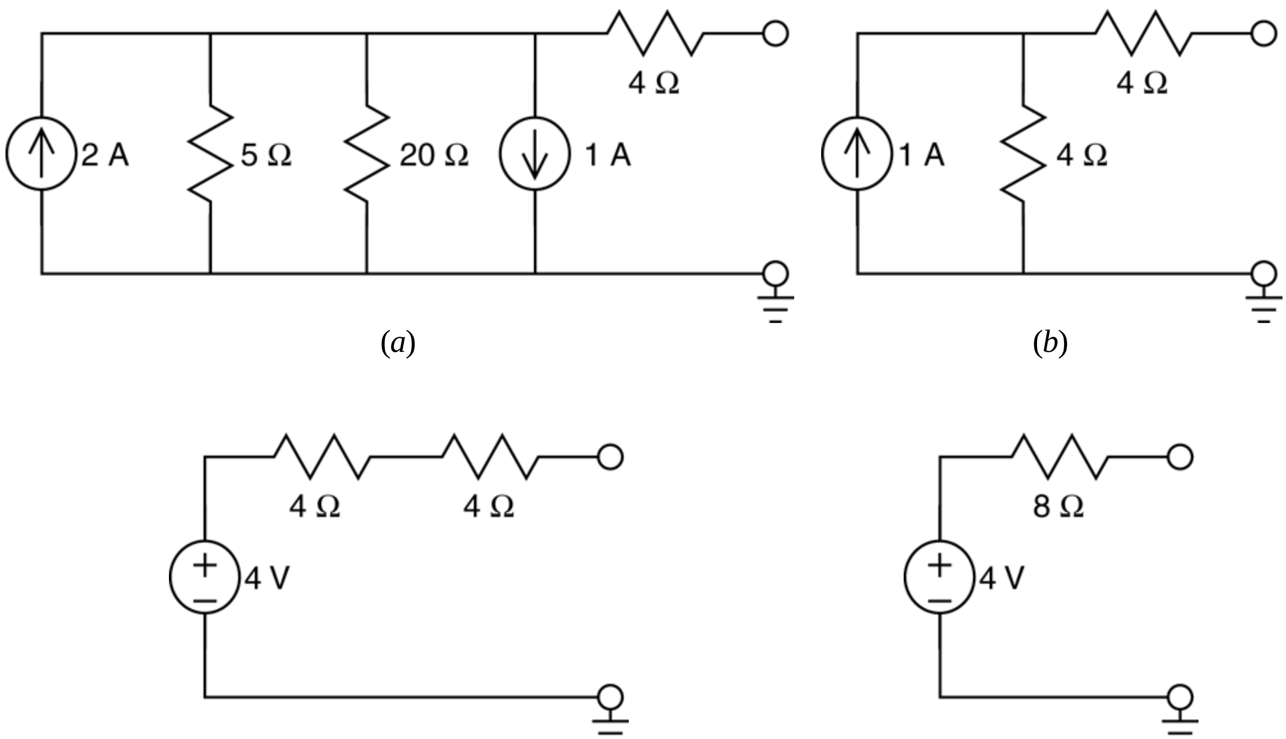


Figure 6 The circuit from Figure 5a can be reduced to its Thevenin equivalent circuit in four steps shown here as (*a*), (*b*), (*c*), and (*d*).

Example 4:

The circuit shown in Figure 7b is the Thevenin equivalent circuit of the circuit shown in Figure 7a. Find the value of the open circuit voltage, V_{oc} and Thevenin resistance, R_{th}. Also, determine the value of the short circuit current, I_{sc}.

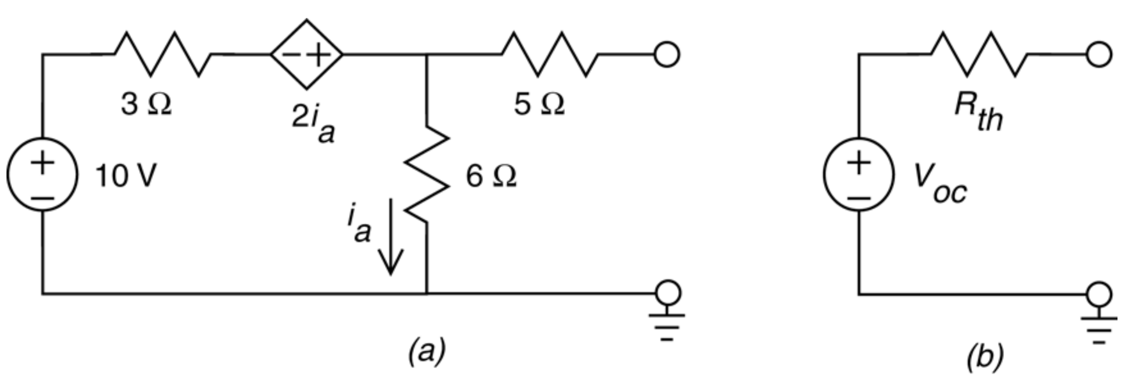


Figure 7 The circuit considered in Example 4.

Solution: To determine the value of the open circuit voltage, V_{oc}, we connect an open circuit across the terminals of the circuit and then calculate the value of the voltage across that open circuit. Figure 8 shows the circuit from Figure 7a after adding the open circuit and labeling the open circuit voltage. Also, the meshes have been identified and labeled in anticipation of writing mesh equations. Let i_1 and i_2 denote the mesh currents in meshes 1 and 2, respectively.

In Figure 8, mesh current i_2 is equal to the current in the open circuit. Consequently, $i_2 = 0$ A. The controlling current of the CCVS is expressed in terms of the mesh currents as

$$i_a = i_1 - i_2 = i_1 - 0 = i_1$$

Apply KVL to mesh 1 to get

$$3\,i_1 - 2\left(i_1 - i_2\right) + 6\left(i_1 - i_2\right) - 10 = 0 \quad\Rightarrow\quad 3\,i_1 - 2\left(i_1 - 0\right) + 6\left(i_1 - 0\right) - 10 = 0$$

$$\Rightarrow\quad i_1 = \frac{10}{7} = 1.43 \text{ A}$$

Apply KVL to mesh 2 to get

$$5\,i_2 + V_{oc} - 6\left(i_1 - i_2\right) = 0 \quad\Rightarrow\quad V_{oc} = 6\left(i_1\right) = 6\left(1.43\right) = 8.58 \text{ V}$$

Next, to determine the value of the short circuit current, I_{sc}, we connect a short circuit across the terminals of the circuit and then calculate the value of the current in that short circuit. Figure 9 shows the circuit from Figure 7a after adding the short circuit and labeling the short circuit current. Also, the meshes have been identified and labeled in anticipation of writing mesh equations. Let i_1 and i_2 denote the mesh currents in meshes 1 and 2, respectively.

In Figure 9, mesh current i_2 is equal to the current in the short circuit. Consequently, $i_2 = I_{sc}$. The controlling current of the CCVS is expressed in terms of the mesh currents as

$$i_a = i_1 - i_2 = i_1 - I_{sc}$$

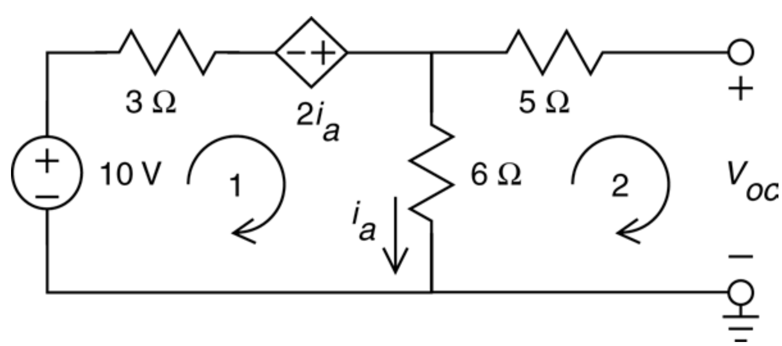


Figure 8 Calculating the open circuit voltage, V_{oc}, using mesh equations.

Apply KVL to mesh 1 to get

$$3\,i_1 - 2\left(i_1 - i_2\right) + 6\left(i_1 - i_2\right) - 10 = 0 \quad\Rightarrow\quad 7\,i_1 - 4\,i_2 = 10 \qquad (1)$$

Apply KVL to mesh 2 to get

$$5\,i_2 - 6\left(i_1 - i_2\right) = 0 \quad\Rightarrow\quad -6\,i_1 + 11\,i_2 = 0 \quad\Rightarrow\quad i_1 = \frac{11}{6}\,i_2$$

Substituting into equation 1 gives

$$7\left(\frac{11}{6}\,i_2\right) - 4\,i_2 = 10 \quad\Rightarrow\quad i_2 = 1.13\text{ A} \quad\Rightarrow\quad I_{sc} = 1.13\text{ A}$$

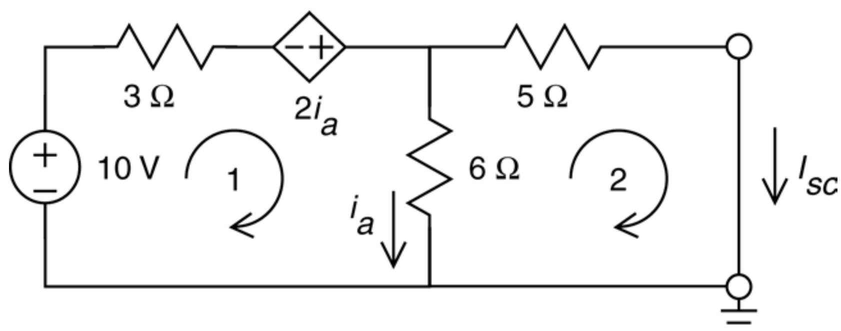


Figure 9 Calculating the short circuit current, I_{sc}, using mesh equations.

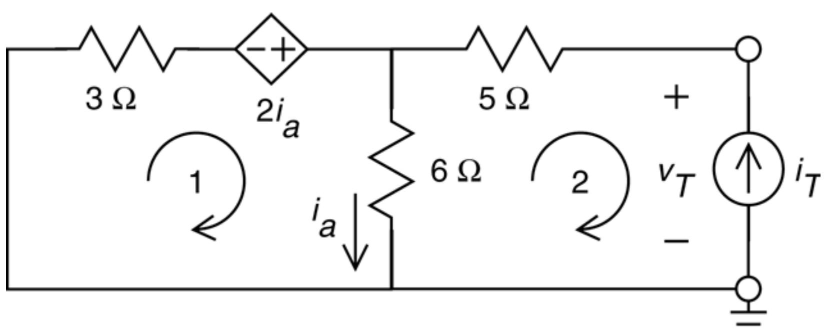


Figure 10 Calculating the Thevenin resistance, $R_{th} = \dfrac{v_T}{i_T}$, using mesh equations.

To determine the value of the Thevenin resistance, R_{th}, first replace the 10 V voltage source by a 0 V voltage source, i.e. a short circuit. Next, connect a current source across the terminals of the circuit and then label the voltage across that current source as shown in Figure 10. The Thevenin resistance will be calculated from the current and voltage of the current source as

$$R_{th} = \frac{v_T}{i_T}$$

In Figure 10, the meshes have been identified and labeled in anticipation of writing mesh equations. Let i_1 and i_2 denote the mesh currents in meshes 1 and 2, respectively.

In Figure 10, mesh current i_2 is equal to the negative of the current source current. Consequently, $i_2 = -i_T$. The controlling current of the CCVS is expressed in terms of the mesh currents as

$$i_a = i_1 - i_2 = i_1 + i_T$$

Apply KVL to mesh 1 to get

$$3\, i_1 - 2\left(i_1 - i_2\right) + 6\left(i_1 - i_2\right) = 0 \quad \Rightarrow \quad 7\, i_1 - 4\, i_2 = 0 \quad \Rightarrow \quad i_1 = \frac{4}{7} i_2 \qquad (2)$$

Apply KVL to mesh 2 to get

$$5\, i_2 + v_T - 6\left(i_1 - i_2\right) = 0 \quad \Rightarrow \quad -6\, i_1 + 11\, i_2 = -v_T$$

Substituting for i_1 using equation 2 gives

$$-6\left(\frac{4}{7} i_2\right) + 11\, i_2 = -v_T \quad \Rightarrow \quad 7.57\, i_2 = -v_T$$

Finally,

$$R_{th} = \frac{v_T}{i_T} = \frac{-v_T}{-i_T} = \frac{-v_T}{i_2} = 7.57\ \Omega$$

As a check, notice that

$$R_{th}\, I_{sc} = \left(7.57\right)\left(1.13\right) = 8.55 \approx V_{oc}$$

Example 5:

The circuit shown in Figure 11b is the Thevenin equivalent circuit of the circuit shown in Figure 11a. Find the value of the open circuit voltage, V_{oc} and Thevenin resistance, R_{th}. Also, determine the value of the short circuit current, I_{sc}.

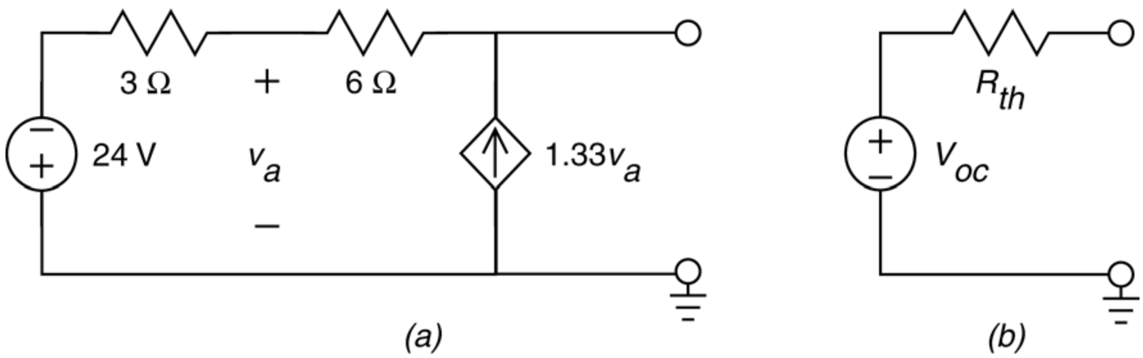


Figure 11 The circuit considered in Example 5.

Solution: To determine the value of the open circuit voltage, V_{oc}, we connect an open circuit across the terminals of the circuit and then calculate the value of the voltage across that open circuit. Figure 12 shows the circuit from Figure 11a after adding the open circuit and labeling the open circuit voltage. Also, the nodes have been identified and labeled in anticipation of writing node equations. Let v_1, v_2 and v_3 denote the node voltages at nodes 1, 2 and 3, respectively.

In Figure 12, node voltage v_1 is equal to the negative of the voltage source voltage. Consequently, $v_1 = -24\text{ V}$. The controlling voltage of the VCCS, v_a, is equal to the node voltage at node 2, i.e. $v_a = v_2$. The voltage at node 3 is equal to the open circuit voltage, i.e. $v_3 = V_{oc}$.

Apply KCL at node 2 to get

$$\frac{v_1 - v_2}{3} = \frac{v_2 - v_3}{6} \quad \Rightarrow \quad 2\,v_1 + v_3 = 3\,v_2 \quad \Rightarrow \quad -48 + V_{oc} = 3\,v_a$$

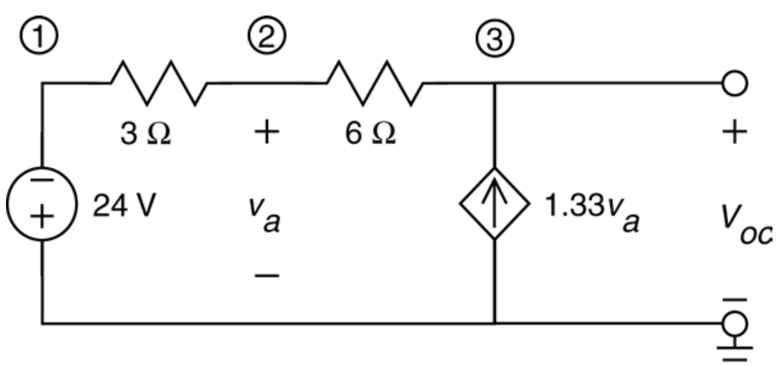


Figure 12 Calculating the open circuit voltage, V_{oc}, using node equations.

Apply KCL at node 3 to get

$$\frac{v_2 - v_3}{6} + \frac{4}{3} v_2 = 0 \quad \Rightarrow \quad 9 v_2 - v_3 = 0 \quad \Rightarrow \quad 9 v_a = V_{oc}$$

Combining these equations gives

$$3\left(-48 + V_{oc}\right) = 9\, v_a = V_{oc} \quad \Rightarrow \quad V_{oc} = 72 \text{ V}$$

Next, to determine the value of the short circuit current, I_{sc}, we connect a short circuit across the terminals of the circuit and then calculate the value of the current in that short circuit. Figure 13 shows the circuit from Figure 7a after adding the short circuit and labeling the short circuit current. Also, the nodes have been identified and labeled in anticipation of writing node equations. Let v_1, v_2 and v_3 denote the node voltages at nodes 1, 2 and 3, respectively.

In Figure 13, node voltage v_1 is equal to the negative of the voltage source voltage. Consequently, $v_1 = -24$ V. The voltage at node 3 is equal to the voltage across a short, $v_3 = 0$. The controlling voltage of the VCCS, v_a, is equal to the node voltage at node 2, i.e. $v_a = v_2$. The voltage at node 3 is equal to the voltage across a short, i.e. $v_3 = 0$.

Apply KCL at node 2 to get

$$\frac{v_1 - v_2}{3} = \frac{v_2 - v_3}{6} \quad \Rightarrow \quad 2 v_1 + v_3 = 3 v_2 \quad \Rightarrow \quad -48 = 3 v_a \quad \Rightarrow \quad v_a = -16 \text{ V}$$

Apply KCL at node 3 to get

$$\frac{v_2 - v_3}{6} + \frac{4}{3} v_2 = I_{sc} \quad \Rightarrow \quad \frac{9}{6} v_a = I_{sc} \quad \Rightarrow \quad I_{sc} = \frac{9}{6}\left(-16\right) = -24 \text{ A}$$

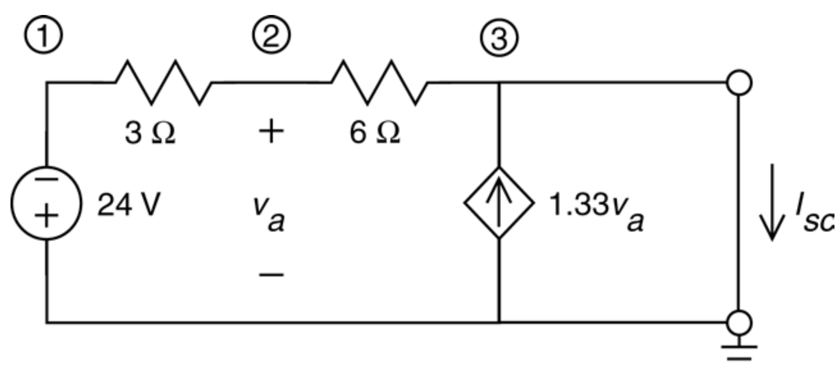


Figure 13 Calculating the short circuit current, I_{sc}, using mesh equations.

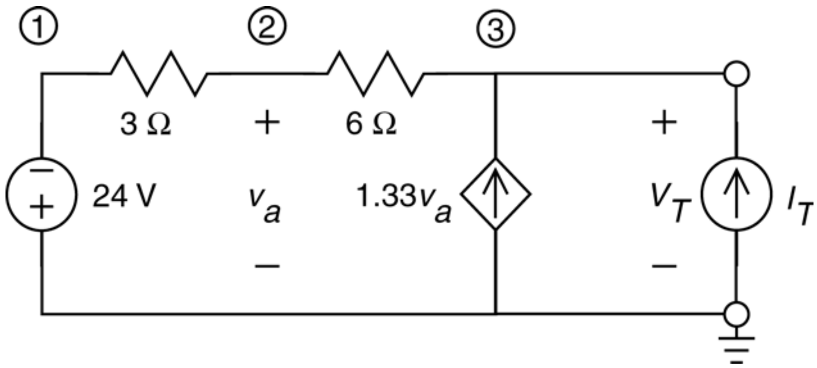


Figure 14 Calculating the Thevenin resistance, $R_{th} = \dfrac{v_T}{i_T}$, using mesh equations.

To determine the value of the Thevenin resistance, R_{th}, first replace the 24 V voltage source by a 0 V voltage source, i.e. a short circuit. Next, connect a current source circuit across the terminals of the circuit and then label the voltage across that current source as shown in Figure 14. The Thevenin resistance will be calculated from the current and voltage of the current source as

$$R_{th} = \frac{v_T}{i_T}$$

Also, the nodes have been identified and labeled in anticipation of writing node equations. Let v_1, v_2 and v_3 denote the node voltages at nodes 1, 2 and 3, respectively.

In Figure 14, node voltage v_1 is equal to the across a short circuit, i.e. $v_1 = 0$. The controlling voltage of the VCCS, v_a, is equal to the node voltage at node 2, i.e. $v_a = v_2$. The voltage at node 3 is equal to the voltage across the current source, i.e. $v_3 = v_T$.

Apply KCL at node 2 to get

$$\frac{v_1 - v_2}{3} = \frac{v_2 - v_3}{6} \quad \Rightarrow \quad 2\,v_1 + v_3 = 3\,v_2 \quad \Rightarrow \quad v_T = 3\,v_a$$

Apply KCL at node 3 to get

$$\frac{v_2 - v_3}{6} + \frac{4}{3}v_2 + i_T = 0 \quad \Rightarrow \quad 9\,v_2 - v_3 + 6\,i_T = 0$$

$$\Rightarrow \quad 9\,v_a - v_T + 6\,i_T = 0$$

$$\Rightarrow \quad 3\,v_T - v_T + 6\,i_T = 0 \quad \Rightarrow \quad 2\,v_T = -6\,i_T$$

Finally,

$$R_{th} = \frac{v_T}{i_T} = -3\,\Omega$$

As a check, notice that

Bipolar Transistor Basics

In the **Diode** tutorials we saw that simple diodes are made up from two pieces of semiconductor material, either silicon or germanium to form a simple PN-junction and we also learnt about their properties and characteristics. If we now join together two individual signal diodes back-to-back, this will give us two PN-junctions connected together in series that share a common P or N terminal. The fusion of these two diodes produces a three layer, two junction, three terminal device forming the basis of a **Bipolar Transistor**, or **BJT** for short.

Transistors are three terminal active devices made from different semiconductor materials that can act as either an insulator or a conductor by the application of a small signal voltage. The transistor's ability to change between these two states enables it to have two basic functions: "switching" (digital electronics) or "amplification" (analogue electronics). Then bipolar transistors have the ability to operate within three different regions:

- 1. Active Region - the transistor operates as an amplifier and Ic = β.Ib
-
- 2. Saturation - the transistor is "fully-ON" operating as a switch and Ic = I(saturation)
-
- 3. Cut-off - the transistor is "fully-OFF" operating as a switch and Ic = 0

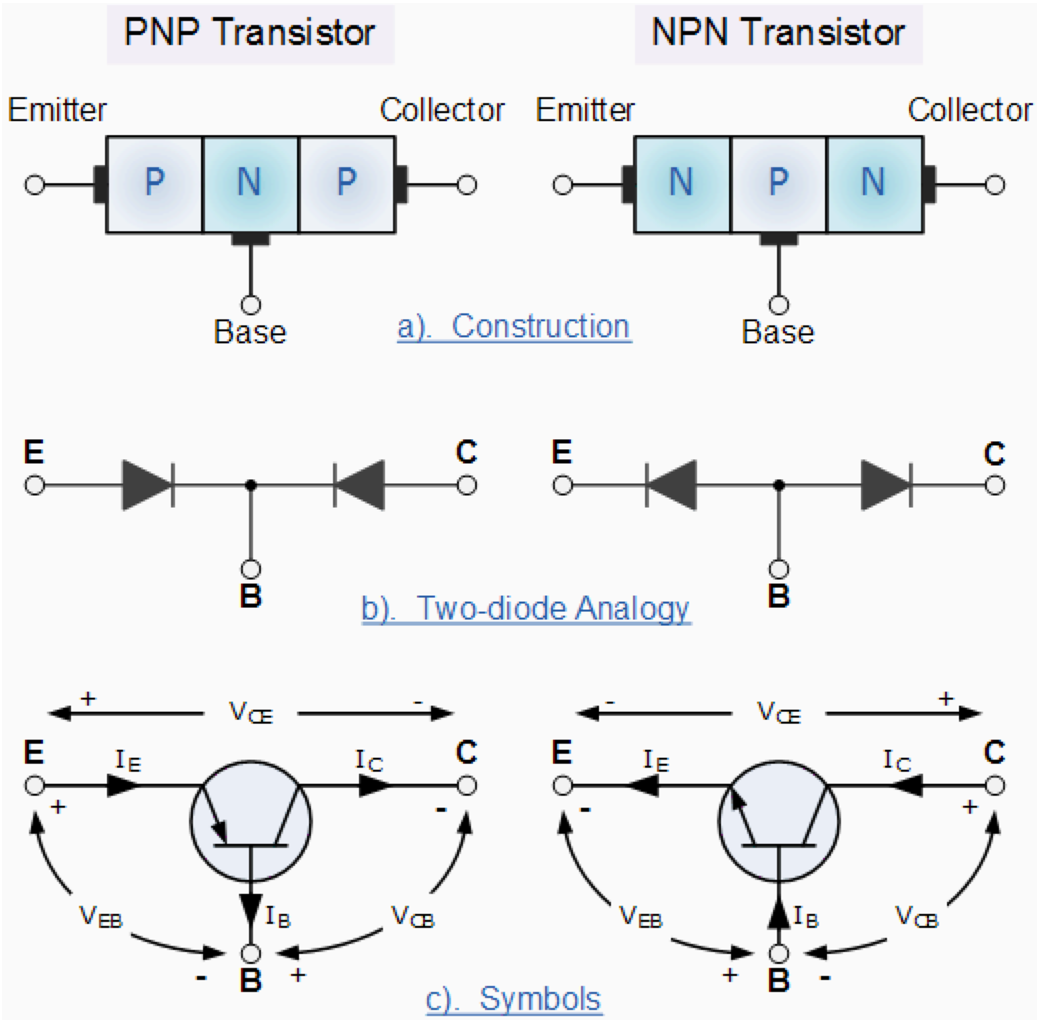
Typical Bipolar Transistor

The word Transistor is an acronym, and is a combination of the words Transfer Varistor used to describe their mode of operation way back in their early days of development. There are two basic types of bipolar transistor construction, NPN and PNP, which basically describes the physical arrangement of the P-type and N-type semiconductor materials from which they are made.

The **Bipolar Transistor** basic construction consists of two PN-junctions producing three connecting terminals with each terminal being given a name to identify it from the other two. These three terminals are known and labelled as the Emitter (E), the Base (B) and the Collector (C) respectively.

Bipolar Transistors are current regulating devices that control the amount of current flowing through them in proportion to the amount of biasing voltage applied to their base terminal acting like a current-controlled switch. The principle of operation of the two transistor types NPN and PNP, is exactly the same the only difference being in their biasing and the polarity of the power supply for each type.

Bipolar Transistor Construction



The construction and circuit symbols for both the NPN and PNP bipolar transistor are given above with the arrow in the circuit symbol always showing the direction of "conventional current flow" between the base terminal and its emitter terminal. The direction of the arrow always points from the positive P-type region to the negative N-type region for both transistor types, exactly the same as for the standard diode symbol.

Bipolar Transistor Configurations

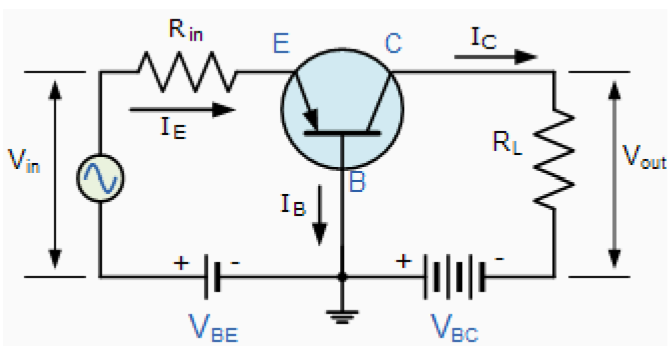
As the **Bipolar Transistor** is a three terminal device, there are basically three possible ways to connect it within an electronic circuit with one terminal being common to both the input and output. Each method of connection responding differently to its input signal within a circuit as the static characteristics of the transistor vary with each circuit arrangement.

- 1. Common Base Configuration - has Voltage Gain but no Current Gain.
-
- 2. Common Emitter Configuration - has both Current and Voltage Gain.
-
- 3. Common Collector Configuration - has Current Gain but no Voltage Gain.

The Common Base (CB) Configuration

As its name suggests, in the **Common Base** or grounded base configuration, the BASE connection is common to both the input signal AND the output signal with the input signal being applied between the base and the emitter terminals. The corresponding output signal is taken from between the base and the collector terminals as shown with the base terminal grounded or connected to a fixed reference voltage point. The input current flowing into the emitter is quite large as its the sum of both the base current and collector current respectively therefore, the collector current output is less than the emitter current input resulting in a current gain for this type of circuit of "1" (unity) or less, in other words the common base configuration "attenuates" the input signal.

The Common Base Transistor Circuit



This type of amplifier configuration is a non-inverting voltage amplifier circuit, in that the signal voltages Vin and Vout are in-phase. This type of transistor arrangement is not very common due to its unusually high voltage gain characteristics. Its output characteristics represent that of a forward biased diode while the input characteristics represent that of an illuminated photo-diode. Also this type of bipolar transistor configuration has a high ratio of output to input resistance or more importantly "load" resistance (RL) to "input" resistance (Rin) giving it a value of "Resistance Gain". Then the voltage gain (Av for a common base configuration is therefore given as:

Common Base Voltage Gain

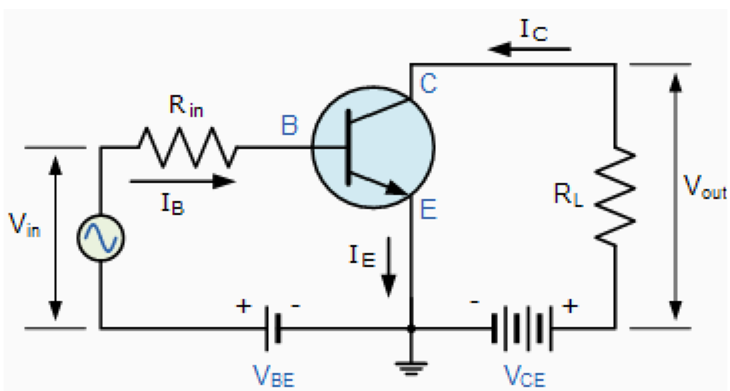
$$A_V = \frac{Vout}{Vin} = \frac{I_C \times R_L}{I_E \times R_{IN}}$$

The common base circuit is generally only used in single stage amplifier circuits such as microphone pre-amplifier or radio frequency (Rf) amplifiers due to its very good high frequency response.

The Common Emitter (CE) Configuration

In the **Common Emitter** or grounded emitter configuration, the input signal is applied between the base, while the output is taken from between the collector and the emitter as shown. This type of configuration is the most commonly used circuit for transistor based amplifiers and which represents the "normal" method of bipolar transistor connection. The common emitter amplifier configuration produces the highest current and power gain of all the three bipolar transistor configurations. This is mainly because the input impedance is LOW as it is connected to a forward-biased PN-junction, while the output impedance is HIGH as it is taken from a reverse-biased PN-junction.

The Common Emitter Amplifier Circuit



In this type of configuration, the current flowing out of the transistor must be equal to the currents flowing into the transistor as the emitter current is given as $Ie = Ic + Ib$. Also, as the load resistance (RL) is connected in series with the collector, the current gain of the common emitter transistor configuration is quite large as it is the ratio of Ic/Ib and is given the Greek symbol of Beta, (β). As the emitter current for a common emitter configuration is defined as $Ie = Ic + Ib$, the ratio of Ic/Ie is called Alpha, given the Greek symbol of α. Note: that the value of Alpha will always be less than unity.

Since the electrical relationship between these three currents, Ib, Ic and Ie is determined by the physical construction of the transistor itself, any small change in the base current (Ib), will result in a much larger change in the collector current (Ic). Then, small changes in current flowing in the base will thus control the current in the emitter-collector circuit. Typically, Beta has a value between 20 and 200 for most general purpose transistors.

By combining the expressions for both Alpha, α and Beta, β the mathematical relationship between these parameters and therefore the current gain of the transistor can be given as:

$$\text{Alpha}, (\alpha) = \frac{I_C}{I_E} \quad \text{and} \quad \text{Beta}, (\beta) = \frac{I_C}{I_B}$$

$$\therefore I_C = \alpha.I_E = \beta.I_B$$

$$\text{as:} \quad \alpha = \frac{\beta}{\beta + 1} \qquad \beta = \frac{\alpha}{1 - \alpha}$$

$$I_E = I_C + I_B$$

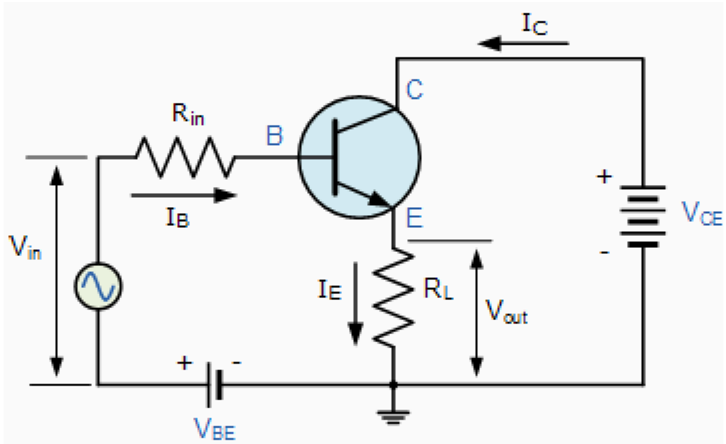
Where: "Ic" is the current flowing into the collector terminal, "Ib" is the current flowing into the base terminal and "Ie" is the current flowing out of the emitter terminal.

Then to summarise, this type of bipolar transistor configuration has a greater input impedance, current and power gain than that of the common base configuration but its voltage gain is much lower. The common emitter configuration is an inverting amplifier circuit resulting in the output signal being 180^{o} out-of-phase with the input voltage signal.

The Common Collector (CC) Configuration

In the **Common Collector** or grounded collector configuration, the collector is now common through the supply. The input signal is connected directly to the base, while the output is taken from the emitter load as shown. This type of configuration is commonly known as a **Voltage Follower** or **Emitter Follower** circuit. The emitter follower configuration is very useful for impedance matching applications because of the very high input impedance, in the region of hundreds of thousands of Ohms while having a relatively low output impedance.

The Common Collector Transistor Circuit



The common emitter configuration has a current gain approximately equal to the β value of the transistor itself. In the common collector configuration the load resistance is situated in series with the emitter so its current is equal to that of the emitter current. As the emitter current is the combination of the collector AND the base current combined, the load resistance in this type of transistor configuration also has both the collector current and the input current of the base flowing through it. Then the current gain of the circuit is given as:

The Common Collector Current Gain

$$I_E = I_C + I_B$$

$$A_i = \frac{I_E}{I_B} = \frac{I_C + I_B}{I_B}$$

$$A_i = \frac{I_C}{I_B} + 1$$

$$A_i = \beta + 1$$

This type of bipolar transistor configuration is a non-inverting circuit in that the signal voltages of Vin and Vout are in-phase. It has a voltage gain that is always less than "1" (unity). The load resistance of the common collector transistor receives both the base and collector currents giving a large current gain (as with the common emitter configuration) therefore, providing good current amplification with very little voltage gain.

Bipolar Transistor Summary

Then to summarise, the behaviour of the bipolar transistor in each one of the above circuit configurations is very different and produces different circuit characteristics with regards to input impedance, output impedance and gain whether this is voltage gain, current gain or power gain and this is summarised in the table below.

Bipolar Transistor Characteristics

The static characteristics for a **Bipolar Transistor** can be divided into the following three main groups.

Input Characteristics:-	Common Base -	$\Delta V_{EB} / \Delta I_E$
	Common Emitter -	$\Delta V_{BE} / \Delta I_B$
Output Characteristics:-	Common Base -	$\Delta V_C / \Delta I_C$
	Common Emitter -	$\Delta V_C / \Delta I_C$
Transfer Characteristics:-	Common Base -	$\Delta I_C / \Delta I_E$
	Common Emitter -	$\Delta I_C / \Delta I_B$

with the characteristics of the different transistor configurations given in the following table:

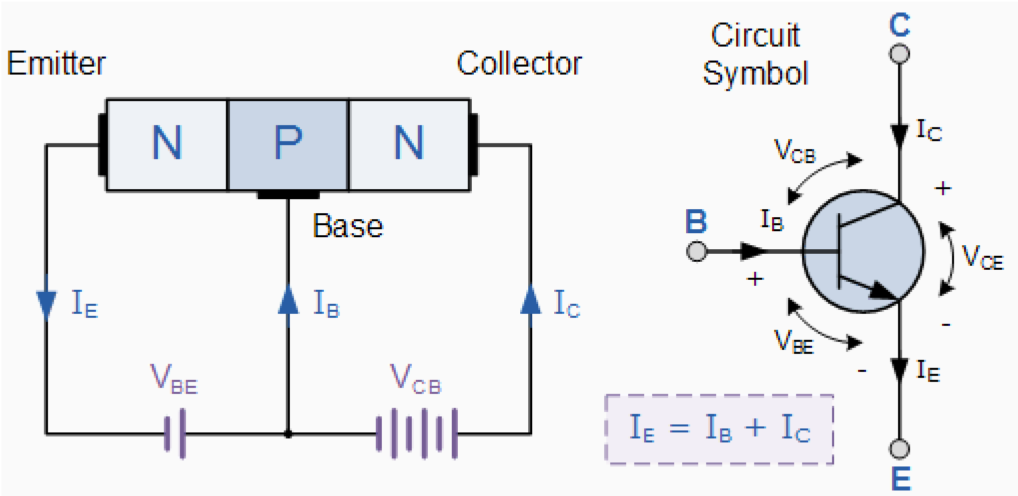
Characteristic	Common Base	Common Emitter	Common Collector
Input Impedance	Low	Medium	High
Output Impedance	Very High	High	Low
Phase Angle	0^o	180^o	0^o
Voltage Gain	High	Medium	Low
Current Gain	Low	Medium	High
Power Gain	Low	Very High	Medium

In the next tutorial about **Bipolar Transistors**, we will look at the NPN Transistor in more detail when used in the common emitter configuration as an amplifier as this is the most widely used configuration due to its flexibility and high gain. We will also plot the output characteristics curves commonly associated with amplifier circuits as a function of the collector current to the base current.

The NPN Transistor

In the previous tutorial we saw that the standard **Bipolar Transistor** or BJT, comes in two basic forms. An NPN (Negative-Positive-Negative) type and a PNP (Positive-Negative-Positive) type, with the most commonly used transistor type being the **NPN Transistor**. We also learnt that the transistor junctions can be biased in one of three different ways - **Common Base**, **Common Emitter** and **Common Collector**. In this tutorial we will look more closely at the "Common Emitter" configuration using **NPN Transistors** with an example of the construction of a NPN transistor along with the transistors current flow characteristics is given below.

An NPN Transistor Configuration



Note: Conventional current flow.

We know that the transistor is a **"current"** operated device (Beta model) and that a large current (Ic) flows freely through the device between the collector and the emitter terminals when the transistor is switched "fully-ON". However, this only happens when a small biasing current (Ib) is flowing into the base terminal of the transistor at the same time thus allowing the Base to act as a sort of current control input. The transistor current in an NPN transistor is the ratio of these two currents (Ic/Ib), called the *DC Current Gain* of the device and is given the symbol of hfe or nowadays Beta, (β). The value of β can be large up to 200 for standard transistors, and it is this large ratio between Ic and Ib that makes the NPN transistor a useful amplifying device when used in its active region as Ib provides the input and Ic provides the output. Note that Beta has no units as it is a ratio.

Also, the current gain of the transistor from the Collector terminal to the Emitter terminal, Ic/Ie, is called Alpha, (α), and is a function of the transistor itself (electrons diffusing across the junction). As the emitter current Ie is the product of a very small base current plus a very large collector current, the value of alpha α, is very close to unity, and for a typical low-power signal transistor this value ranges from about 0.950 to 0.999

α and β Relationship in a NPN Transistor

$$\text{DC Current Gain} = \frac{\text{Output Current}}{\text{Input Current}} = \frac{I_C}{I_B}$$

$$I_E = I_B + I_C \; \ldots\ldots \; (\text{KCL}) \quad \text{and} \quad \frac{I_C}{I_E} = \alpha$$

$$\text{Thus:} \quad I_E = I_B + I_C = \frac{I_C}{\alpha}$$

$$\text{and} \quad I_B = I_C\left(1 - \frac{1}{\alpha}\right)$$

$$\therefore \quad \beta = \frac{I_C}{I_B} = \frac{1}{\left(1 - \frac{1}{\alpha}\right)} = \frac{\alpha}{1-\alpha}$$

By combining the two parameters α and β we can produce two mathematical expressions that gives the relationship between the different currents flowing in the transistor.

$$\beta = \frac{\alpha}{1-\alpha} \quad \text{and} \quad \alpha = \frac{\beta}{\beta+1}$$

$$\text{If} \quad \alpha = 0.99 \qquad \beta = \frac{0.99}{0.01} = 99$$

The values of Beta vary from about 20 for high current power transistors to well over 1000 for high frequency low power type bipolar transistors. The value of Beta for most standard NPN transistors can be found in the manufactures datasheets but generally range between 50 - 200.

The equation above for Beta can also be re-arranged to make Ic as the subject, and with a zero base current (Ib = 0) the resultant collector current Ic will also be zero, (β x 0). Also when the base current is high the corresponding collector current will also be high resulting in the base current controlling the collector current. One of the most important properties of the **Bipolar Junction Transistor** is that a small base current can control a much larger collector current. Consider the following example.

Example No1

An NPN Transistor has a DC current gain, (Beta) value of 200. Calculate the base current Ib required to switch a resistive load of 4mA.

$$I_B = \frac{I_C}{\beta} = \frac{4 \times 10^{-3}}{200} = 20\mu A$$

Therefore, β = 200, Ic = 4mA and Ib = 20µA.

One other point to remember about **NPN Transistors**. The collector voltage, (Vc) must be greater and positive with respect to the emitter voltage, (Ve) to allow current to flow through the transistor between the collector-emitter junctions. Also, there is a voltage drop between the Base and the Emitter terminal of about 0.7v (one diode volt drop) for silicon devices as the input characteristics of an NPN Transistor are of a forward biased diode. Then the base voltage, (Vbe) of a NPN transistor must be greater than this 0.7V otherwise the transistor will not conduct with the base current given as.

$$I_B = \frac{V_B - V_{BE}}{R_B}$$

Where: Ib is the base current, Vb is the base bias voltage, Vbe is the base-emitter volt drop (0.7v) and Rb is the base input resistor. Increasing Ib, Vbe slowly increases to 0.7V but Ic rises exponentially.

Example No2

An NPN Transistor has a DC base bias voltage, Vb of 10v and an input base resistor, Rb of 100kΩ. What will be the value of the base current into the transistor.

$$I_B = \frac{V_B - V_{BE}}{R_B} = \frac{10 - 0.7}{100k\Omega} = 93\mu A$$

Therefore, Ib = 93µA.

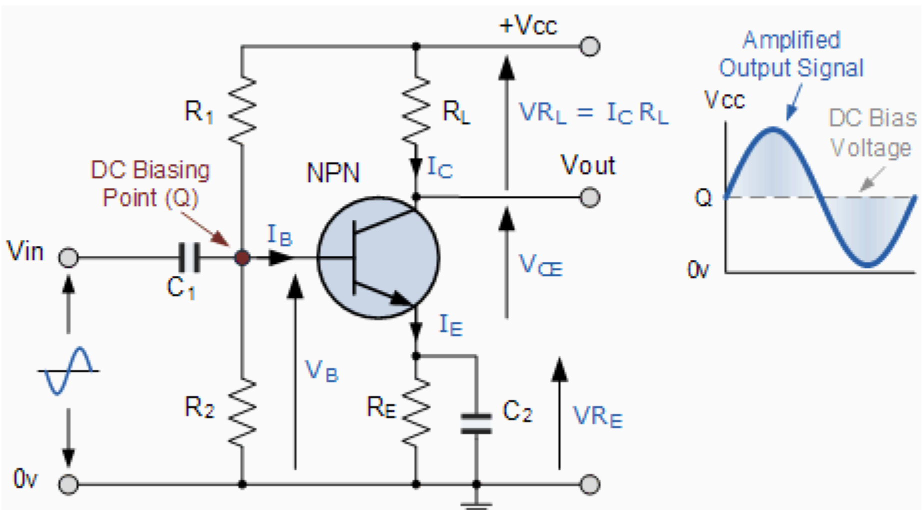
The Common Emitter Configuration.

As well as being used as a semiconductor switch to turn load currents "ON" or "OFF" by controlling the Base signal to the transistor in ether its saturation or cut-off regions, **NPN Transistors** can also be used in its active region to produce a circuit which will amplify any small AC signal applied to its Base terminal with the Emitter grounded. If a suitable DC "biasing" voltage is firstly applied to the transistors Base terminal thus allowing it to always operate within its linear active region, an inverting amplifier circuit called a single stage common emitter amplifier is produced.

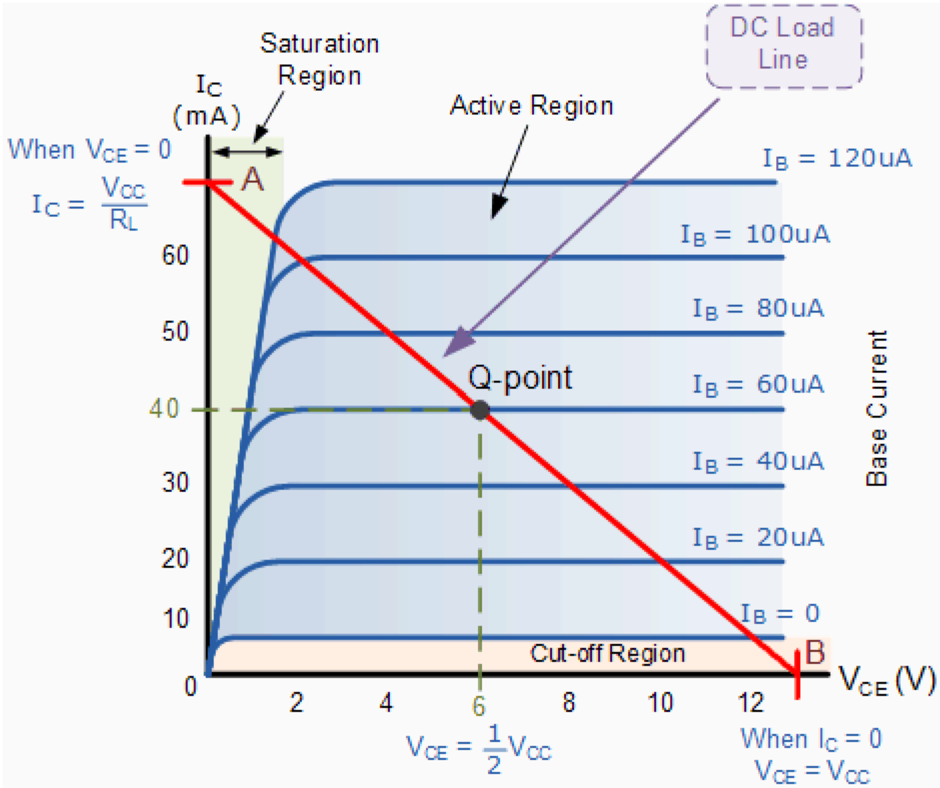
One such *Common Emitter Amplifier* configuration of an NPN transistor is called a **Class A Amplifier**. A "Class A Amplifier" operation is one where the transistors Base terminal is biased in such a way as to forward bias the Base-emitter junction. The result is that the transistor is always operating halfway between its cut-off and saturation regions, thereby allowing the transistor amplifier to accurately reproduce the positive and negative halves of any AC input signal superimposed upon this DC biasing voltage. Without this "Bias Voltage" only one half of the input waveform would be amplified. This common emitter amplifier configuration using an NPN transistor has many applications but is commonly used in audio circuits such as pre-amplifier and power amplifier stages.

With reference to the common emitter configuration shown below, a family of curves known as the **Output Characteristics Curves**, relates the output collector current, (Ic) to the collector voltage, (Vce) when different values of Base current, (Ib) are applied to the transistor for transistors with the same β value. A DC "Load Line" can also be drawn onto the output characteristics curves to show all the possible operating points when different values of base current are applied. It is necessary to set the initial value of Vce correctly to allow the output voltage to vary both up and down when amplifying AC input signals and this is called setting the operating point or Quiescent Point, **Q-point** for short and this is shown below.

Single Stage Common Emitter Amplifier Circuit



Output Characteristics Curves for a Typical Bipolar Transistor



The most important factor to notice is the effect of Vce upon the collector current Ic when Vce is greater than about 1.0 volts. We can see that Ic is largely unaffected by changes in Vce above this value and instead it is almost entirely controlled by the base current, Ib. When this happens we can say then that the output circuit represents that of a "Constant Current Source". It can also be seen from the common emitter circuit above that the emitter current Ie is the sum of the collector current, Ic and the base current, Ib, added together so we can also say that " Ie = Ic + Ib " for the common emitter configuration.

By using the output characteristics curves in our example above and also Ohm´s Law, the current flowing through the load resistor, (RL), is equal to the collector current, Ic entering the transistor which inturn corresponds to the supply voltage, (Vcc) minus the voltage drop between the collector and the emitter terminals, (Vce) and is given as:

$$\text{Collector Current, } I_C = \frac{V_{CC} - V_{CE}}{R_L}$$

Also, a straight line representing the **Load Line** of the transistor can be drawn directly onto the graph of curves above from the point of "Saturation" (A) when Vce = 0 to the point of "Cut-off" (B) when Ic = 0 thus giving us the "Operating" or **Q-point** of the transistor. These two points are joined together by a straight line and any position along this straight line represents the "Active Region" of the transistor. The actual position of the load line on the characteristics curves can be calculated as follows:

$$\text{When}: \left(V_{CE} = 0\right) \quad I_C = \frac{V_{CC} - 0}{R_L}, \quad I_C = \frac{V_{CC}}{R_L}$$

$$\text{When}: \left(I_C = 0\right) \quad 0 = \frac{V_{CC} - V_{CE}}{R_L}, \quad V_{CC} = V_{CE}$$

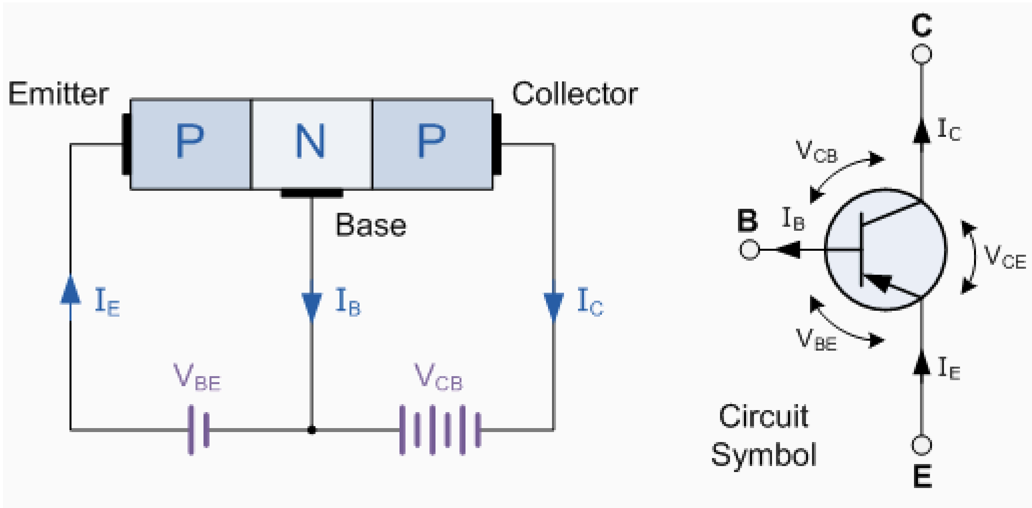
Then, the collector or output characteristics curves for **Common Emitter NPN Transistors** can be used to predict the Collector current, Ic, when given Vce and the Base current, Ib. A Load Line can also be constructed onto the curves to determine a suitable Operating or **Q-point** which can be set by adjustment of the base current. The slope of this load line is equal to the reciprocal of the load resistance which is given as: $-1/R_L$

In the next tutorial about **Bipolar Transistors**, we will look at the opposite or compliment form of the NPN Transistor called the **PNP Transistor** and show that the PNP Transistor has very similar characteristics to their NPN transistor except that the polarities (or biasing) of the current and voltage directions are reversed.

The PNP Transistor

The **PNP Transistor** is the exact opposite to the **NPN Transistor** device we looked at in the previous tutorial. Basically, in this type of transistor construction the two diodes are reversed with respect to the NPN type, with the arrow, which also defines the Emitter terminal this time pointing inwards in the transistor symbol. Also, all the polarities are reversed which means that *PNP Transistors* "sink" current as opposed to the NPN transistor which "sources" current. Then, PNP Transistors use a small output base current and a negative base voltage to control a much larger emitter-collector current. The construction of a PNP transistor consists of two P-type semiconductor materials either side of the N-type material as shown below.

A PNP Transistor Configuration



Note: Conventional current flow.

The **PNP Transistor** has very similar characteristics to their NPN bipolar cousins, except that the polarities (or biasing) of the current and voltage directions are reversed for any one of the possible three configurations looked at in the first tutorial, Common Base, Common Emitter and Common Collector. Generally, PNP Transistors require a negative (-ve) voltage at their Collector terminal with the flow of current through the emitter-collector terminals being **Holes** as opposed to **Electrons** for the NPN types. Because the movement of holes across the depletion layer tends to be slower than for electrons, PNP transistors are generally more slower than their equivalent NPN counterparts when operating.

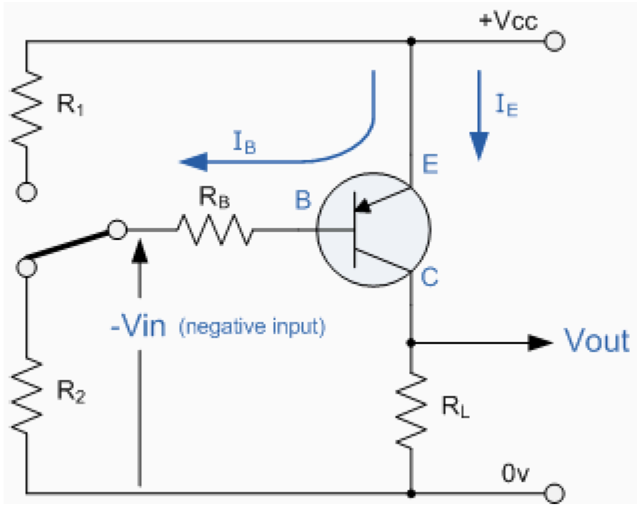
To cause the Base current to flow in a PNP transistor the Base needs to be more negative than the Emitter (current must leave the base) by approx 0.7 volts for a silicon device or 0.3 volts for a germanium device with the formulas used to calculate the Base resistor, Base current or Collector current are the same as those used for an equivalent NPN transistor and is given as.

$$I_E = I_C + I_B$$

$$I_C = \beta I_B \qquad I_B = \frac{I_C}{\beta}$$

Generally, the PNP transistor can replace NPN transistors in electronic circuits, the only difference is the polarities of the voltages, and the directions of the current flow. PNP Transistors can also be used as switching devices and an example of a PNP transistor switch is shown below.

A PNP Transistor Circuit



The **Output Characteristics Curves** for a PNP transistor look very similar to those for an equivalent NPN transistor except that they are rotated by 180^o to take account of the reverse polarity voltages and currents, (the currents flowing out of the Base and Collector in a PNP transistor are negative).

Transistor Matching

You may think what is the point of having a **PNP Transistor**, when there are plenty of NPN Transistors available?. Well, having two different types of transistors PNP & NPN, can be an advantage when designing amplifier circuits such as **Class B Amplifiers** that use "Complementary" or "Matched Pair" transistors or for reversible **H-Bridge** motor control circuits. A pair of corresponding NPN and PNP transistors with near identical characteristics to each other are called **Complementary Transistors** for example, a TIP3055 (NPN), TIP2955 (PNP) are good examples of complementary or matched pair silicon power transistors. They have a DC current gain, Beta, (Ic / Ib) matched to within 10% and high Collector current of about 15A making them suitable for general motor control or robotic applications.

Identifying the PNP Transistor

We saw in the first tutorial of this Transistors section, that transistors are basically made up of two **Diodes** connected together back-to-back. We can use this analogy to determine whether a transistor is of the type PNP or NPN by testing its Resistance between the three different leads, Emitter, Base and Collector. By testing each pair of transistor leads in both directions will result in six tests in total with the expected resistance values in Ohm's given below.

- 1. Emitter-Base Terminals - The Emitter to Base should act like a normal diode and conduct one way only.
-
- 2. Collector-Base Terminals - The Collector-Base junction should act like a normal diode and conduct one way only.

-
- 3. Emitter-Collector Terminals - The Emitter-Collector should not conduct in either direction.

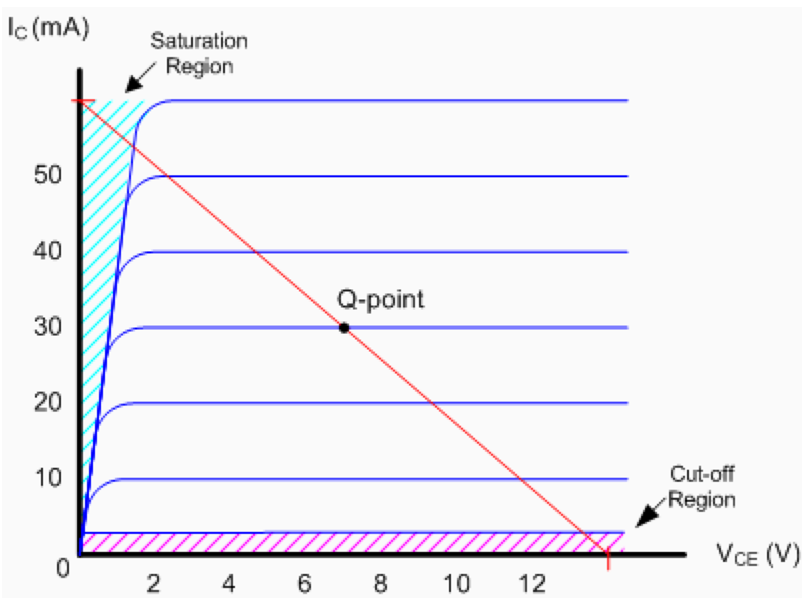
Transistor Resistance Values for the PNP transistor and NPN transistor types

Between Transistor Terminals		PNP	NPN
Collector	Emitter	R_{HIGH}	R_{HIGH}
Collector	Base	R_{LOW}	R_{HIGH}
Emitter	Collector	R_{HIGH}	R_{HIGH}
Emitter	Base	R_{LOW}	R_{HIGH}
Base	Collector	R_{HIGH}	R_{LOW}
Base	Emitter	R_{HIGH}	R_{LOW}

The Transistor as a Switch

When used as an AC signal amplifier, the transistors Base biasing voltage is applied so that it operates within its "**Active**" region and the linear part of the output characteristics curves are used. However, both the NPN & PNP type bipolar transistors can be made to operate as an "ON/OFF" type solid state switch for controlling high power devices such as motors, solenoids or lamps. If the circuit uses the **Transistor as a Switch**, then the biasing is arranged to operate in the output characteristics curves seen previously in the areas known as the "**Saturation**" and "**Cut-off**" regions as shown below.

Transistor Curves

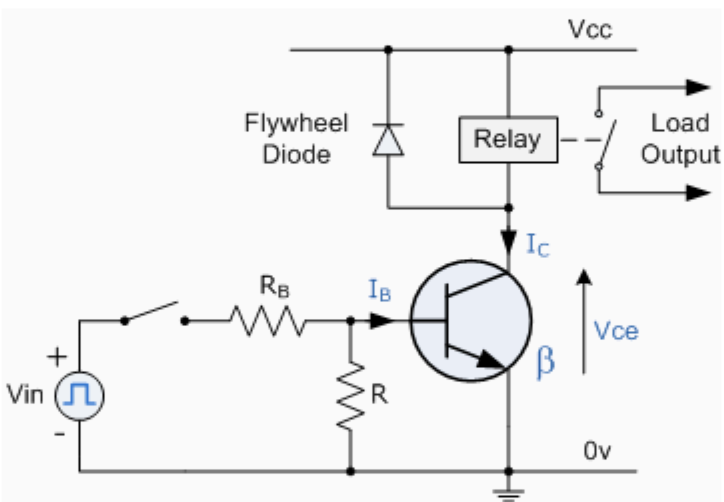


The pink shaded area at the bottom represents the "Cut-off" region. Here the operating conditions of the transistor are zero input base current (Ib), zero output collector current (Ic) and maximum collector voltage (Vce) which results in a large depletion layer and no current flows through the device. The transistor is switched "Fully-OFF". The lighter blue area to the left represents the "Saturation" region. Here the transistor will be biased so that the maximum amount of base current is applied, resulting in maximum collector current flow and minimum collector emitter voltage which results in the depletion layer being as small as possible and maximum current flows through the device. The transistor is switched "Fully-ON". Then we can summarize this as:

- 1. Cut-off Region - Both junctions are Reverse-biased, Base current is zero or very small resulting in zero Collector current flowing, the device is switched fully "OFF".
-
- 2. Saturation Region - Both junctions are Forward-biased, Base current is high enough to give a Collector-Emitter voltage of 0v resulting in maximum Collector current flowing, the device is switched fully "ON".

An example of an NPN Transistor as a switch being used to operate a relay is given below. With inductive loads such as relays or solenoids a flywheel diode is placed across the load to dissipate the back EMF generated by the inductive load when the transistor switches "OFF" and so protect the transistor from damage. If the load is of a very high current or voltage nature, such as motors, heaters etc, then the load current can be controlled via a suitable relay as shown.

Transistor Switching Circuit



The circuit resembles that of the **Common Emitter** circuit we looked at in the previous tutorials. The difference this time is that to operate the transistor as a switch the transistor needs to be turned either fully "OFF" (Cut-off) or fully "ON" (Saturated). An ideal transistor switch would have an infinite resistance when turned "OFF" resulting in zero current flow and zero resistance when turned "ON", resulting in maximum current flow. In practice when turned "OFF", small leakage currents flow through the transistor and when fully "ON" the device has a low resistance value causing a small saturation voltage (Vce) across it. In both the Cut-off and Saturation regions the power dissipated by the transistor is at its minimum.

To make the Base current flow, the Base input terminal must be made more positive than the Emitter by increasing it above the 0.7 volts needed for a silicon device. By varying the Base-Emitter voltage Vbe, the Base current is altered and which in turn controls the amount of Collector current flowing through the transistor as previously discussed. When maximum Collector current flows the transistor is said to be **Saturated**. The value of the Base resistor determines how much input voltage is required and corresponding Base current to switch the transistor fully "ON".

Example No1.

For example, using the transistor values from the previous tutorials of: β = 200, Ic = 4mA and Ib = 20uA, find the value of the Base resistor (Rb) required to switch the load "ON" when the input terminal voltage exceeds 2.5v.

$$R_B = \frac{V_{in} - V_{BE}}{I_B} = \frac{2.5v - 0.7v}{20x10^{-6}} = 90k\Omega$$

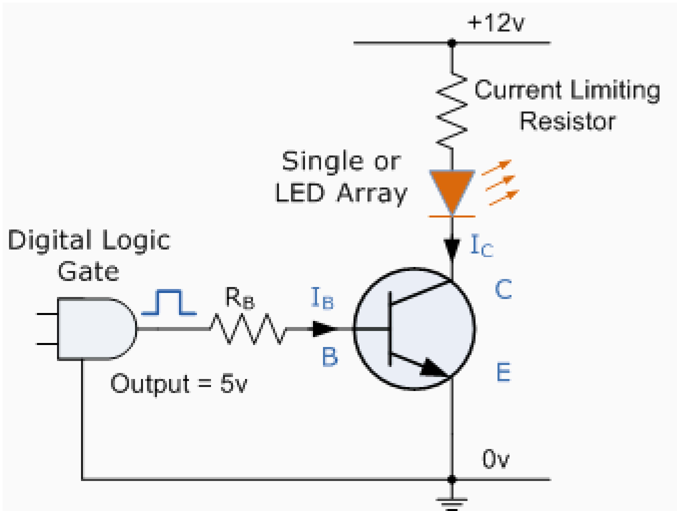
Example No2.

Again using the same values, find the minimum Base current required to turn the transistor fully "ON" (Saturated) for a load that requires 200mA of current.

$$I_B = \frac{I_C}{\beta} = \frac{200mA}{200} = 1mA$$

Transistor switches are used for a wide variety of applications such as interfacing large current or high voltage devices like motors, relays or lamps to low voltage digital logic IC's or gates like AND Gates or OR Gates. Here, the output from a digital logic gate is only +5v but the device to be controlled may require a 12 or even 24 volts supply. Or the load such as a DC Motor may need to have its speed controlled using a series of pulses (Pulse Width Modulation) and transistor switches will allow us to do this faster and more easily than with conventional mechanical switches.

Digital Logic Transistor Switch



The base resistor, Rb is required to limit the output current of the logic gate.

Darlington Transistors

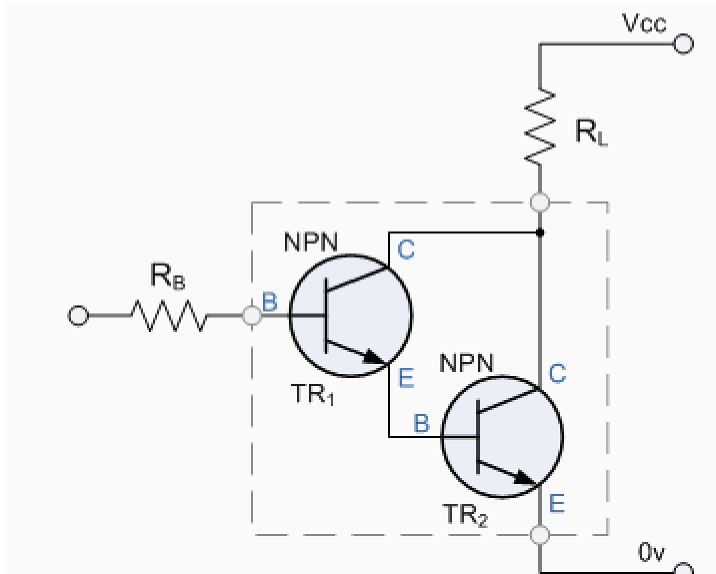
Sometimes the DC current gain of the bipolar transistor is too low to directly switch the load current or voltage, so multiple switching transistors are used. Here, one small input transistor is used to switch "ON" or "OFF" a much larger current handling output transistor. To maximise the signal gain the two transistors are connected in a "Complementary Gain Compounding Configuration" or what is generally called a "**Darlington Configuration**" where the amplification factor is the product of the two individual transistors.

Darlington Transistors simply contain two individual bipolar NPN or PNP type transistors connected together so that the current gain of the first transistor is multiplied with that of the current gain of the second transistor to produce a device which acts like a single transistor with a very high current gain. The overall current gain Beta (β) or Hfe value of a Darlington device is the product of the two individual gains of the transistors and is given as:

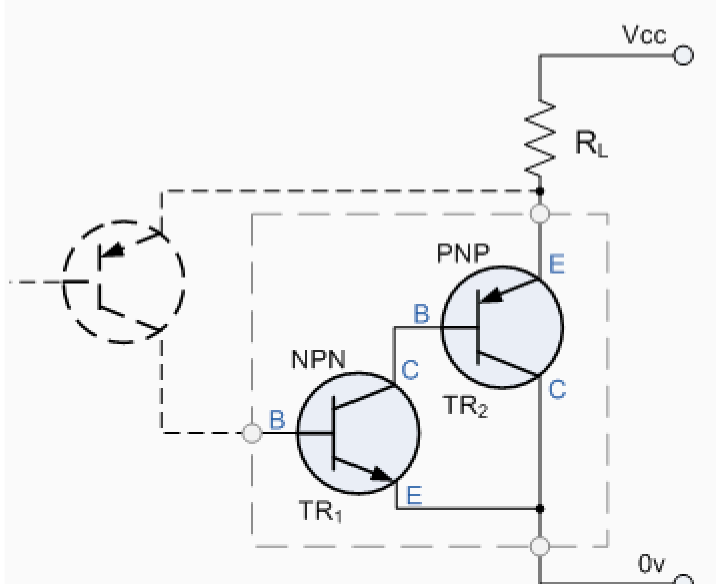
$$\beta_{TOTAL} = \beta_1 \times \beta_2$$

So Darlington Transistors with very high β values and high Collector currents are possible compared to a single transistor. An example of the two basic types of Darlington transistor are given below.

Darlington Transistor Configurations



NPN Darlington Output



Complementary Output

The above NPN Darlington transistor configuration shows the Collectors of the two transistors connected together with the Emitter of the first transistor connected to the Base of the second transistor therefore, the Emitter current of the first transistor becomes the Base current of the second transistor. The first or "input" transistor receives an input signal, amplifies it and uses it to drive the second or "output" transistors which amplifies it again resulting in a very high current gain. As well as its high increased current and voltage switching capabilities, another advantage of a Darlington transistor is in its high switching speeds making them ideal for use in Inverter circuits and DC motor or stepper motor control applications.

One difference to consider when using Darlington transistors over the conventional single bipolar transistor type is that the Base-Emitter input voltage Vbe needs to be higher at approx 1.4v for silicon devices, due to the series connection of the two PN junctions.

Then to summarise when using a **Transistor as a Switch**.

- Transistor switches can be used to switch and control lamps, relays or even motors.
- When using bipolar transistors as switches they must be fully "OFF" or fully "ON".
- Transistors that are fully "ON" are said to be in their **Saturation** region.
- Transistors that are fully "OFF" are said to be in their **Cut-off** region.
- In a transistor switch a small Base current controls a much larger Collector current.
- When using transistors to switch inductive relay loads a "Flywheel Diode" is required.
- When large currents or voltages need to be controlled, **Darlington Transistors** are used.

The Field Effect Transistor

In the **Bipolar Junction Transistor** tutorials, we saw that the output Collector current is determined by the amount of current flowing into the Base terminal of the device and thereby making the Bipolar Transistor a **CURRENT** operated device. The **Field Effect Transistor**, or simply **FET** however, use the voltage that is applied to their input terminal to control the output current, since their operation relies on the electric field (hence the name field effect) generated by the input voltage. This then makes the **Field Effect Transistor** a **VOLTAGE** operated device.

The **Field Effect Transistor** is a unipolar device that has very similar properties to those of the *Bipolar Transistor* ie, high efficiency, instant operation, robust and cheap, and they can be used in most circuit applications that use the equivalent Bipolar Junction Transistors, (BJT). They can be made much smaller than an equivalent BJT transistor and along with their low power consumption and dissipation make them ideal for use in integrated circuits such as the CMOS range of chips.

We remember from the previous tutorials that there are two basic types of Bipolar Transistor construction, NPN and PNP, which basically describes the physical arrangement of the P-type and N-type semiconductor materials from which they are made. There are also two basic types of Field Effect Transistor, N-channel and P-channel. As their name implies, Bipolar Transistors are "Bipolar" devices because they operate with both types of charge carriers, Holes and Electrons. The Field Effect Transistor on the other hand is a "Unipolar" device that depends only on the conduction of Electrons (N-channel) or Holes (P-channel).

The **Field Effect Transistor** has one major advantage over its standard bipolar transistor cousins, in that their input impedance is very high, (Thousands of Ohms) making them very sensitive to input signals, but this high sensitivity also means that they can be easily damaged by static electricity. There are two main types of field effect transistor, the **Junction Field Effect Transistor** or **JFET** and the **Insulated-gate Field Effect Transistor** or **IGFET)**, which is more commonly known as the standard **Metal Oxide Semiconductor Field Effect Transistor** or **MOSFET** for short.

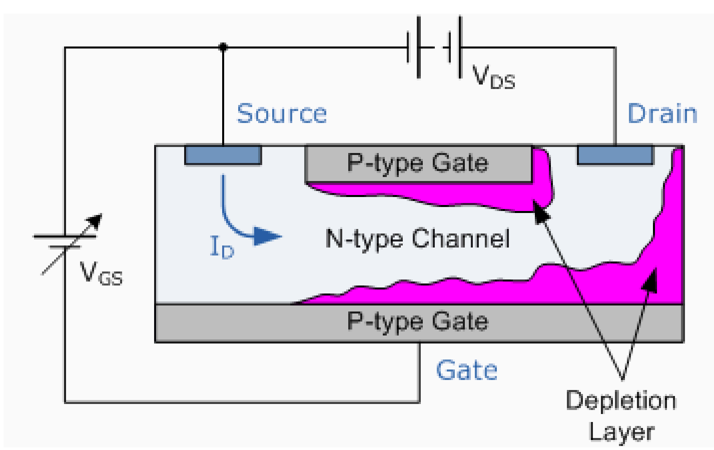
The Junction Field Effect Transistor

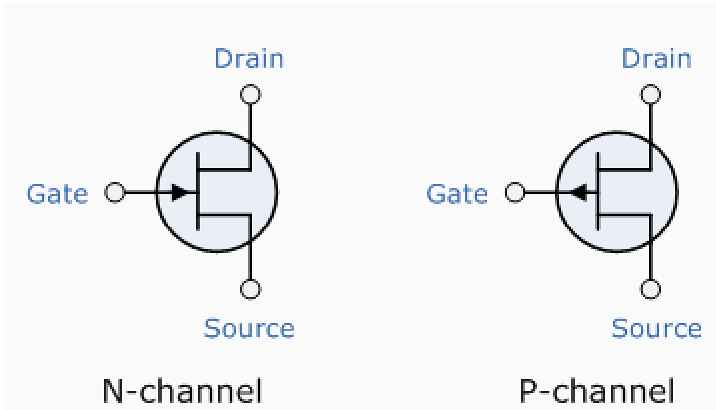
We saw previously that a bipolar junction transistor is constructed using two PN junctions in the main current path between the Emitter and the Collector terminals. The Field Effect Transistor has no junctions but instead has a narrow "Channel" of N-type or P-type silicon with electrical connections at either end commonly called the DRAIN and the SOURCE respectively. Both P-channel and N-channel FET's are available. Within this channel there is a third connection which is called the GATE and this can also be a P or N-type material forming a PN junction and these connections are compared below.

Bipolar Transistor	Field Effect Transistor
Emitter - (E)	Source - (S)
Base - (B)	Gate - (G)
Collector - (C)	Drain - (D)

The semiconductor "Channel" of the Junction Field Effect Transistor is a resistive path through which a voltage V_{ds} causes a current I_d to flow. A voltage gradient is thus formed down the length of the channel with this voltage becoming less positive as we go from the drain terminal to the source terminal. The PN junction therefore has a high reverse bias at the drain terminal and a lower reverse bias at the source terminal. This bias causes a "depletion layer" to be formed within the channel and whose width increases with the bias. FET's control the current flow through them between the drain and source terminals by controlling the voltage applied to the gate terminal. In an N-channel JFET this gate voltage is negative while for a P-channel JFET the gate voltage is positive.

Bias arrangement for an N-channel JFET and corresponding circuit symbols.

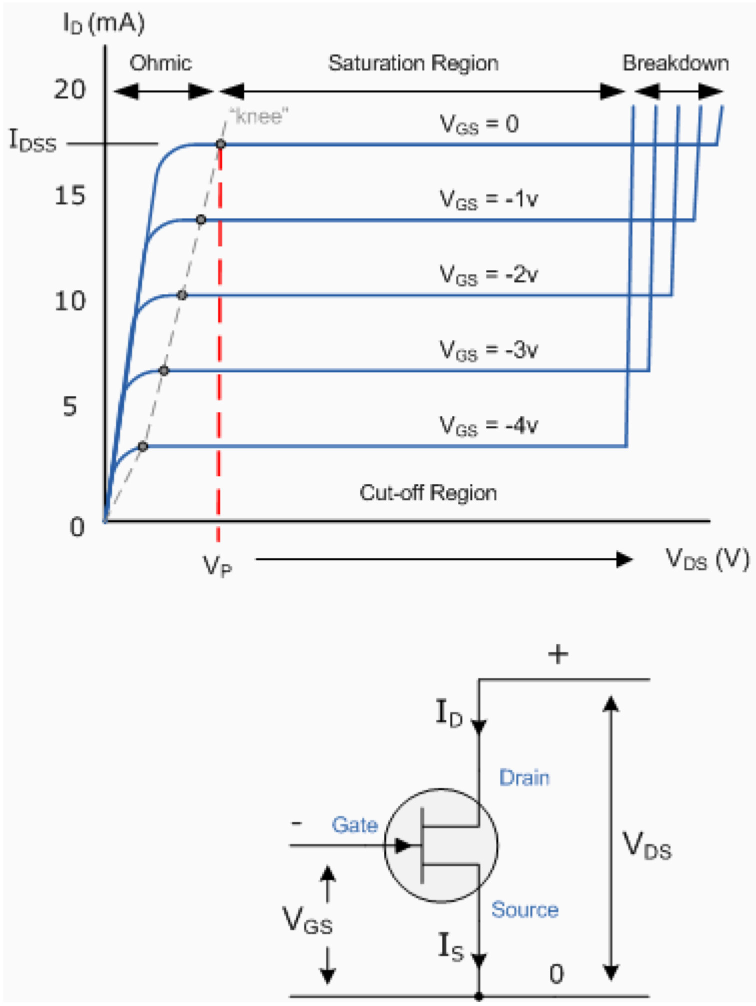




The cross sectional diagram above shows an N-type semiconductor channel with a P-type region called the gate diffused into the N-type channel forming a reverse biased PN junction and its this junction which forms the **depletion layer** around the gate area. This depletion layer restricts the current flow through the channel by reducing its effective width and thus increasing the overall resistance of the channel.

When the gate voltage V_g is equal to 0V and a small external voltage (V_{ds}) is applied between the drain and the source maximum current (I_d) will flow through the channel slightly restricted by the small depletion layer. If a negative voltage (V_{gs}) is now applied to the gate the size of the depletion layer begins to increase reducing the overall effective area of the channel and thus reducing the current flowing through it, a sort of "squeezing" effect. As the gate voltage (V_{gs}) is made more negative, the width of the channel decreases until no more current flows between the drain and the source and the FET is said to be "**pinched-off**". In this pinch-off region the gate voltage, V_{gs} controls the channel current and V_{ds} has little or no effect. The result is that the FET acts more like a voltage controlled resistor which has zero resistance when $V_{gs} = 0$ and maximum "ON" resistance (R_{ds}) when the gate voltage is very negative.

Output characteristic voltage-current curves of a typical junction FET.



The voltage V_{gs} applied to the gate controls the current flowing between the drain and the source terminals. V_{gs} refers to the voltage applied between the gate and the source while V_{ds} refers to the voltage applied between the drain and the source. Because a **Field Effect Transistor** is a VOLTAGE controlled device, "NO current flows into the gate!" then the source current (I_s) flowing out of the device equals the drain current flowing into it and therefore ($I_d = I_s$).

The characteristics curves example shown above, shows the four different regions of operation for a JFET and these are given as:

- Ohmic Region - The depletion layer of the channel is very small and the JFET acts like a variable resistor.
-
- Cut-off Region - The gate voltage is sufficient to cause the JFET to act as an open circuit as the channel resistance is at maximum.
-
- Saturation or Active Region - The JFET becomes a good conductor and is controlled by the gate-source voltage, (V_{gs}) while the drain-source voltage, (V_{ds}) has little or no effect.

-
- Breakdown Region - The voltage between the drain and source, (V_{ds}) is high enough to causes the JFET's resistive channel to break down and pass current.

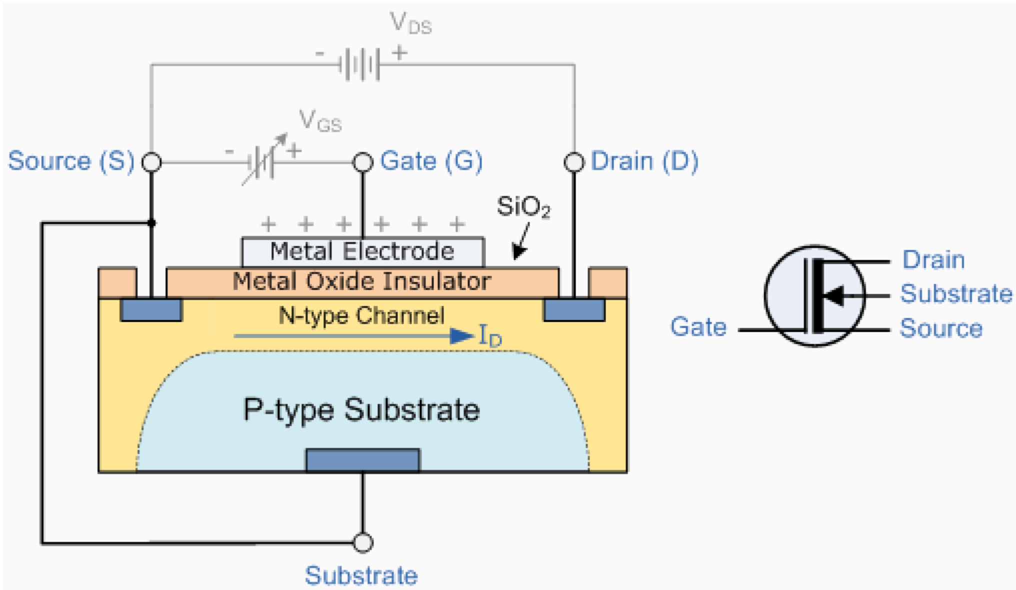
The control of the drain current by a negative gate potential makes the **Junction Field Effect Transistor** useful as a switch and it is essential that the gate voltage is never positive for an N-channel JFET as the channel current will flow to the gate and not the drain resulting in damage to the JFET. The principals of operation for a P-channel JFET are the same as for the N-channel JFET, except that the polarity of the voltages need to be reversed.

The MOSFET

As well as the Junction Field Effect Transistor, there is another type of Field Effect Transistor available whose Gate input is electrically insulated from the main current carrying channel and is therefore called an **Insulated Gate Field Effect Transistor**. The most common type of insulated gate FET or IGFET as it is sometimes called, is the **Metal Oxide Semiconductor Field Effect Transistor** or **MOSFET** for short.

The **MOSFET** type of field effect transistor has a "Metal Oxide" gate (usually silicon dioxide commonly known as glass), which is electrically insulated from the main semiconductor N-channel or P-channel. This isolation of the controlling gate makes the input resistance of the **MOSFET** extremely high in the Mega-ohms region and almost infinite. As the gate terminal is isolated from the main current carrying channel ""NO current flows into the gate"" and like the JFET, the **MOSFET** also acts like a voltage controlled resistor. Also like the JFET, this very high input resistance can easily accumulate large static charges resulting in the **MOSFET** becoming easily damaged unless carefully handled or protected.

Basic MOSFET Structure and Symbol

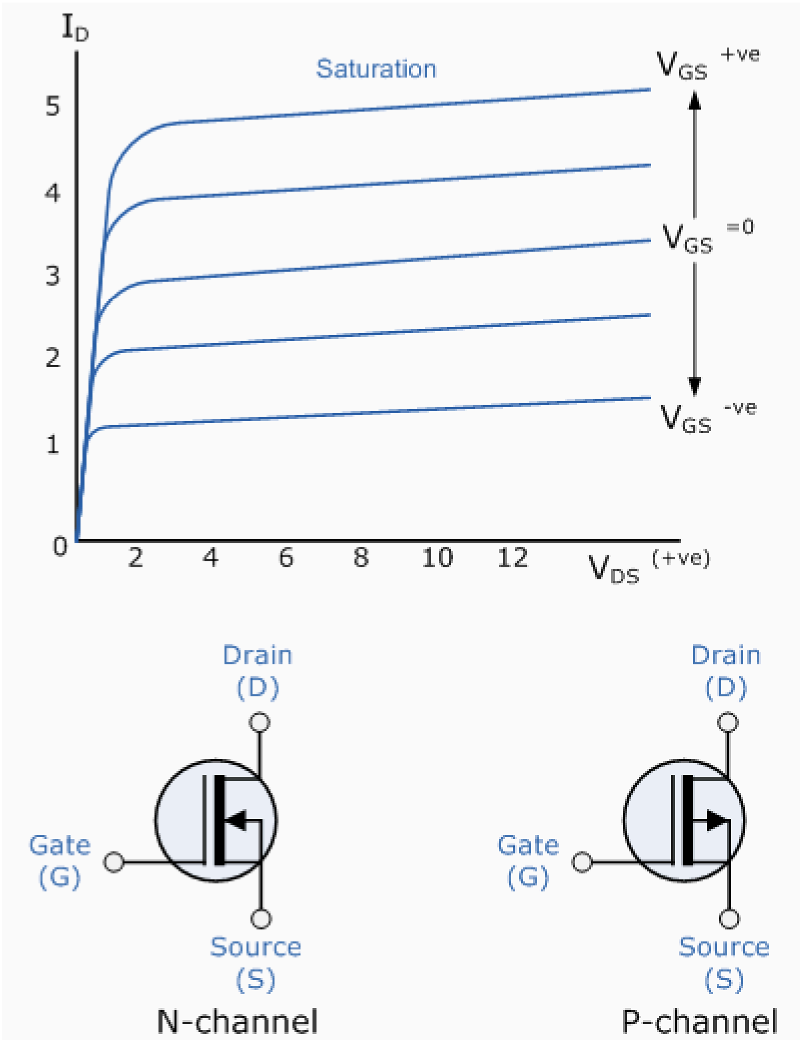


We also saw previously that the gate of a JFET must be biased in such a way as to forward-bias the PN junction but in a MOSFET device no such limitations applies so it is possible to bias the gate in either polarity. This makes MOSFET's specially valuable as electronic switches or to make logic gates because with no bias they are normally non-conducting and the high gate resistance means that very little control current is needed. Both the P-channel and the N-channel MOSFET is available in two basic forms, the **Enhancement** type and the **Depletion** type.

Depletion-mode MOSFET

The **Depletion-mode MOSFET**, which is less common than the enhancement types is normally switched "ON" without a gate bias voltage but requires a gate to source voltage (V_{gs}) to switch the device "OFF". Similar to the JFET types. For N-channel MOSFET's a "Positive" gate voltage widens the channel, increasing the flow of the drain current and decreasing the drain current as the gate voltage goes more negative. The opposite is also true for the P-channel types. The depletion mode MOSFET is equivalent to a "Normally Closed" switch.

Depletion-mode N-Channel MOSFET and circuit Symbols



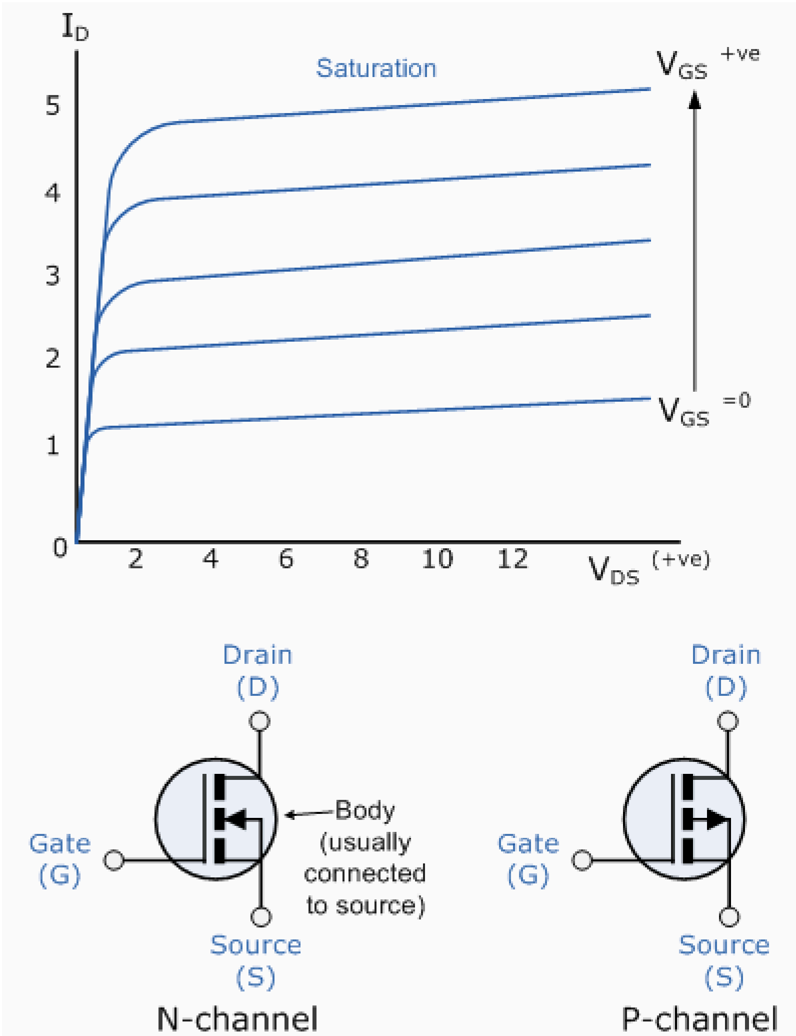
Depletion-mode MOSFET's are constructed similar to their JFET transistor counterparts where the drain-source channel is inherently conductive with electrons and holes already present within the N-type or P-type channel. This doping of the channel produces a conducting path of low resistance between the drain and source with zero gate bias.

Enhancement-mode MOSFET

The more common **Enhancement-mode MOSFET** is the reverse of the depletion-mode type. Here the conducting channel is lightly doped or even undoped making it non-conductive. This results in the device being normally "OFF" when the gate bias voltage is equal to zero.

A drain current will only flow when a gate voltage (V_{gs}) is applied to the gate terminal. This positive voltage creates an electrical field within the channel attracting electrons towards the oxide layer and thereby reducing the overall resistance of the channel allowing current to flow. Increasing this positive gate voltage will cause an increase in the drain current, I_d through the channel. Then, the Enhancement-mode device is equivalent to a "Normally Open" switch.

Enhancement-mode N-Channel MOSFET and circuit Symbols



Enhancement-mode MOSFET's make excellent electronics switches due to their low "ON" resistance and extremely high "OFF" resistance and extremely high gate resistance. Enhancement-mode MOSFET's are used in integrated circuits to produce CMOS type **Logic Gates** and power switching circuits as they can be driven by digital logic levels.

MOSFET Summary

The **MOSFET** has an extremely high input gate resistance and as such a easily damaged by static electricity if not carefully protected. MOSFET's are ideal for use as electronic switches or common-source amplifiers as their power consumption is very small. Typical applications for MOSFET's are in Microprocessors, Memories, Calculators and Logic Gates etc. Also, notice that the broken lines within the symbol indicates a normally "OFF" Enhancement type showing that "NO" current can flow through the channel when zero gate voltage is applied and a continuous line within the symbol indicates a normally "ON" Depletion type showing that current "CAN" flow through the channel with zero gate voltage. For P-Channel types the symbols are exactly the same for both types except that the arrow points outwards.

This can be summarised in the following switching table.

MOSFET type	Vgs = +ve	Vgs = 0	Vgs = -ve
N-Channel Depletion	ON	ON	OFF
N-Channel Enhancement	ON	OFF	OFF
P-Channel Depletion	OFF	ON	ON
P-Channel Enhancement	OFF	OFF	ON

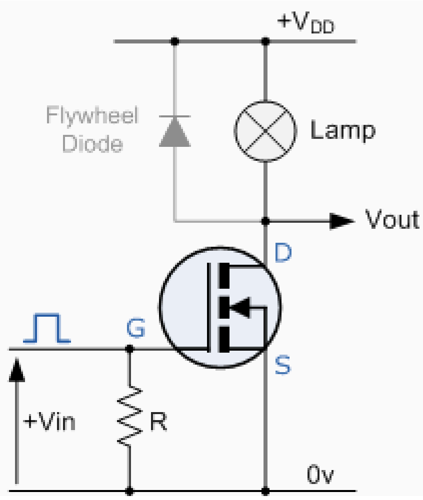
The MOSFET as a Switch

We saw previously, that the N-channel, Enhancement-mode MOSFET operates using a positive input voltage and has an extremely high input resistance (almost infinite) making it possible to interface with nearly any logic gate or driver capable of producing a positive output. Also, due to this very high input (Gate) resistance we can parallel together many different MOSFET's until we achieve the current handling limit required. While connecting together various MOSFET's may enable us to switch high current or high voltage loads, doing so becomes expensive and impractical in both components and circuit board space. To overcome this problem **Power Field Effect Transistors** or **Power FET's** where developed.

We now know that there are two main differences between FET's, Depletion-mode for JFET's and Enhancement-mode for MOSFET's and on this page we will look at using the Enhancement-mode MOSFET as a Switch.

By applying a suitable drive voltage to the Gate of an FET the resistance of the Drain-Source channel can be varied from an "OFF-resistance" of many hundreds of kΩ's, effectively an open circuit, to an "ON-resistance" of less than 1Ω, effectively a short circuit. We can also drive the MOSFET to turn "ON" fast or slow, or to pass high currents or low currents. This ability to turn the power MOSFET "ON" and "OFF" allows the device to be used as a very efficient switch with switching speeds much faster than standard bipolar junction transistors.

An example of using the MOSFET as a switch



In this circuit arrangement an Enhancement-mode N-channel MOSFET is being used to switch a simple lamp "ON" and "OFF" (could also be an LED). The gate input voltage V_{GS} is taken to an appropriate positive voltage level to turn the device and the lamp either fully "ON", ($V_{GS} = +ve$) or a zero voltage level to turn the device fully "OFF", ($V_{GS} = 0$).

If the resistive load of the lamp was to be replaced by an inductive load such as a coil or solenoid, a "Flywheel" diode would be required in parallel with the load to protect the MOSFET from any back-emf.

Above shows a very simple circuit for switching a resistive load such as a lamp or LED. But when using power MOSFET's to switch either inductive or capacitive loads some form of protection is required to prevent the MOSFET device from becoming damaged. Driving an inductive load has the opposite effect from driving a capacitive load. For example, a capacitor without an electrical charge is a short circuit, resulting in a high "inrush" of current and when we remove the voltage from an inductive load we have a large reverse voltage build up as the magnetic field collapses, resulting in an induced back-emf in the windings of the inductor.

For the power MOSFET to operate as an analogue switching device, it needs to be switched between its "Cut-off Region" where $V_{GS} = 0$ and its "Saturation Region" where $V_{GS(on)} = +ve$. The power dissipated in the MOSFET (P_D) depends upon the current flowing through the channel I_D at saturation and also the "ON-resistance" of the channel given as $R_{DS(on)}$. For example.

Example No1

Lets assume that the lamp is rated at 6v, 24W and is fully "ON" and the standard MOSFET has a channel "ON-resistance" ($R_{DS(on)}$) value of 0.1ohms. Calculate the power dissipated in the MOSFET switch.

The current flowing through the lamp is calculated as:

$$P = V \times I, \quad \text{therefore,} \quad I_D = \frac{P}{V} = \frac{24}{6} = 4\,\text{amps}$$

Then the power dissipated in the MOSFET will be given as:

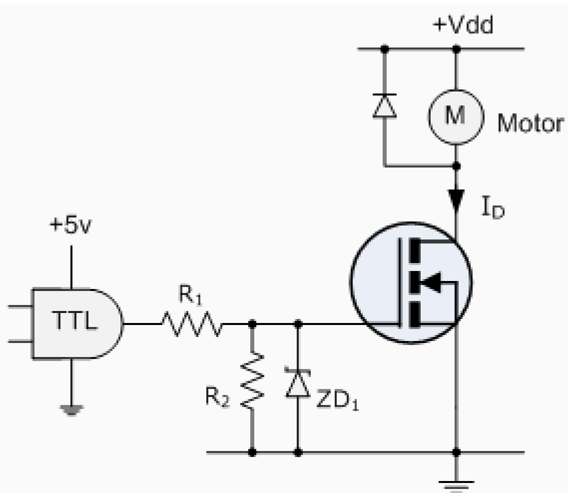
$$P_D = I_D^2 \times R_{DS}, \quad \text{therefore,} \quad P_D = 4^2 \times 0.1 = 1.6\ \text{watts}$$

You may think, well so what!, but when using the MOSFET as a switch to control DC motors or high inrush current devices the "ON" channel resistance ($R_{DS(on)}$) is very important. For example, MOSFET's that control DC motors, are subjected to a high in-rush current as the motor first begins to rotate. Then a high $R_{DS(on)}$ channel resistance value would simply result in large amounts of power being dissipated within the MOSFET itself resulting in an excessive temperature rise, and which in turn could result in the MOSFET becoming very hot and damaged due to a thermal overload. But a low $R_{DS(on)}$ value on the other hand is also desirable to help reduce the effective saturation voltage ($V_{DS(sat)} = I_D \times R_{DS(on)}$) across the MOSFET. When using MOSFET´s or any type of Field Effect Transistor for that matter as a switching device, it is always advisable to select ones that have a very low $R_{DS(on)}$ value or at least mount them onto a suitable heatsink to help reduce any thermal runaway and damage.

Power MOSFET Motor Control

Because of the extremely high input or Gate resistance that the MOSFET has, its very fast switching speeds and the ease at which they can be driven makes them ideal to interface with op-amps or standard logic gates. However, care must be taken to ensure that the gate-source input voltage is correctly chosen because when using the **MOSFET as a switch** the device must obtain a low $R_{DS(on)}$ channel resistance in proportion to this input gate voltage. For example, do not apply a 12v signal if a 5v signal voltage is required. Power MOSFET´s can be used to control the movement of DC motors or brushless stepper motors directly from computer logic or Pulse-width Modulation (PWM) type controllers. As a DC motor offers high starting torque and which is also proportional to the armature current, MOSFET switches along with a PWM can be used as a very good speed controller that would provide smooth and quiet motor operation.

Simple Power MOSFET Motor Controller



As the motor load is inductive, a simple "Free-wheeling" diode is connected across the load to dissipate any back emf generated by the motor when the MOSFET turns it "OFF".

The Zener diode is used to prevent excessive gate-source input voltages.

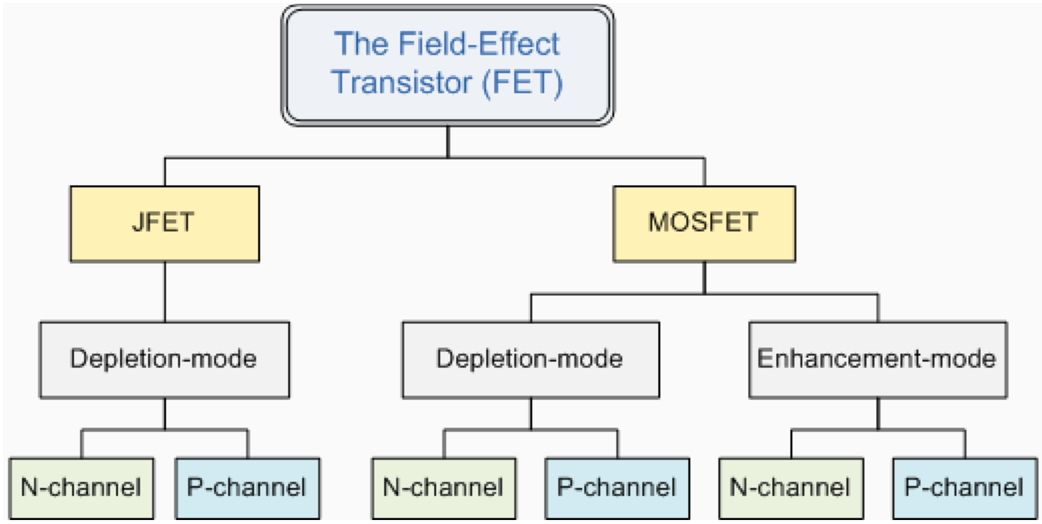
Summary of Bipolar Junction Transistors

- The **Bipolar Junction Transistor** (BJT) is a three layer device constructed form two semiconductor diode junctions joined together, one forward biased and one reverse biased.
- There are two main types of bipolar junction transistors, the NPN and the PNP transistor.
- Transistors are "**Current Operated Devices**" where a much smaller Base current causes a larger Emitter to Collector current, which themselves are nearly equal, to flow.
- The most common transistor connection is the Common-emitter configuration.
- Requires a Biasing voltage for AC amplifier operation.
- The Collector or output characteristics curves can be used to find either Ib, Ic or β to which a load line can be constructed to determine a suitable operating point, Q with variations in base current determining the operating range.
- A transistor can also be used as an electronic switch to control devices such as lamps, motors and solenoids etc.
- Inductive loads such as DC motors, relays and solenoids require a reverse biased "Flywheel" diode placed across the load. This helps prevent any induced back emf's generated when the load is switched "OFF" from damaging the transistor.
- The NPN transistor requires the Base to be more positive than the Emitter while the PNP type requires that the Emitter is more positive than the Base.

Summary of Field Effect Transistors

- **Field Effect Transistors**, or FET's are "**Voltage Operated Devices**" and can be divided into two main types: Junction-gate devices called JFET's and Insulated-gate devices called IGFET´s or more commonly known as MOSFET's.
- Insulated-gate devices can also be sub-divided into Enhancement types and Depletion types. All forms are available in both N-channel and P-channel versions.
- FET's have very high input resistances so very little or no current (MOSFET types) flows into the input terminal making them ideal for use as electronic switches.
- The input impedance of the MOSFET is even higher than that of the JFET due to the insulating oxide layer and therefore static electricity can easily damage MOSFET devices so care needs to be taken when handling them.
- FET's have very large current gain compared to junction transistors.
- They can be used as ideal switches due to their very high channel "OFF" resistance, low "ON" resistance.

The Field Effect Transistor Family-tree



Field Effect Transistors can be used to replace normal Bipolar Junction Transistors in electronic circuits and a simple comparison between FET's and transistors stating both their advantages and their disadvantages is given below.

	Field Effect Transistor (FET)	Bipolar Junction Transistor (BJT)
1	Low voltage gain	High voltage gain
2	High current gain	Low current gain
3	Very input impedance	Low input impedance
4	High output impedance	Low output impedance
5	Low noise generation	Medium noise generation
6	Fast switching time	Medium switching time
7	Easily damaged by static	Robust
8	Some require an input to turn it "OFF"	Requires zero input to turn it "OFF"
9	Voltage controlled device	Current controlled device
10	Exhibits the properties of a Resistor	
11	More expensive than bipolar	Cheap
12	Difficult to bias	Easy to bias

INTRODUCTION TO LOGIC GATES

What are Logic Gates

- Electronic circuits capable of making logical decisions;
- Basic building blocks of digital systems design;
- Can have one or more input signals and an output which is a logical combination of the inputs.

- In computing systems, the symbols 0 and 1 indicate 2 possible states of a circuit or device.

Symbol	Circuit	Switch	Voltage	Statement
0	OFF	OPEN	LOW	FALSE
1	ON	CLOSED	HIGH	TRUE

The following logic gates will be treated in this lesson:

- OR;
- AND;
- NOT;
- XOR;
- NOR;
- NAND and
- XNOR

- Logic gates operate based on a logical algebraic system known as Boolean algebra.

- In this system, the variables used can assume only one of two values i.e. 0 and 1.

OR Gate

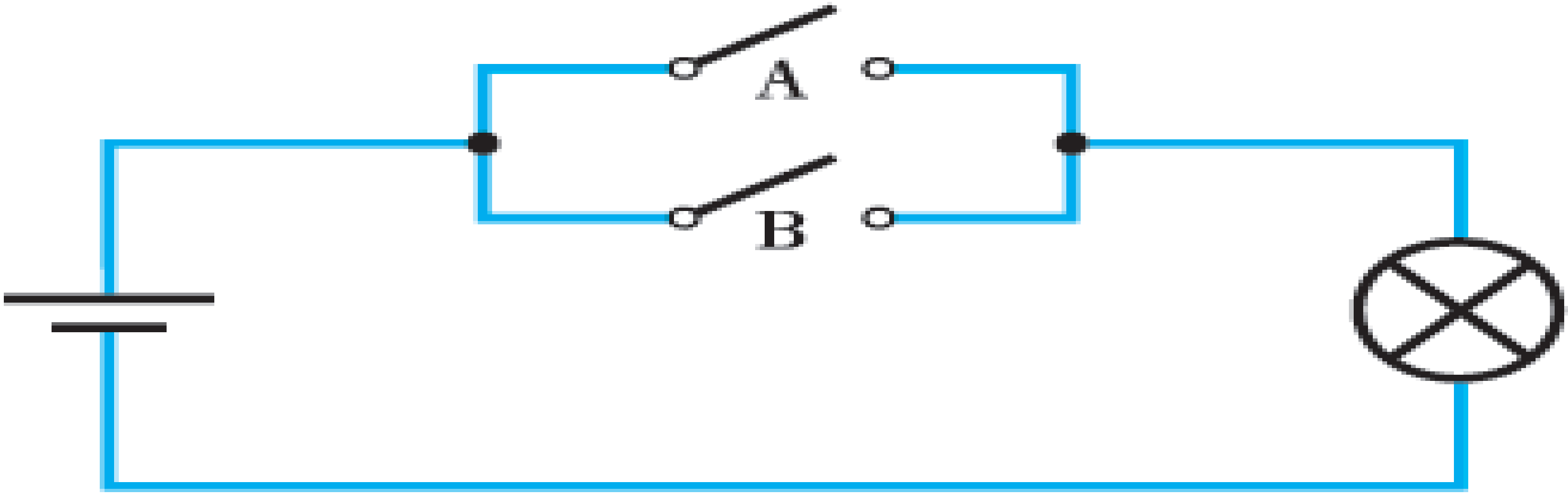
- Produces an output 1 when any or all of the inputs are 1.
- It is therefore also called an any-or-all gate.

- The logical operation of a 2-input OR gate can be summarized in the truth table below.

Table 1: OR Truth Table

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

- A practical example of the OR gate is shown in the figure below.



- For the lamp to glow, either switch A or B or both are closed.

- The Boolean equation for the OR gate is:

$$A + B = C$$

- This operation is also applicable for an OR gate with more than two inputs.

AND Gate

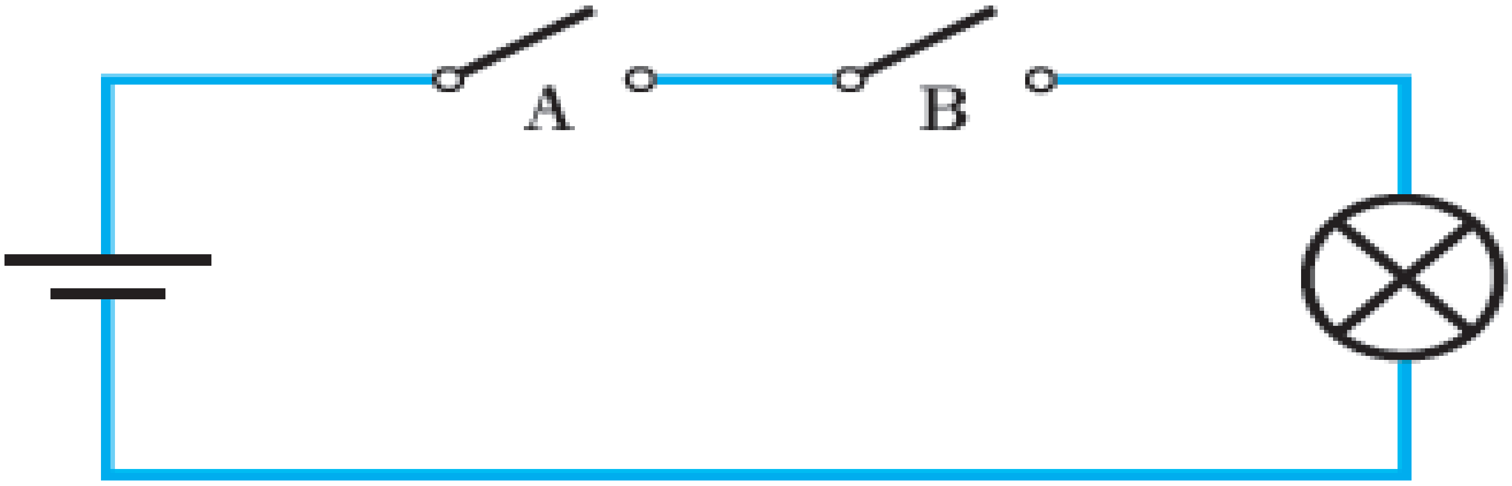
- Produces an output of 1 only when all inputs are present (i.e. 1).
- It is also known as an all-or-nothing gate.

- The logical operation of a 2-input AND gate can be summarized in the following truth table.

Table 2: AND Truth Table

A	B	$A \cdot B$
0	0	0
0	1	0
1	0	0
1	1	1

- A practical example of the AND gate is shown in the figure below:

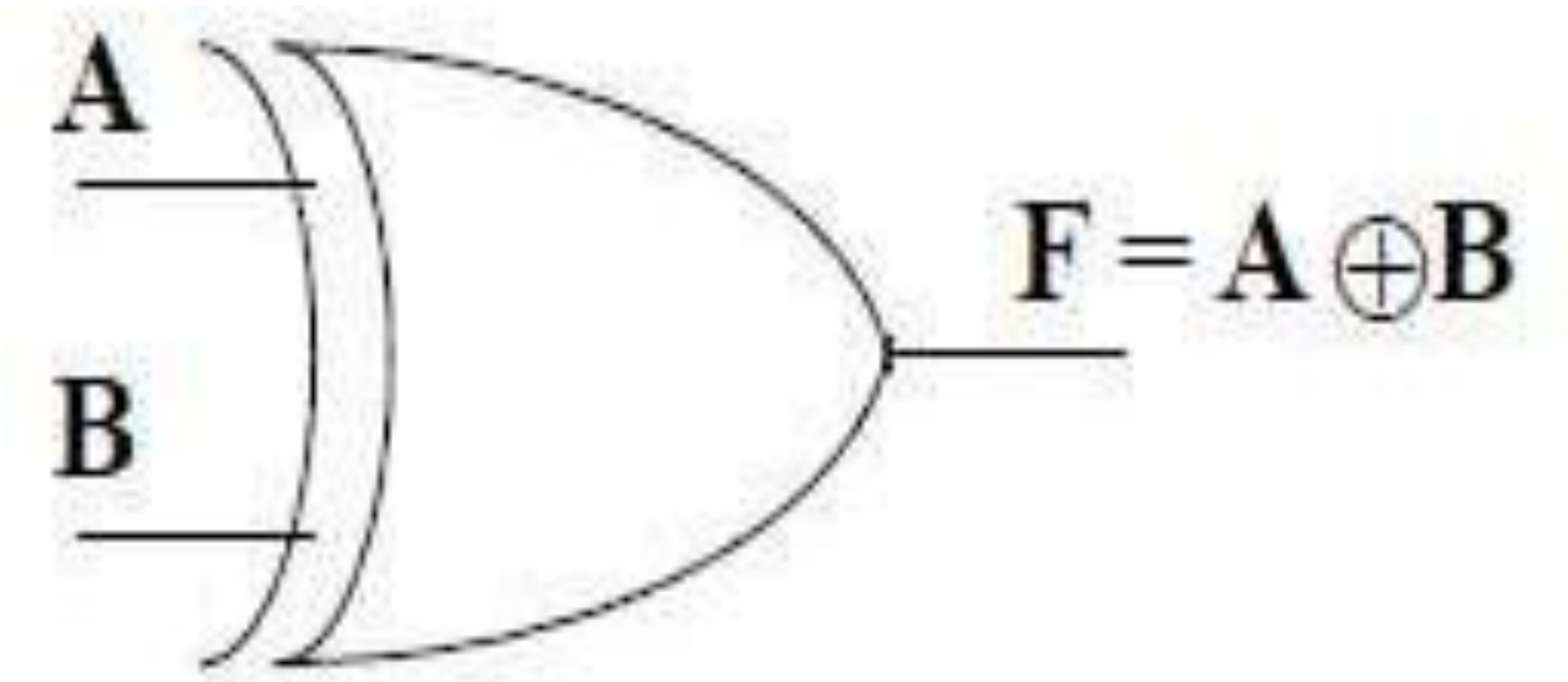


- The lamp will be ON only when both switches A and B are CLOSED.
- The Boolean equation for this gate is

$$A \times B = C \text{ or } AB = C$$

XOR Gate

- The output is 1 only if both inputs are different.
- Excludes the case where both inputs are the same.
- Also referred to as an inequality comparator



- The truth table for a 2-input XOR gate is given below

Table 3: XOR Truth Table

A	B	$A \oplus B$
0	0	0
0	1	1
1	0	1
1	1	0

NOT Gate

- It has one input and one output. The output is simply the complement of the input.
- Also called an inverter
- The logical symbol for inversion or complementation is Ā.
- The truth table for a NOT gate is shown below:

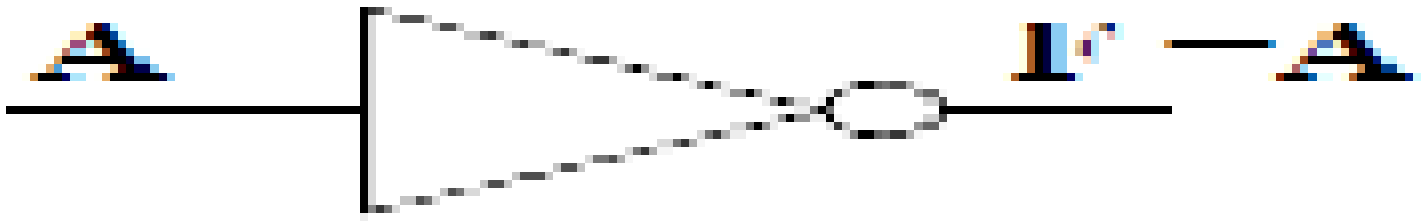
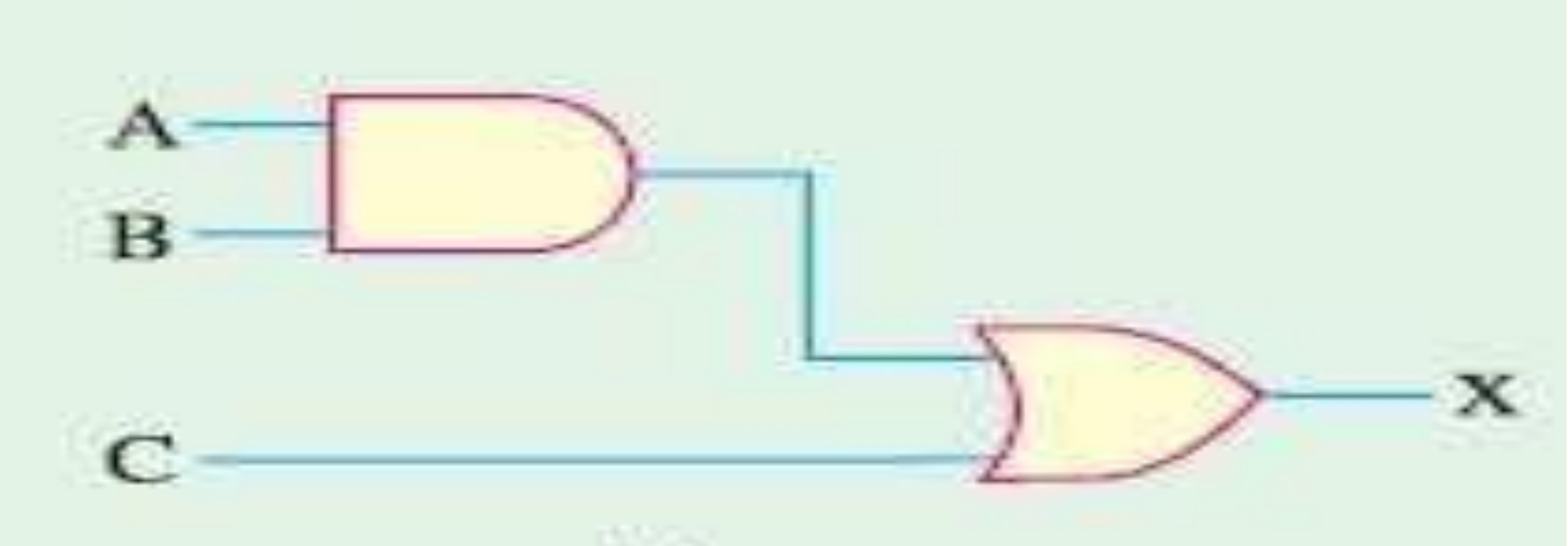


Table 4: NOT Truth Table

A	$\overline{A}$
0	1
1	0

Example

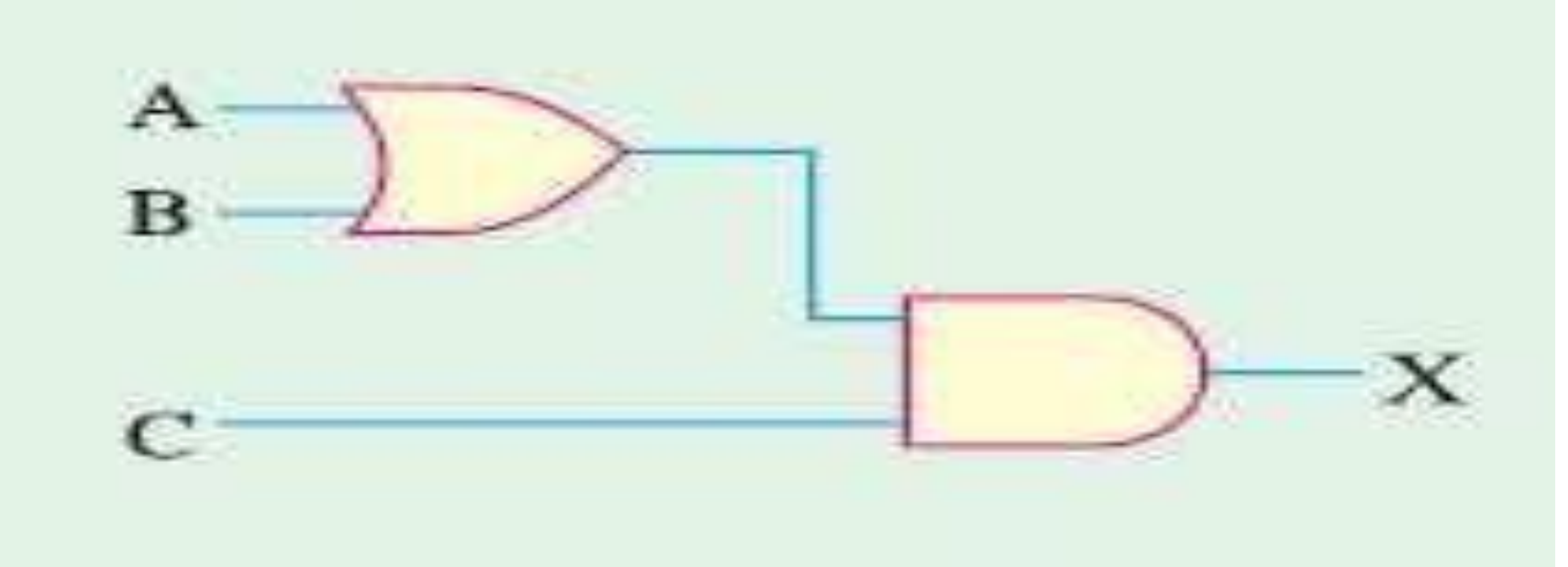
- Considering the figure below, derive a logical expression for X and determine its value when A = 1, B = 0 and C = 1.



(a)

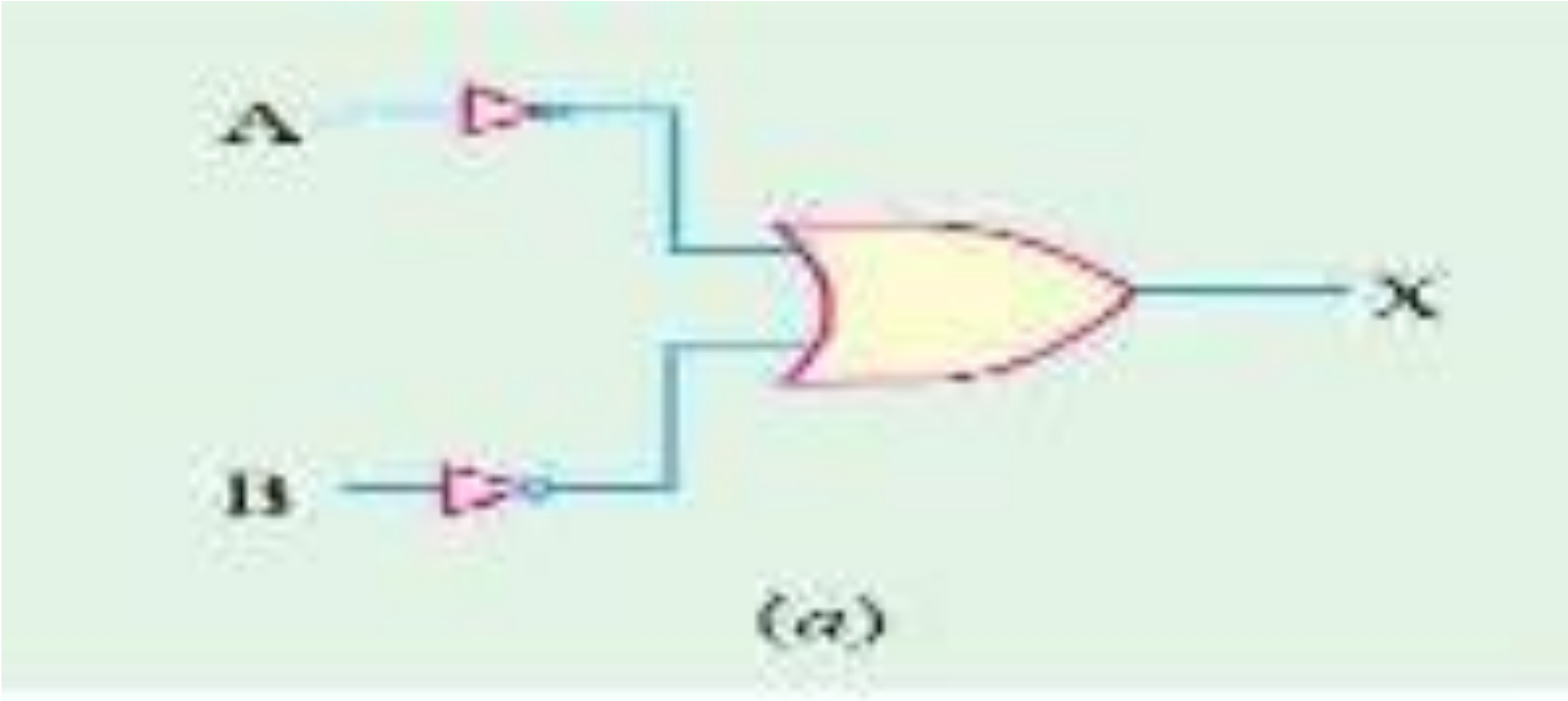
Example

- From the below diagram, find X when A and B are 1 and C = 0.



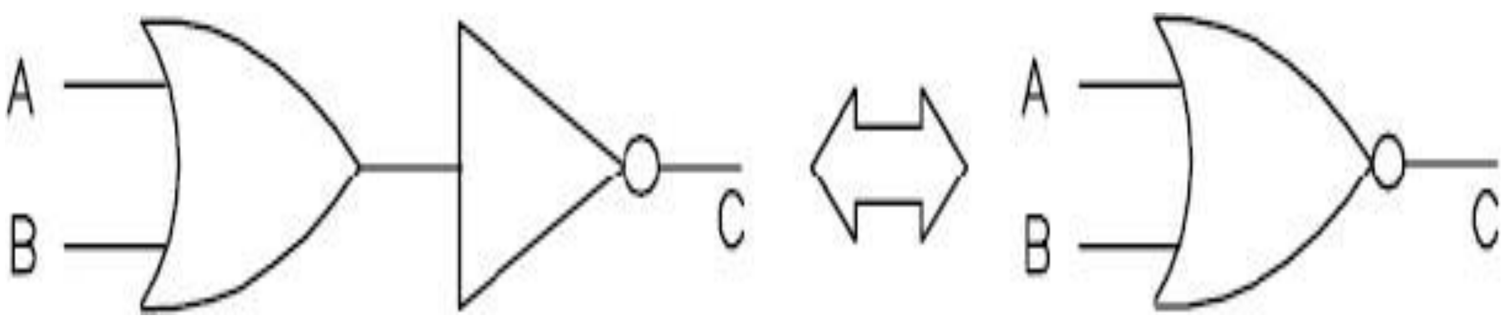
(a)

- Determine the value of X when (a) A = 0, B = 1 (b) A = 1, B = 1



NOR Gate

- Also called NOT-OR Gate
- Made by connecting an inverter to the output of an OR gate.
- Produces an output of TRUE when all inputs are FALSE.



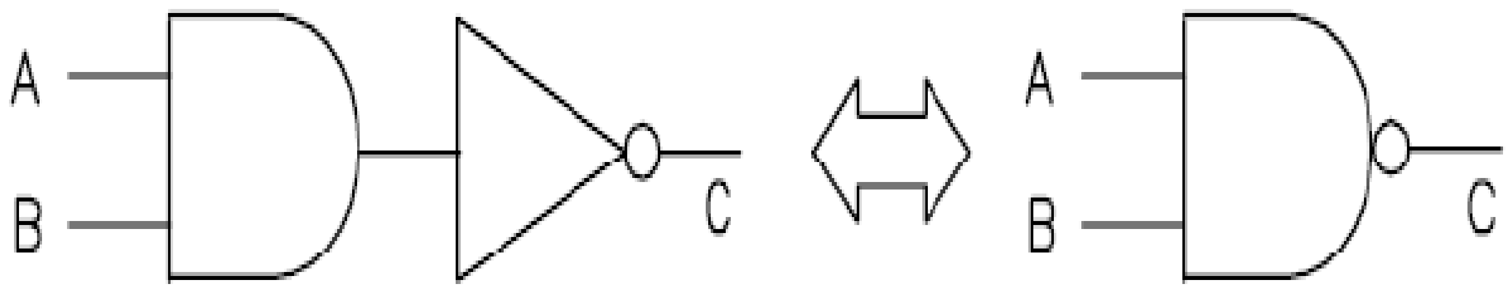
- The truth table for a 2-input NOR gate is shown below:

Table 5: NOR Truth Table

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

NAND Gate

- It is actually a NOT-AND gate.
- Made by connecting a NOT gate to the output of an AND gate.
- Gives an output of 1 if both inputs are not 1.



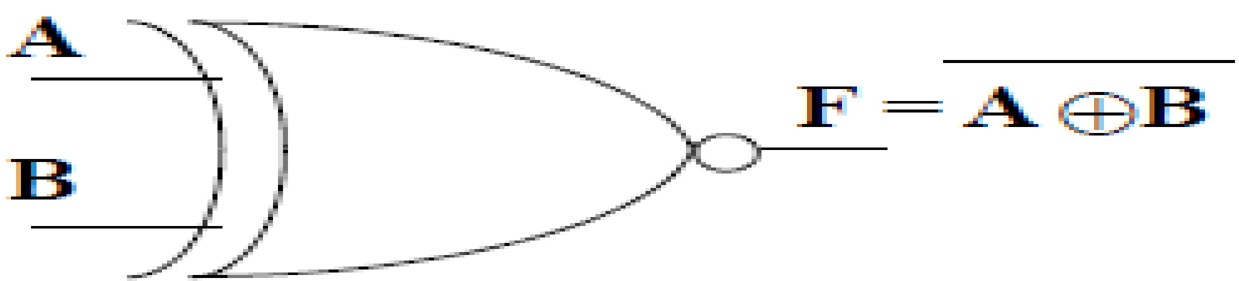
- The truth table for a 2-input NAND gate is shown below

Table 6: NAND Truth Table

A	B	$\overline{A \cdot B}$
0	0	1
0	1	1
1	0	1
1	1	0

XNOR Gate

- Also referred to as a NOT-XOR Gate
- Made by connecting a NOT gate to the output of an AND gate.
- Gives an output of 1 if both inputs are the same.



- The truth table for a 2-input XNOR gate is shown below

Table 7: XNOR Truth Table

A	B	$\overline{A \oplus B}$
0	0	1
0	1	0
1	0	0
1	1	1

Types of Logic Circuit

Logic circuits are basically categorized into two types:

- Combinational Logic Circuits

- Sequential Logic Circuits

Combinational Logic Circuits

- Has input set, a memory-less logic network to operate on the inputs and a set of outputs.

- The output depends only on the present input values.

- Output does not depend on the previous state of the circuit.

- Examples include multiplexers, demultiplexers, encoders, etc.

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Combinational Logic Circuits

Sequential Logic Circuits

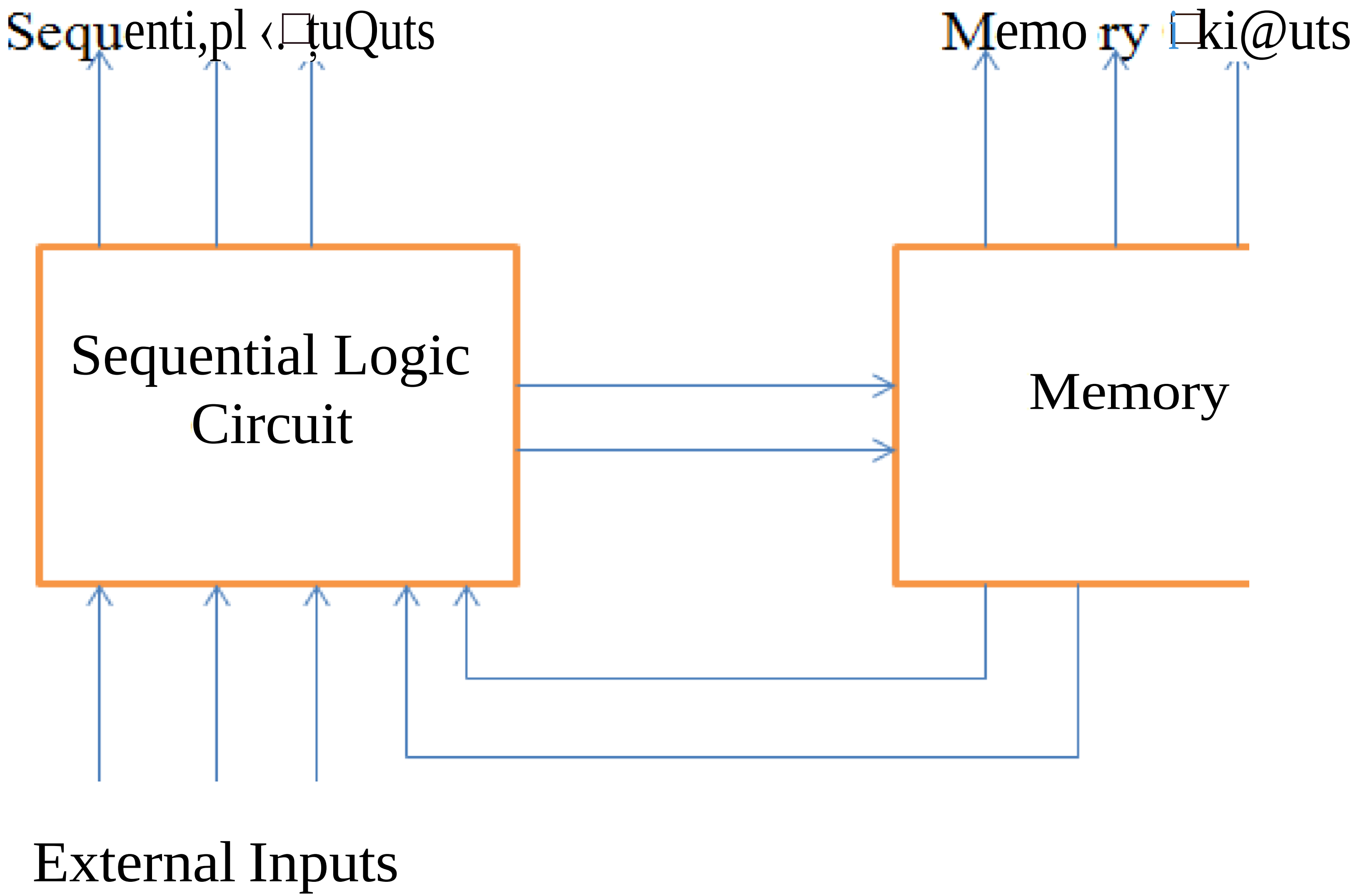
- Has input set, logic network, outputs and memory.
- Present output depends not only on the present input states but also on the previous logic states of the outputs.
- Examples include latches and flip-flops.

Sequential Logic Circuits

Sequential Logic Circuits (SLCs) are further classified as:

- Synchronous SLCs: They operate at a clocked rate, i.e. all the outputs change at the same time, in step with each other (i.e. they are synchronized). This timing is usually provided by one edge of the clock signal.

- Asynchronous SLCs: Operate without clocking, i.e. the outputs change at different times.



Sequential Logic Circuit

Applications of Logic Circuits

- Design of more complex devices like binary counters
- Decision making in automatic control of machines and various industrial processes
- Digital measuring techniques
- Digital processing of communication signals
- Calculators and computers

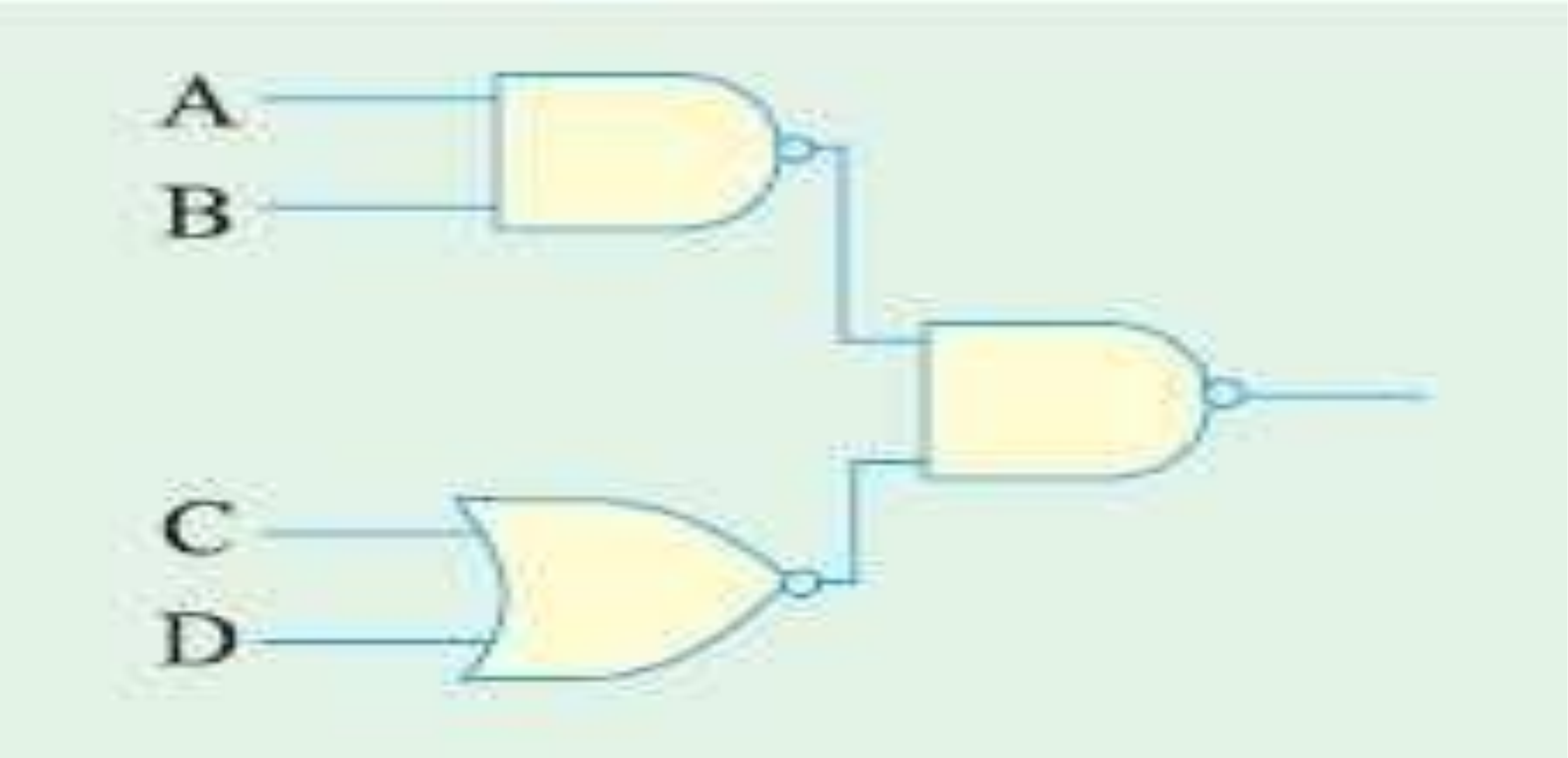
Example

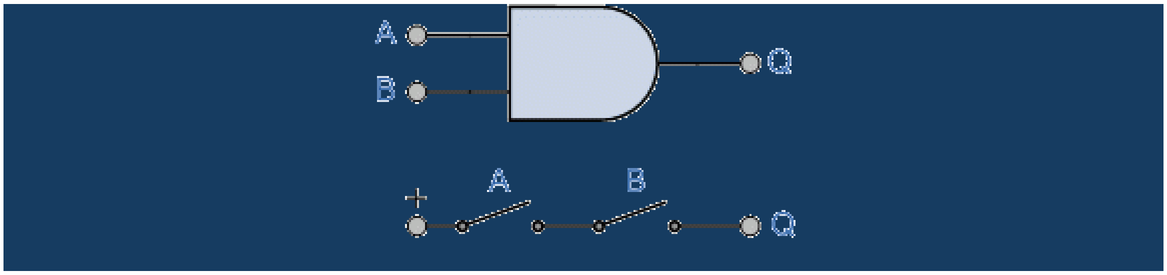
- An electrical signal is expressed as 10110011. Explain its meaning. If the signal is applied to a NOT Gate, what will be the output signal?

- Two electrical signals 1100111 and 1010101 are applied to a 2-input AND Gate. Give a sketch of the output signal.

- Two signals 11011 and 01001 are inclusive-OR combined. The output is then exclusive-OR combined with a third signal 10111. Draw the complete logic circuit describing this scenario, and then give a sketch of the final output signal.

- Given that A = 11011, B = 01101, C = 10100 and D = 00101, determine the output of the following logic circuit.





Universal Logic Gates

Universal Logic gates can be used to produce any other logic or Boolean function with the NAND and NOR gates being minimal

Individual logic gates can be connected together to form a variety of different switching functions and combinational logic circuits. As we have seen throught this *Digital Logic* tutorial section, the three most basic logic gates are the: AND, OR and NOT gates, and given this set of logic gates it is possible to implement all of the possible Boolean switching functions, thus making them a “full set” of **Universal Logic Gates**.

By using logical sets in this way, the various laws and theorems of Boolean Algebra can be implemented with a complete set of logic gates. In fact, it is possible to produce every other Boolean function using just the set of AND and NOT gates since the OR function can be created using just these two gates. Likewise, the set of OR and NOT can be used to create the AND function.

Any logic gate which can be combined into a set to realise all other logical functions is said to be a universal gate with a complete logic set being a group of gates that can be used to form any other logic function.

For example, AND and NOT constitute a complete set of logic, as does OR and NOT as cascading together an AND with a NOT gate would give us a NAND gate. Similarly cascading an OR and NOT gate together will produce a NOR gate, and so on. However, the two functions of AND and OR on their own do not form a complete logic set.

So by using these three *Universal Logic Gates* we can create a range of other Boolean functions and gates. However, the NAND and NOR gates are classed as minimal sets because they have the property of being a complete set in themselves since they can be used individually or together to construct many other logic circuits. Therefore we can define the complete sets of operations of the main logic gates as follows:

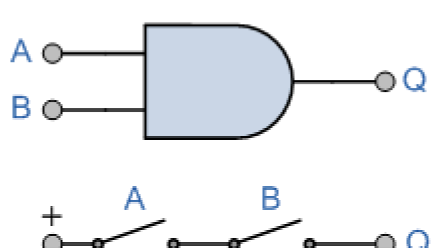
- AND, OR and NOT (a Full Set)
- AND and NOT (a Complete Set)
- OR and NOT (a Complete Set)
- NAND (a Minimal Set)
- NOR (a Minimal Set)

Thus we can use these five sets of gates, together or individually as the building blocks to produce more complex logic circuits called *combinational logic circuits*. But first let us remind ourselves of the switching characteristics of the three basic logic gates, AND, OR and NOT.

The AND Function

In mathematics, the number or quantity obtained by multiplying two (or more) numbers together is called the *product*. In Boolean Algebra the AND function is the equivalent of multiplication and so its output state represents the product of its inputs. The AND function is represented in Boolean Algebra by a single "dot" (.) so for a two input AND gate the Boolean equation is given as: Q = A.B, that is Q equals both A AND B.

The 2-input Logic AND Gate

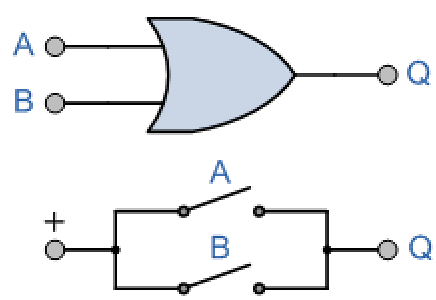
Symbol	Truth Table		
	B	A	Q
	0	0	0

	0	1	0
	1	0	0
	1	1	1

The OR Function

In mathematics, the number or quantity obtained by adding two (or more) numbers together is called the *sum*. In Boolean Algebra the OR function is the equivalent of addition so its output state represents the addition of its inputs. In Boolean Algebra the OR function is represented by a “plus” sign (+) so for a two input OR gate the Boolean equation is given as: Q = A+B, that is Q equals either A OR B.

The 2-input Logic OR Gate

Symbol	Truth Table		
	B	A	Q
	0	0	0
	0	1	1

	1	0	1
	1	1	1

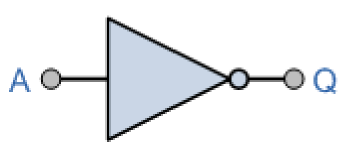
The NOT Function

The NOT gate, which is also known as an “inverter” is given a symbol whose shape is that of a triangle pointing to the right with a circle at its end. This circle is known as an “inversion bubble”.

The NOT function is not a decision making logic gate like the AND, or OR gates, but instead is used to invert or complement a digital signal. In other words, its output state will always be the opposite of its input state.

The NOT gate symbol has a single input and a single output as shown.

The Logic NOT Gate

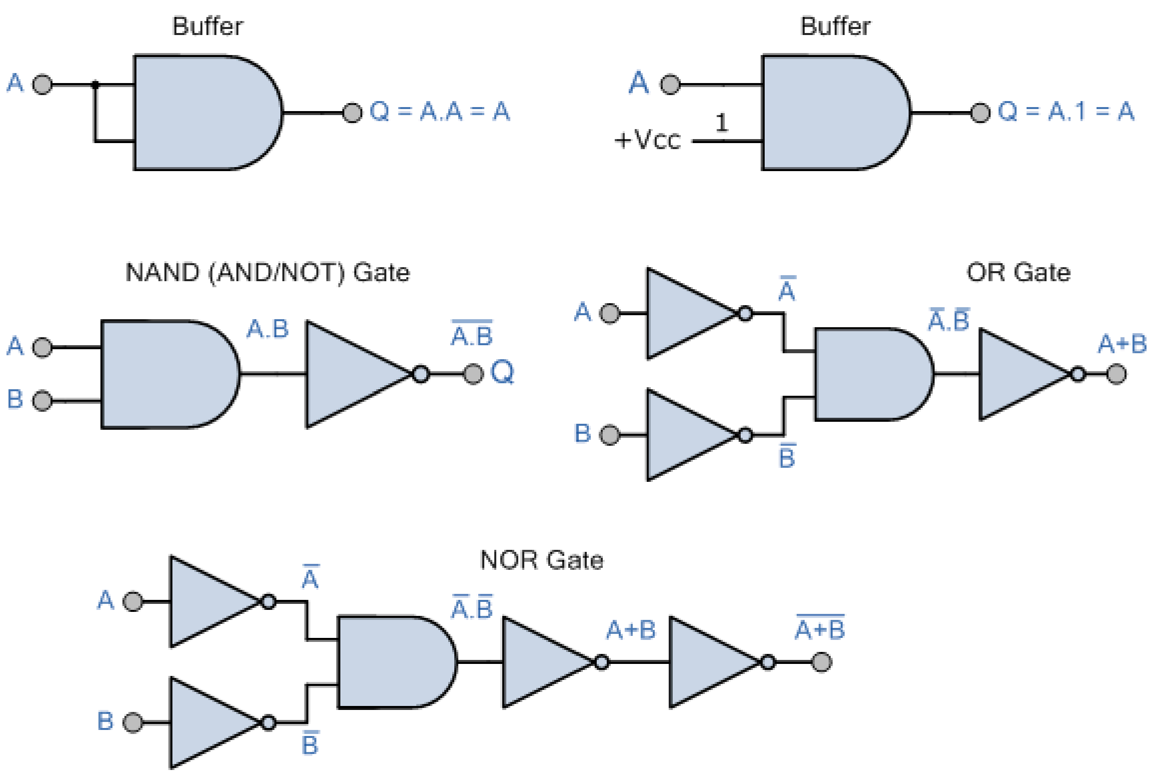
Symbol	Truth Table	
	A	Q
	0	1
	1	0

The single input NOT gate or invert function can be cascaded with itself to produce what is called a digital buffer. The first NOT gate will invert the input and the second will re-invert it back to its original level performing a double inversion of the single input. Non-inverting Digital Buffers have many uses in digital electronics as this double inversion of the input can be used to provide digital amplification and circuit isolation.

Using the AND and NOT Set

Using just the AND and NOT set of logic gates we can create the following Boolean functions and equivalent gates.

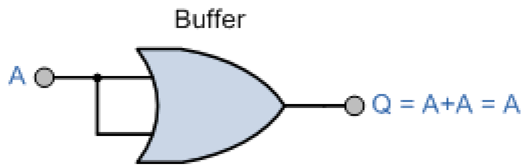
AND/NOT Set Equivalents

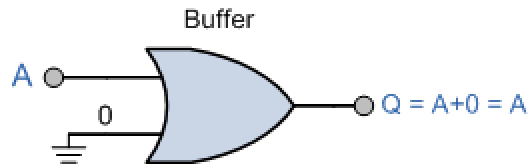


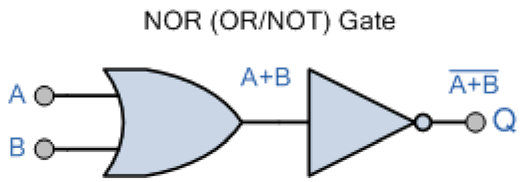
Using the OR and NOT Set

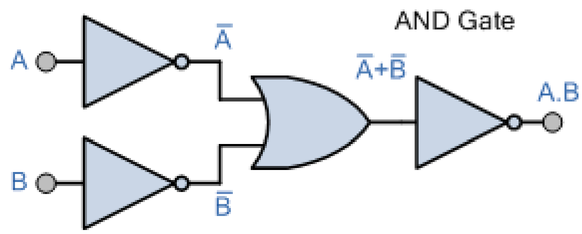
Using the OR and NOT set of logic gates we can create the following Boolean functions and equivalent gates.

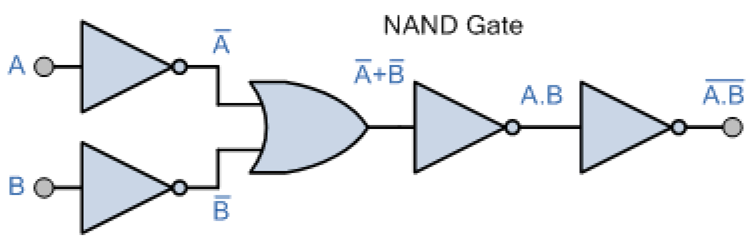
OR/NOT Set Equivalents







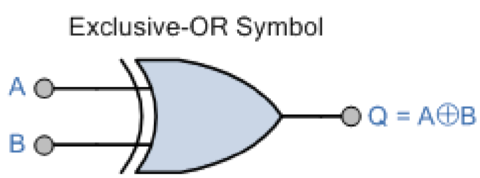


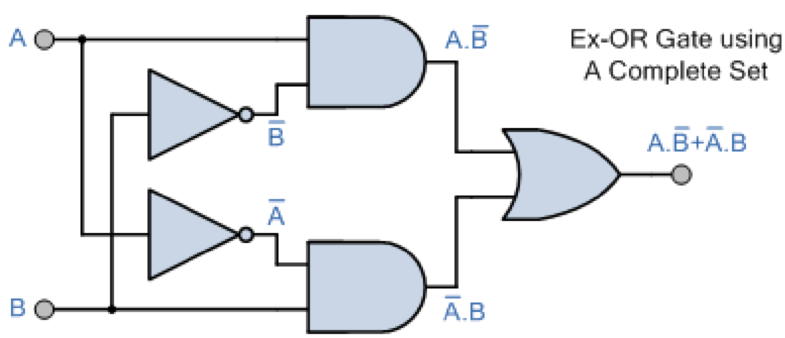


Using the Full AND, OR and NOT Set

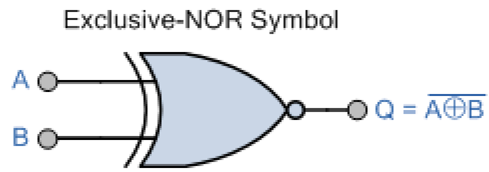
Using the full AND, OR and NOT set of logic gates we can create the Boolean expressions for the Exclusive-OR (Ex-OR) and the NOT Exclusive-OR (Ex-NOR) gates as shown.

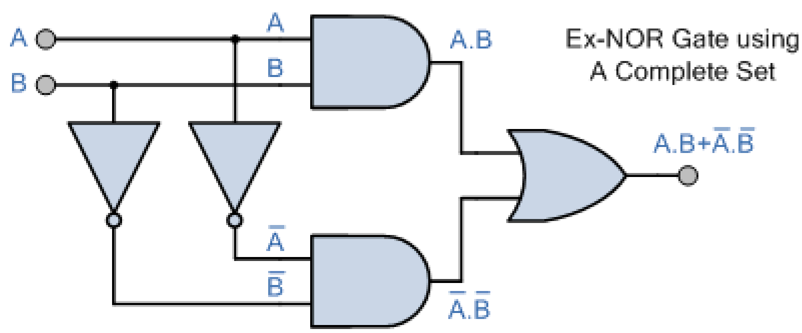
Full AND/OR/NOT Set to Implement Ex-OR





Full AND/OR/NOT Set to Implement Ex-NOR





Note that neither the Exclusive-OR gate or the Exclusive-NOR gate can be classed as a universal logic gate as they can not be used on their own or together to produce any other Boolean function.

Universal Logic Gates

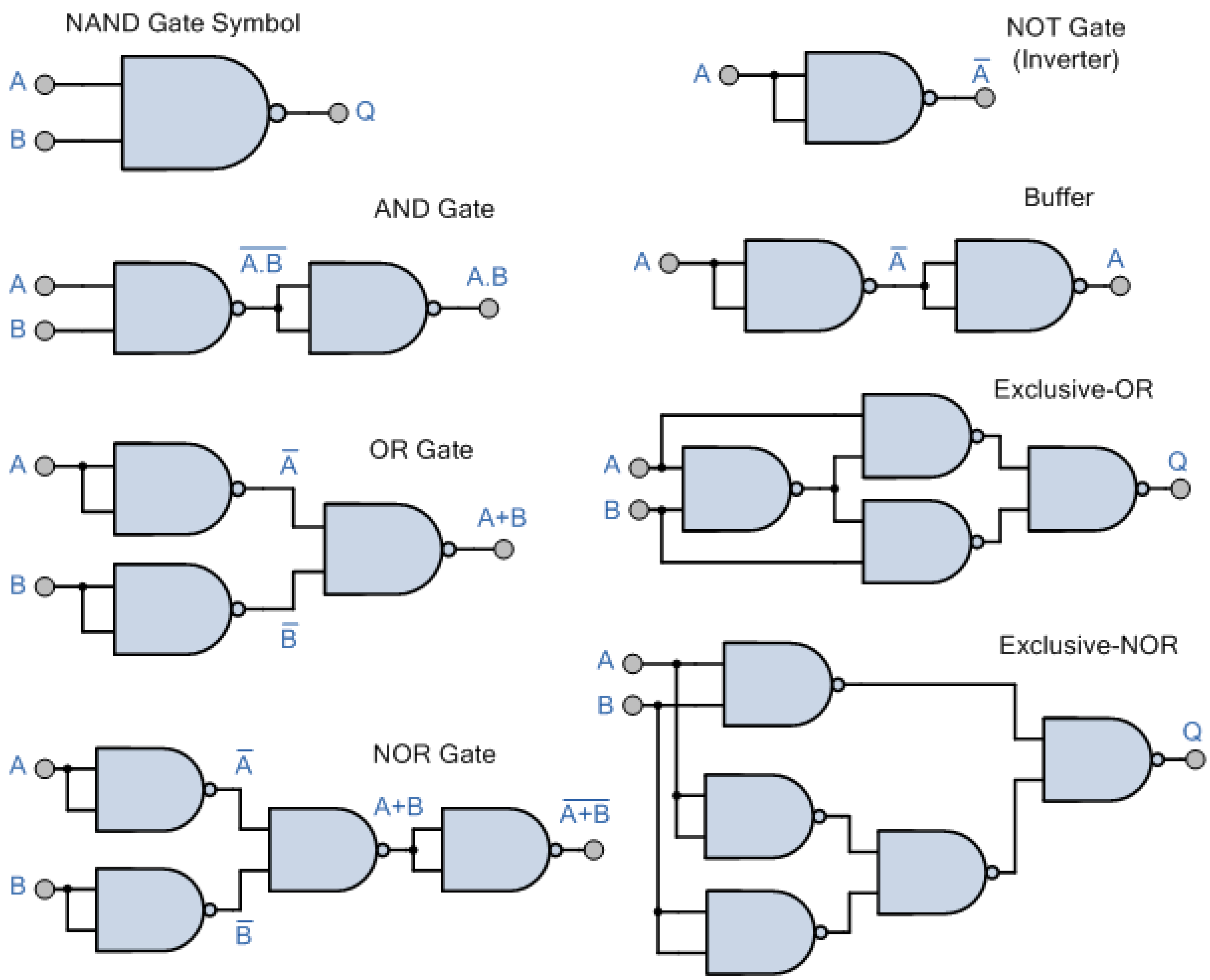
One of the main disdvantages of using the complete sets of AND, OR and NOT gates is that to produce any equivalent logic gate or function we require two (or more) different types of logic gate, AND and NOT, or OR and NOT, or all three as shown above. However, we can realise all of the other Boolean functions and gates by using just one single type of universal logic gate, the NAND (NOT AND) or the NOR (NOT OR) gate, thereby reducing the number of different types of logic gates required, and also the cost.

The NAND and NOR gates are the complements of the previous AND and OR functions respectively and are individually a complete set of logic as they can be used to implement any other Boolean function or gate. But as we can construct other logic switching functions using just these gates on their own, they are both called a minimal set of gates. Thus the NAND and the NOR gates are commonly referred to as **Universal Logic Gates**.

Implementation of Logic Functions Using Only NAND Gates

The 7400 (or the 74LS00 or 74HC00) quad 2-input NAND TTL chip has four individual NAND gates within a single IC package. Thus we can use a single 7400 TTL chip to produce all the Boolean functions from a NOT gate to a NOR gate as shown.

Logic Gates using only NAND Gates

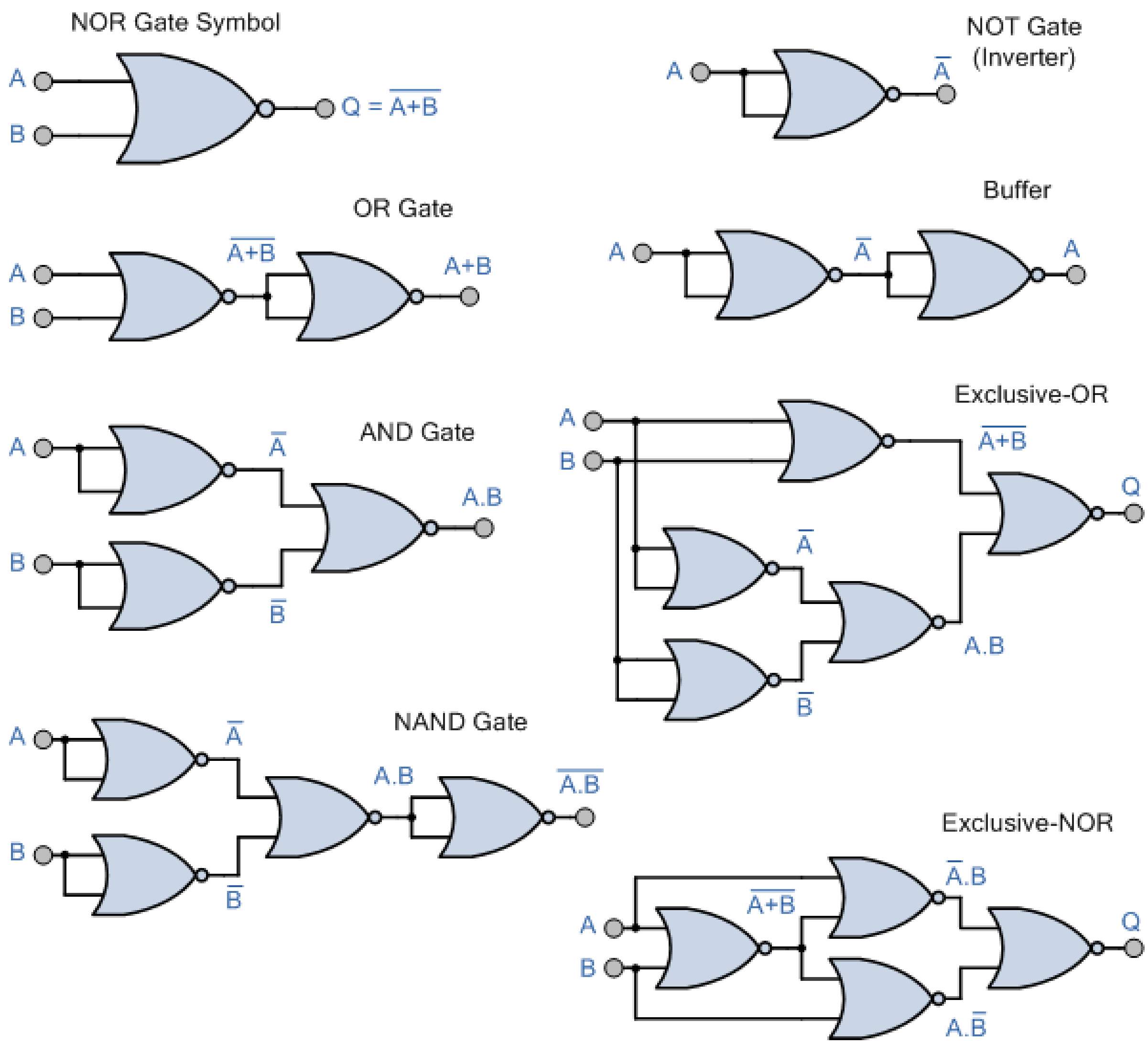


Thus ALL other logic gate functions can be created using only NAND gates making it a universal logic gate.

Implementation of Logic Functions Using Only NOR Gates

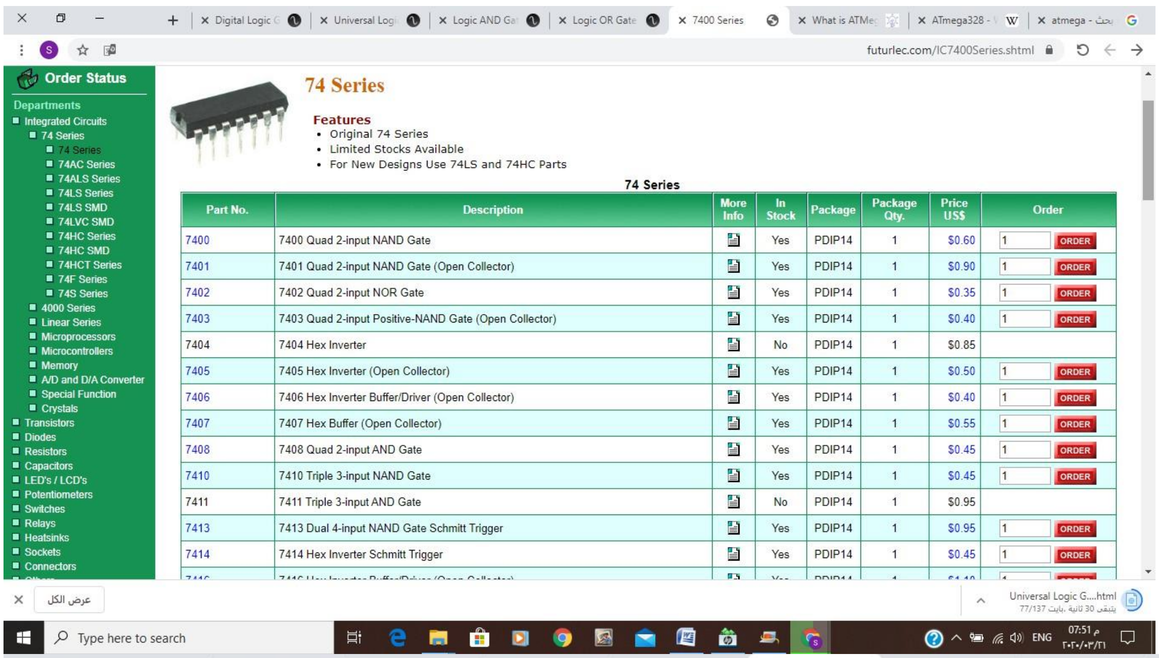
The 7402 (or the 74LS02 or 74HC02) quad 2-input NOR TTL chip has four individual NOR gates within a single IC package. Thus like the previous 7400 NAND IC we can use a single 7402 TTL chip to produce all the Boolean functions from a single NOT gate to a NAND gate as shown.

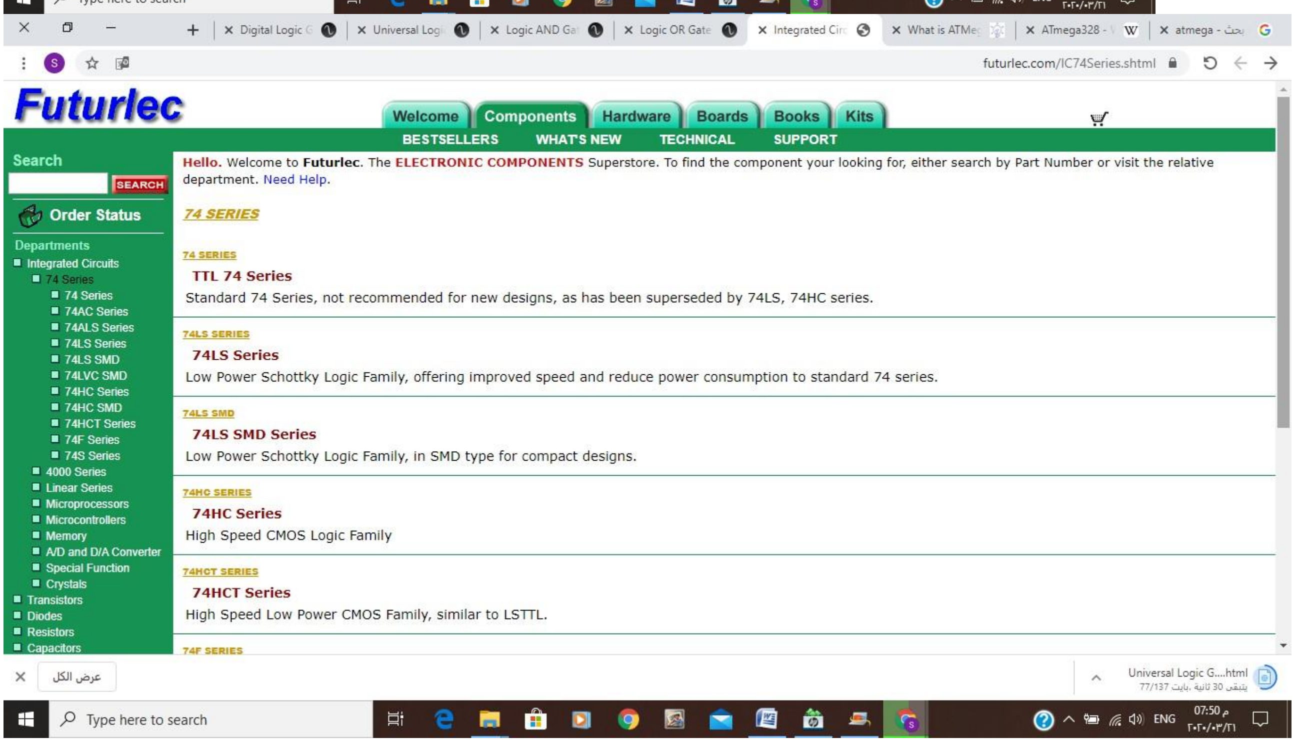
Logic Gates using only NOR Gates



Thus ALL other logic gate functions can be created using only NOR gates making it also a universal logic gate.

Note also that the implementation of the Exclusive-OR gate is more efficient using NAND gates compared to using NOR gates, while the implementation of the Exclusive-NOR gate is more efficient with NOR gates compared to using NAND gates as in each case only four individual logic gates are required. In other words we can create all the Boolean functions using just one 7400 NAND or one 7402 NOR chip including its various sub-families.





OPERATIONAL AMPLIFIERS

- The integrated circuit or IC is a Miniature, low cost electronic circuit consisting of active and passive components that are joined together on a single crystal chip of silicon

- It is a versatile device that can be used to amplify DC as well as AC input signals and was originally designed for computing such mathematical functions as Addition,Subtraction,Multiplication and Integration

APPLICATIONS OF AN INTEGRATED CIRCUIT

- **Communication**
- **Control**
- **Instrumentation**
- **Computer**
- **Electronics**

ADVANTAGES

- Small size
- Low cost
- Less weight
- Low supply voltages
- Low power consumption
- High reliable
- Matched devices
- Fast speed

DISADVANTAGES

- **Most Op-amp are designed for low power operation.**

- **For high output the Op-Amp should be designed specifically.**

- **Commercial Op-Amp shuts off when the load resistance is below the specific level**

CLASIFICATION OF IC „S

- **Digital IC"s**
- **Linear IC"s**

- **Integrated circuits**

  i) Monolithic circuits

  a) Bipolar

  i)PN junction isolation

  ii) Dielectric isolation

  ` b) Unipolar

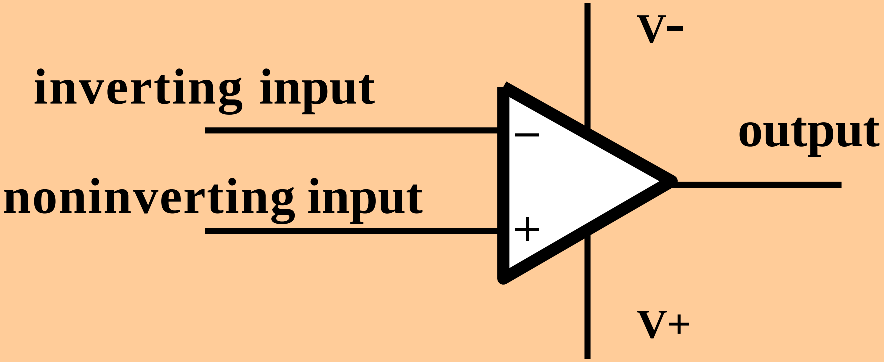
  i) MOSFET

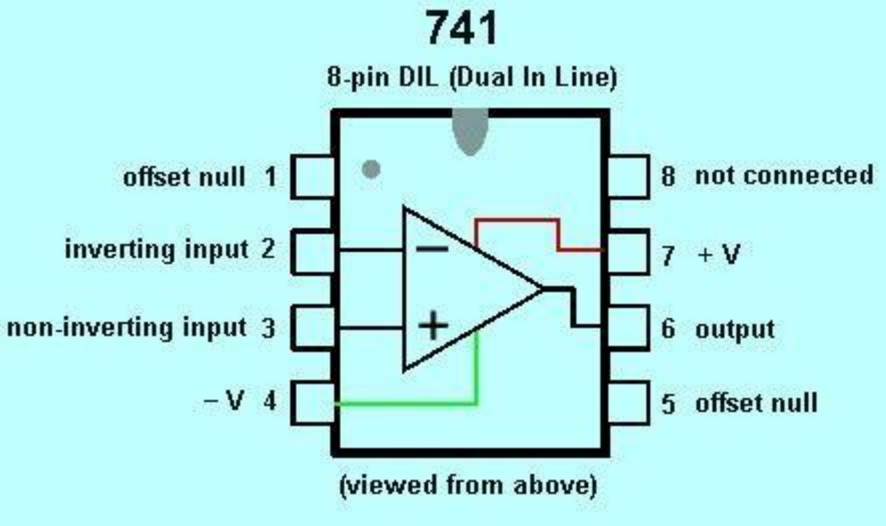
  II) JFET

  ii) Thick and Thin Film

  iii) Hybrid circuits

SYMBOL OF OP-AMP





7- Terminals, 4- Input, 1-Output =IC 741

IDEAL CHARACTERISTICS OF OP-AMP

- Infinite input impedance
- Infinite open-loop gain
- Zero output impedance
- Infinite bandwidth
- Zero noise.
- It has positive and negative inputs which allow circuits that use feedback to achieve a wide range of functions.

PERFORMANCE PARAMETERS OF OP-AMP

- **Input Offset voltage**
- **Input Offset current**
- **Input bias current**
- **Differential Input resistance**
- **Open loop Voltage gain**
- **CMRR**
- **Output resistance**
- **Input voltage range**
- **Power supply rejection ratio**
- **Power consumption**
- **Slew rate**
- **Gain**
- **Output offset voltage**

INPUT OFFSET VOLTAGE

- It is defined as the **voltage** that must be applied between the two **input** terminals of an **OPAMP** to null or zero the output.

- The input offset voltage of IC741 Op-Amp is 6mv

INPUT OFFSET CURRENT

- The algebraic difference between the currents flowing into the two input terminals of the Op-Amp.

- The input offset current of IC741 Op-Amp is 200nA

INPUT BIAS CURRENT

- **The average value of the two currents flowing into the Op-Amp input terminals.**

- **The input bias current of IC741 Op-Amp is 500nA**

DIFFERENTIAL INPUT RESISTANCE

- **It is the equivalent resistance measured at either the Inverting or Non-Inverting Input terminal with the other Input terminal grounded.**

- **The Differential Input Resistance of IC741 Op-Amp is 2MΩ**

OPEN LOOP VOLTAGE GAIN

- **It is the ratio of output voltage to the differential input voltage.**

- **It is denoted by AOL = Vo/Vd**

- **The Open loop Voltage gain of IC741 Op-Amp is typically 200,000**

CMRR

- **It is the ratio of differential voltage gain Ad to the Common mode voltage gain Ac.**

- **It is denoted by CMRR = Ad/Ac**

- **The CMRR of IC741 Op-Amp is 90db**

OUTPUT RESISTANCE

- It is the equivalent resistance measured between the output terminal of the Op-Amp and Ground.

- It is denoted by Ro.

- The Output Resistance of IC741 Op-Amp is 75 Ω

INPUT VOLTAGE RANGE

- It is the range of a common mode input signal for which a differential amplifier remains linear.

- The Input Voltage Range of IC741 Op-Amp is ± 13V

POWER SUPPLY REJECTION RATIO

- It is defined as the ratio of the change in supply voltage to the equivalent (differential) output voltage it produces.

- The Power Supply Rejection Ratio of IC741 Op-Amp is 30 μV/V

POWER CONSUMPTION

- It is the amount of quiescent power to be consumed by Op-Amp with zero input voltage, for its proper functioning.

- The Power Consumption of IC741 Op-Amp is 85mW.

SLEW RATE

- It is defined as the maximum rate of change of output voltage with time.

GAIN

- It is the bandwidth of an Op-Amp when voltage gain is unity.

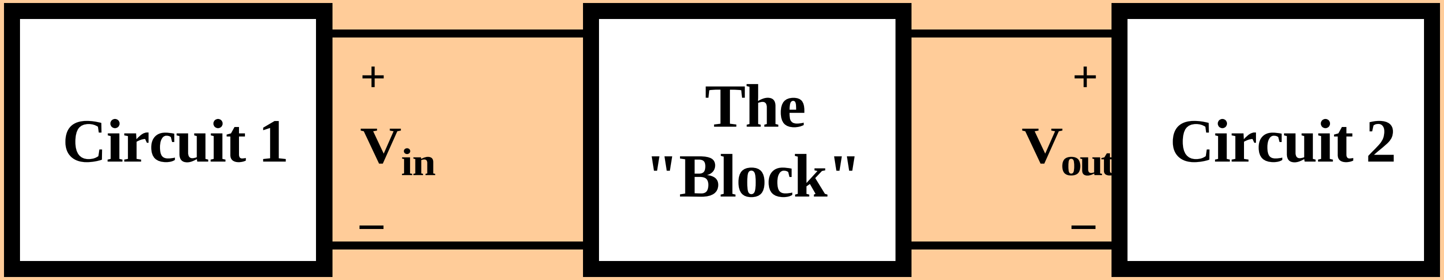
- The Gain of IC741 Op-Amp is 1MHz

OUTPUT OFFSET VOLTAGE

- It is the DC voltage present at the Output terminals when both the input terminals are grounded

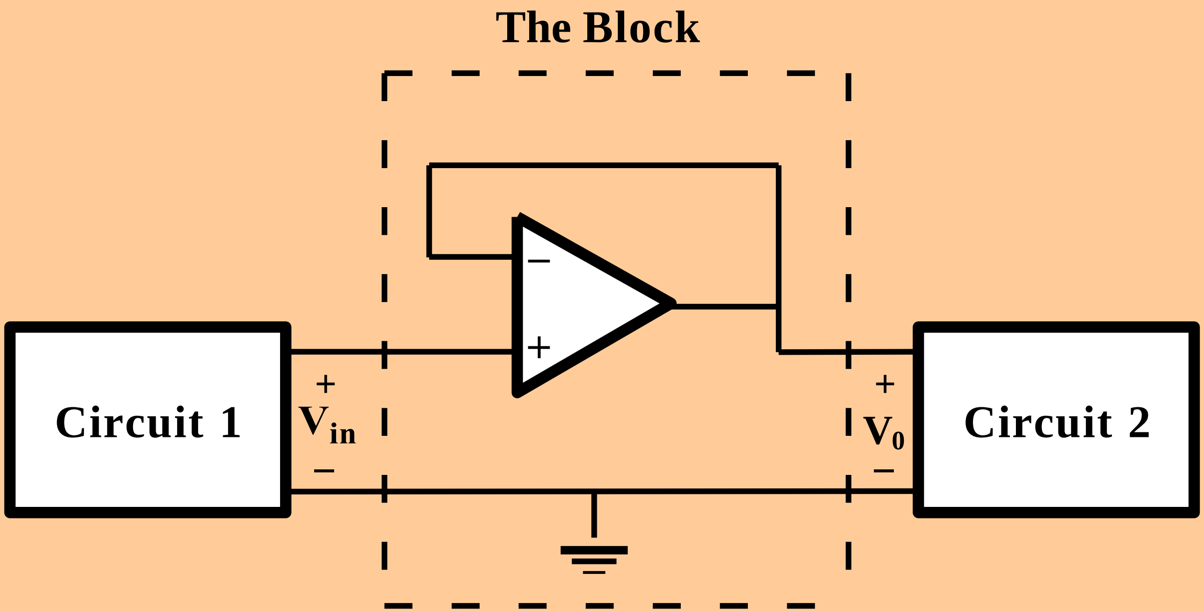
ISOLATION OR VOLTAGE FOLLOWER.

- **Applications arise in which we wish to connect one circuit to another without the first circuit loading the second. This requires that we connect to a "block" that has infinite input impedance and zero output impedance. An operational amplifier does a good job of approximating this. Consider the following:**



Illustrating Isolation.

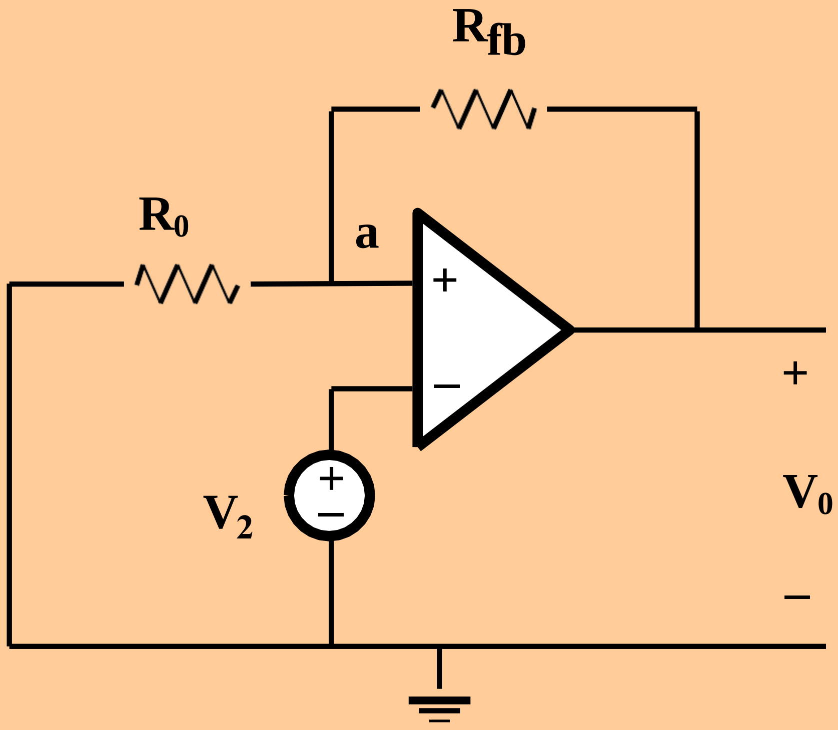
ISOLATION OR VOLTAGE FOLLOWER.....



Circuit isolation with an op amp.

It is easy to see that: $V_0 = V_{in}$

NONINVERTING OP AMP



Non-inverting op amp configuration.

NON- INVERTING OP AMP…

Writing a node equation at “a” gives;

$$\frac{V_2}{R_0} + \frac{(V_2 - V_0)}{R_{fb}} = 0$$

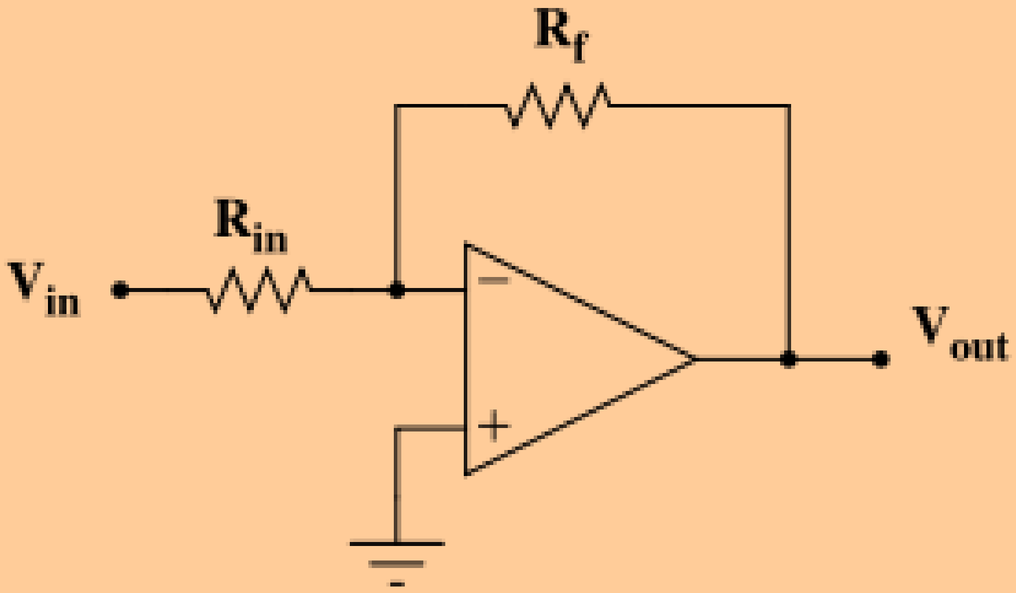
so

$$\frac{V_0}{R_{fb}} = V_2\left[\frac{1}{R_0} + \frac{1}{R_{fb}}\right]$$

which gives,

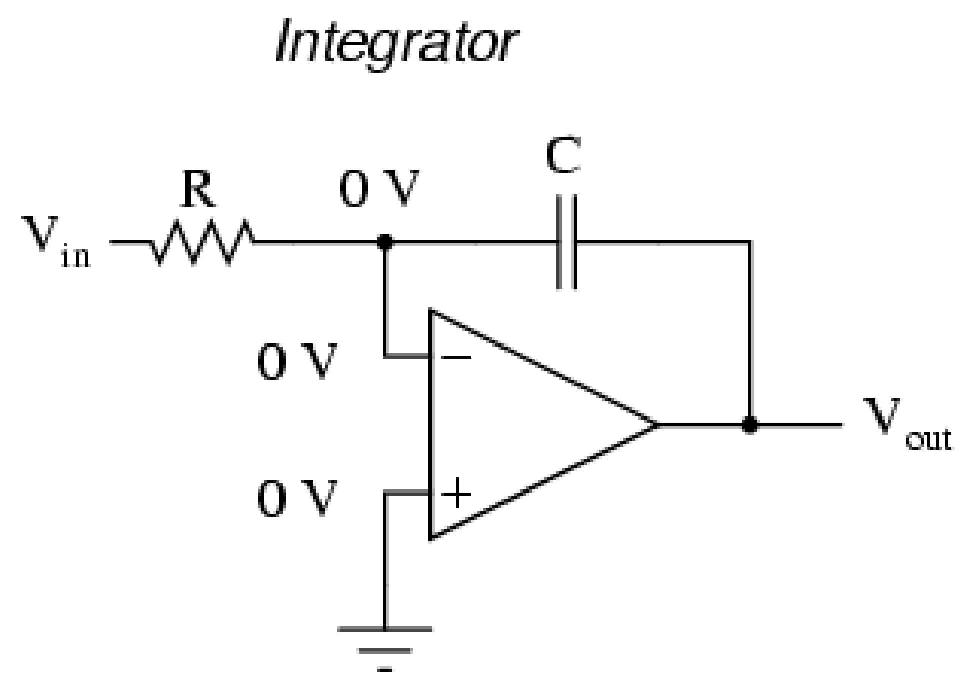
$$V_0 = \left(1 + \frac{R_{fb}}{R_0}\right)V_2$$

INVERTING OP AMP



$$V_{out} = -V_{in}(R_f/R_{in})$$

INTEGRATOR



$$\frac{dv_{out}}{dt} = - \frac{V_{in}}{RC}$$

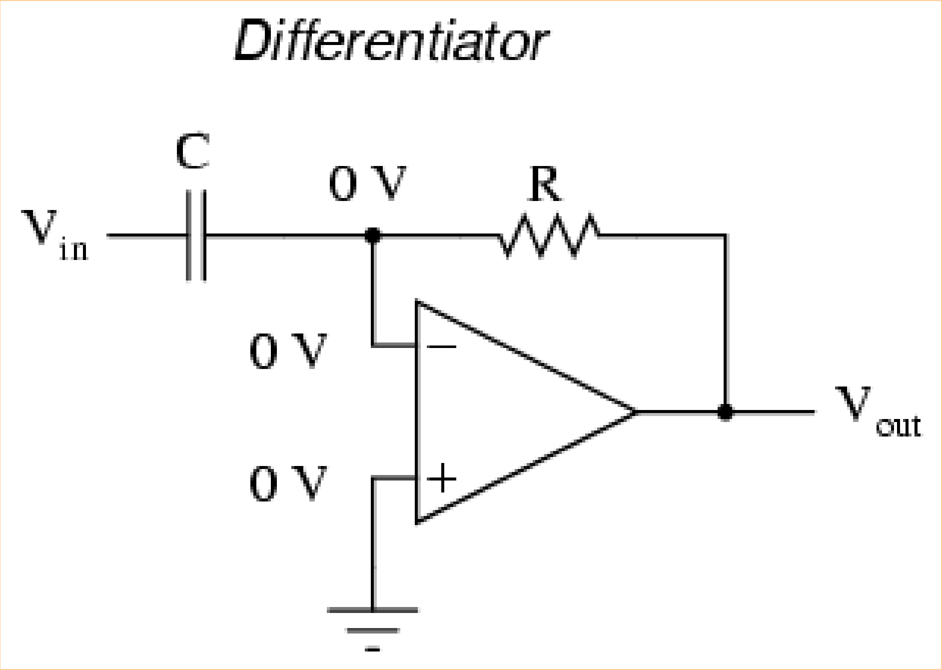
or

$$V_{out} = \int_0^t - \frac{V_{in}}{RC}\, dt + c$$

Where,

c = Output voltage at start time (t=0)

DIFFERENTIATOR



$$V_{out} = -RC \frac{dv_{in}}{dt}$$

Digital Electronics

Lesson: Timers (Use Black Box approach):- 555 Timer and its Applications: Astable and Monostable Multivibrator

Lesson Developer: Dr. Arijit Chowdhuri
College/Dept: Acharya Narendra Dev College
University of Delhi

TABLE OF CONTENTS

Timers (Use Black Box approach):- 555 Timer and its Applications, Astable and Monostable Multivibrator

1. Introduction - Timers (Black box approach) 555 timer IC

Timers are generally described as repetitive waveform generators (popularly called clock) that are essentially used to control certain sequence of an occurrence while counting in stipulated time intervals. Timers find applications typically in fields including:

a) Microprocessors and Microcontrollers
b) Counters
c) Transducers
d) Data Acquisition
e) Starting and ending industrial processes
f) Traffic lights
g) Car Tachometer
h) Remote TV jammers
i) Sirens, light detectors, touch switches etc.

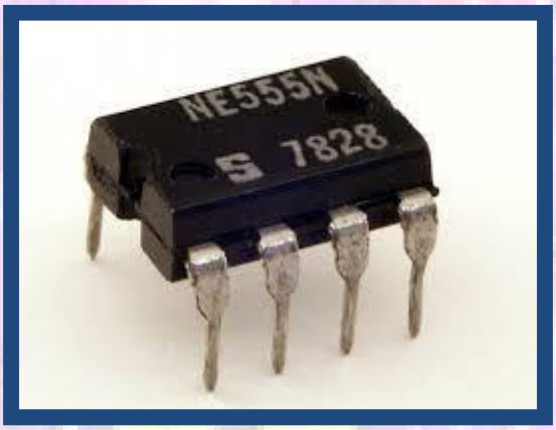


Figure 1: NE 555 timer IC

Developed by an US company Signetics and introduced worldwide in 1971, 555 is one of the most well-known timer integrated circuits (ICs) till date. It finds use in a variety of timing and oscillator applications, time delays, flip-flop element besides pulse generation. Although the manufacturing technology of 555 timer IC has matured from bipolar (original) to low-power CMOS, however it is still popular worldwide (more than a billion units are sold annually) simply because of its low price, ease of use, and stability.

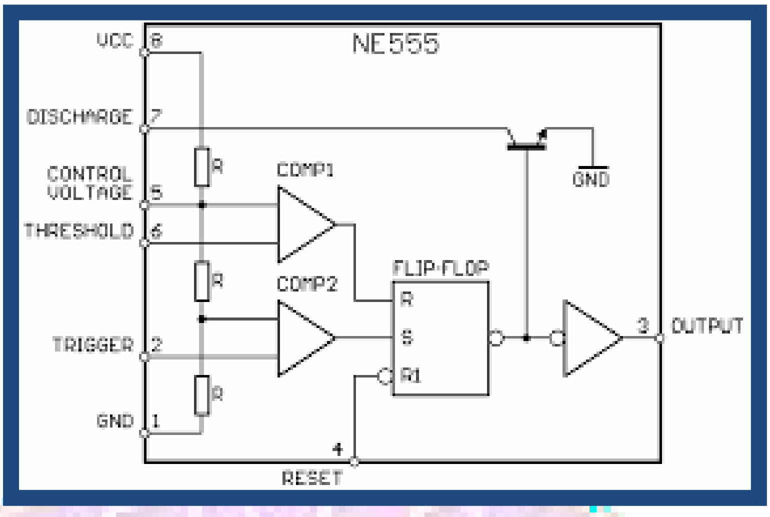


Figure 2: Basic connection details within 555 timer IC

555 IC is essentially a timer that can be configured to produce a simple pulse, a continuous rectangular wave (that can be modified to a square waveform) or a triangular / sawtooth wave (modified from capacitor charging and discharging). The type of signals that would be generated by the 555 timer IC is governed by the following:

a) The kind of electronic components connected externally to the 555 IC

b) The means how the electronic components are connected externally to the 555 IC

2. Internal components of 555 timer

The 555 timer IC has essentially five kinds of internal components that govern its functioning and the same are listed as here-under

i) Voltage divider

ii) Comparator

iii) R-S Flipflop

iv) Transistor (Bipolar Junction Transistor)

v) Out buffer

2.1 Voltage divider

Internally 555 IC consists of three resistors (each of 5 KΩ). The function of these three resistors is to from a voltage divider that applies two-thirds of the power supply voltage (Vcc) to the inverting input terminal of upper comparator (COMP 1) while applying one-third of Vcc to the non-inverting terminal of the lower comparator (COMP 2) as shown in Figure 2.

2.2 Comparator

Two voltage comparators upper (COMP 1) and lower (COMP 2) are inside the 555 timer IC. The connections of the two comparators to the voltage divider ensures the following:

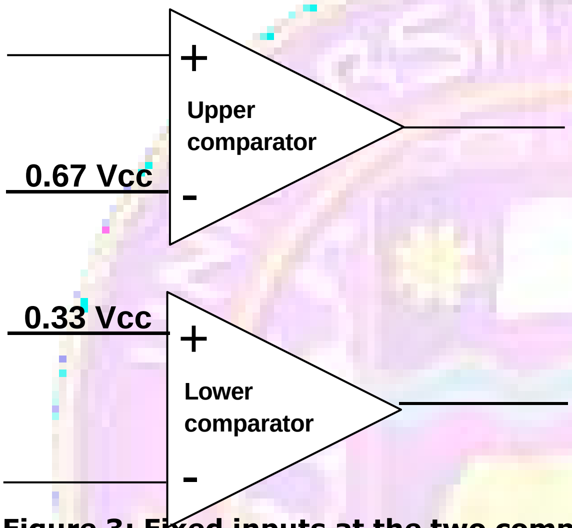


Figure 3: Fixed inputs at the two comparators

Comparators have a characteristic that whenever input voltage at their non-inverting input is greater in magnitude than on its inverting input then their outputs produce positive voltage. Internal conditions ensure that output from both the comparators can never be a positive voltage at the same time, however they can be zero.

2.3 R-S flip flop

The output of the upper comparator (COMP 1) is connected to the R input of the flip-flop while output of the lower comparator (COMP 2) is connected to its S input. Flip flops are digital 'electronic component' that typically have two inputs (R & S) and two outputs (Q and Q'). One out is ALWAYS complement state of the other. Complement refers to the fact if one is logic HIGH then its complement would be logic LOW. The inputs and outputs of the flip flop are either logic HIGH or logic LOW and nothing in between. Logic High and logic LOW are preset voltages and generally logic LOW is zero volts (0 V), while logic HIGH is typically +5 V. The output of the RS flip flop is summarized in the following truth table

R input	S input	Q output
0	**0**	**Last state**
0	**1**	**0**
1	**0**	**1**
1	**1**	**NOT ALLOWED**

It is interesting to note that since output from both the comparators can never be positive (HIGH) voltage simultaneously hence the condition of R = 1 = S would never occur.

Also complement of the output of the RS flip flop is connected to the output buffer besides the base of the NPN bipolar junction transistor (BJT).

2.4 NPN bipolar junction transistor (BJT)

The NPN bipolar junction transistor (BJT) acts as a switch and its main function is to act as a path of discharge. The NPN BJT conducts current between its emitter and collector whenever a positive voltage is present at its base. Likewise it stops the flow of current between the emitter and collector whenever the base has zero voltage.

2.5 Output buffer

The job of the output buffer is to produce high current and voltage so as to be able to produce sufficient power in the 555 IC to drive external devices / circuitry. Figure 2 shows that output buffer receives its input from the complement voltage output of the RS flip flop.

3. Basic working of 555 timer

555 timer IC (Figure 2) is thus mainly seen to consist of three 5 KΩ resistors (hence the name 555) constituting a voltage divider, two voltage comparators, flip-flop and transistors for discharge. Inside the IC the 5 KΩ resistors are connected in series with the DC power supply (Vcc). The 555 timer IC functions in a stable manner within the DC supply range of 5 – 15 V while 18 V is the absolute maximum. Within the 555 timer IC, the lower voltage comparator (COMP 2) has 1/3 Vcc supply voltage applied to its positive input terminal while 2/3 Vcc voltage is applied to the negative terminal of the upper comparator (COMP 1). It is advisable to connect 555 timer ICs to 6V, 9V or 12V (Vcc

values) because of its operation between 2/3 and 1/3 Vcc and hence ease of plotting on CROs.

SUPPLEMENTARY READING

Operational amplifiers (op-amps) and a special class of differential amplifiers which possess a balanced difference input with a very high gain and most voltage comparators are based on them. Typically low performance (cheap) voltage comparators are realized by using a standard op-amp (741C) operating in open-loop configuration (without negative feedback). Whenever, non-inverting input (V_+) has a higher voltage input than its inverting input counterpart (V_-), the high open-loop gain of the op-amp causes its output to saturate at the highest positive voltage the op-amp IC can output. On the contrary whenever non-inverting input (V_+) drops below the inverting input (V_-), the output saturates at the most negative voltage it can output. The op-amp's output voltage is limited by the supply voltage.

In th [illegible] below 1/3 Vcc, the set (S) terminal of the flip-flop (FF) attains a high level and the FF is said to be set. Likewise whenever the voltage of at the threshold terminal (THRESHOLD) becomes higher than 2/3 Vcc, the reset (R) terminal of the FF attains a high level and the FF is considered to be reset. The output of the 555 timer IC exhibits various patterns as it oscillates between 2/3 Vcc and 1/3 Vcc

SUPPLEMENTARY READING

Flipflops (FFs) are bistable binary circuits that act as the basic memory element in digital electronics. The FFs change their state (from 0 to 1 and vice-versa) when signals are applied to its one or more control inputs and which influence their one or two outputs.

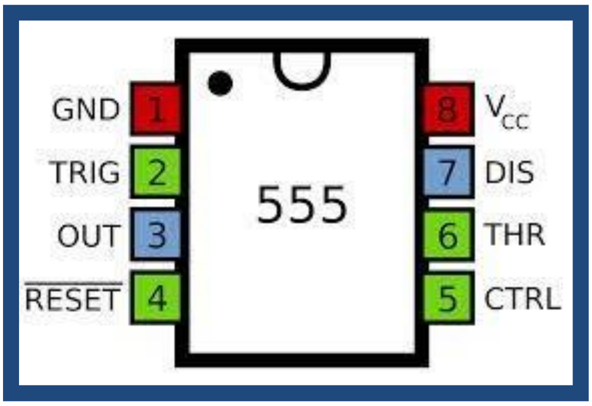


Figure 4: Pin-out diagram of 555 timer IC

4. Description of various pin terminals of 555 timer

Figure 4 shows the pin-out diagram of 555 timer IC which is typically available as a 8 – pin dual-in-line package (DIP). Pin #1 (0 V) and pin #8 (+ 5 to +15 V) are used to connect DC power supply (5 – 15 V).

Pin #2 is TRIGGER, in monostable configuration of 555 timer, initiates a high to low transition and otherwise whenever voltage at this pin falls below 1/3 Vcc triggers the timer.

Pin #3 is the OUTPUT pin which exhibits a rectangular or square wave (astable operation) or a high value for a predetermined set time (monostable operation).

Pin #4 is the RESET which if NOT used is connected to Vcc.

Pin #5 is CONTROL VOLTAGE, 555 timer manufacturer states that for reliable operation a 0.01 µF capacitor needs to be connected between this and the circuit ground.

Pin #6 is the THRESHOLD that detects whether the voltage on the timing capacitor has risen over 2/3 Vcc and resets the output whenever this takes place.

Pin #7 is the DISCHARGE and is used to provide a discharge path from the timing capacitor to ground when the output is low.

Suggested Simulation

https://www.wisc-online.com/learn/career-clusters/stem/sse7806/internal-elements-of-a-555-timer

As the name suggests a multivibrator (generator of multiple frequencies) in astable mode has no stable output. It always has an output that switches back and forth between two states and in the case of 555 IC generally a rectangular output is obtained. This rectangular output can be converted to square wave output with some minor modifications to the external circuit. Also the rate at which the output switches back and forth (frequency) between the high and low states can be accurately controlled by the end-user / designer. 555 timer IC therefore finds applications as a clock generator over a broad range of applications. Another advantage that 555 timer IC has, is the wide range of time-period (= 1/frequency) over which it can generate stable waveforms (microseconds to hours).

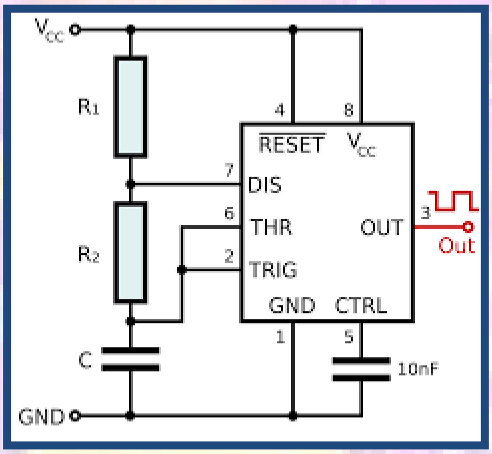


Figure 5: 555 timer IC configured in astable mode

Figure 5 shows the 555 timer IC in astable configuration mode with two external resistors R_1 and R_2 and a timing capacitor C. Manufacturer of 555 timer IC warrants that a 0.01 μF (microfarad) capacitor be affixed between its CONTROL (Pin # 5) and ground for stable operation.

As soon as the 555 timer IC is biased with Vcc (DC source), the following zero state conditions are assumed:

i) Timing capacitor C is fully discharged

ii) Output of the upper comparator (COMP 1) is LOW

iii) Output of the lower comparator (COMP 2) is HIGH

iv) Discharge BJT is switched OFF

v) RS Flip flop output is HIGH and its complemented output is LOW

vi) Output of the buffer is HIGH

As soon as the Vcc power is applied to the circuit current begins to flow through R_1, R_2 and C. The timing capacitor (C) begins to charge in an exponential fashion and the potential across the capacitor is directly connected to the inverting terminal of the lower comparator (COMP 2). As soon as the capacitor C charges beyond 0.33 Vcc the output of the lower comparator goes low. This is because the non-inverting terminal of the lower comparator is fixed at 0.33 Vcc due to connection with the 5 KΩ voltage divider. As the capacitor keeps charging towards Vcc and crosses the 0.67 Vcc threshold value then the upper comparator (COMP 1) changes its output to HIGH. As soon as this happens, R input of the flip-flop goes HIGH and its S input goes LOW. This results in the flip flop output Q going LOW and, its complement out Q' going HIGH. This change in RS flip flop output results in output buffer going LOW. Further, a HIGH Q' results in the NPN BJT switching ON and providing the timing capacitor C a path to discharge. As soon as the capacitor begins to discharge the potential across it begins to fall, leading to the upper comparator going LOW. With constant discharge when the capacitor potential falls below 0.33 Vcc the output of the lower comparator goes HIGH. With the upper comparator at LOW output and lower comparator with HIGH output again the RS flip flop changes its output (Q) to HIGH and hence its complement state Q' goes LOW. The output buffer goes HIGH while the NPN BJT gets cut-off thus blocking any more discharge of the capacitor. Hence the capacitor starts to charge once again through R_1 and R_2. The cycle starts repeating all over again. It is therefore noted that as long as power (Vcc) is provided to the astable configuration of the 555 timer IC the potential on its timing capacitor would oscillate between 0.67 Vcc and 0.33 Vcc. Only the first time the capacitor would charge from 0V to 0.67 Vcc and thereafter the oscillation would begin.

Suggested simulation

https://www.wisc-online.com/learn/technical/electronics-solid-state/sse8106/the-555-astable-multivibrator#

5.1 Timing calculations in 555 timer in astable configuration

The charging of the timing capacitor happens through R_1 and R_2 and hence the time for which one obtains a HIGH value at the output (Pin # 3) of the 555 timer IC is given by

$T_{HIGH} = 0.693\,(R_1 + R_2)\,C$ seconds [since RC = time constant]

The discharge of the capacitor takes place only through the resistor R_2 and hence the time for which one obtains a LOW value at the output (Pin # 3) of the 555 timer IC is given by

T_{LOW} = 0.693 (R_2) C seconds

> **Activity**
>
> Take a dual-trace CRO/DSO and fix up its two vertical channel probes at Pin # 2 and Pin # 3 of a 555 timer IC configured in astable mode. Plot the waveforms thus obtained.

5.2 Waveforms obtained during the above activity

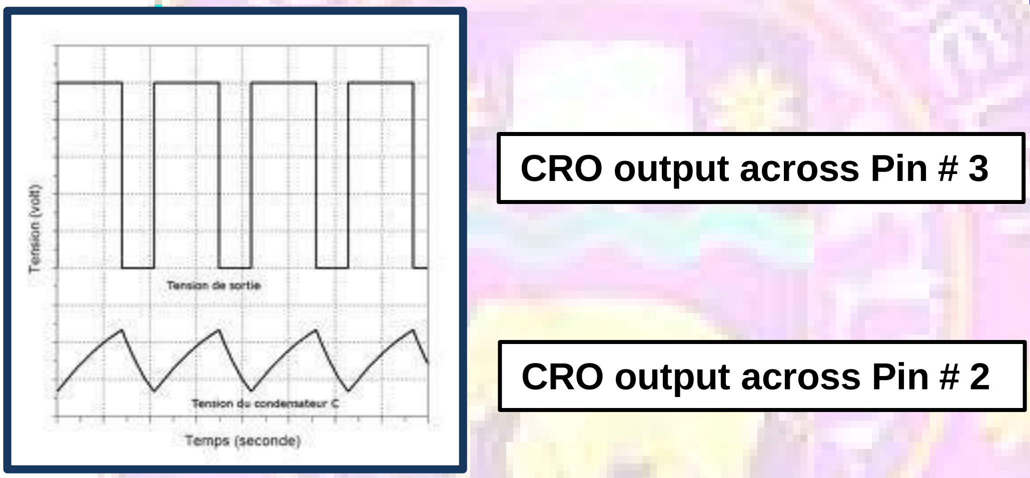


Figure 6: Waveforms obtained on a dual-trace CRO/DSO at Pin # 3 and Pin # 2 of a 555 timer IC configured in astable mode

> **Important Tip**
>
> Whenever NO output is obtained at Pin # 3 of the 555 timer IC it is prudent to check whether the timing capacitor is charging and discharging properly i.e. a saw-tooth wave is being obtained across it.

Duty cycle (%) of the waveform is defined as

$$D = T_{HIGH} / (T_{HIGH} + T_{LOW}) \times 100$$

It is important to note in 555 time IC configured in astable mode, that the timing capacitor (C) would always charge through R_1 and R_2 but discharge through R_2 only. Hence the output waveform normally would always be rectangular in nature with HIGH time being larger than the LOW time.

50% DUTY CYCLE (Square wave output)

In order to obtain a square wave output from 555 timer in astable mode, one has to somehow realize $\mathbf{T_{HIGH} = T_{LOW}}$ (50% Duty Cycle)

The easiest option seen is to put $R_1 = 0\Omega$, however it is NOT feasible as it would wreck the stability and integrity of the 555 timer as astable multivibrator. Also having same resistance values for R_1 and R_2 (i.e. $R_1 = R_2$) does NOT solve the problem.

PRACTICAL SOLUTION TO OBTAIN 50% DUTY CYCLE

The practical solution to obtain 50% duty cycle is to use a diode across the R_2 resistor while keeping the values of the resistors R_1 and R_2 same.

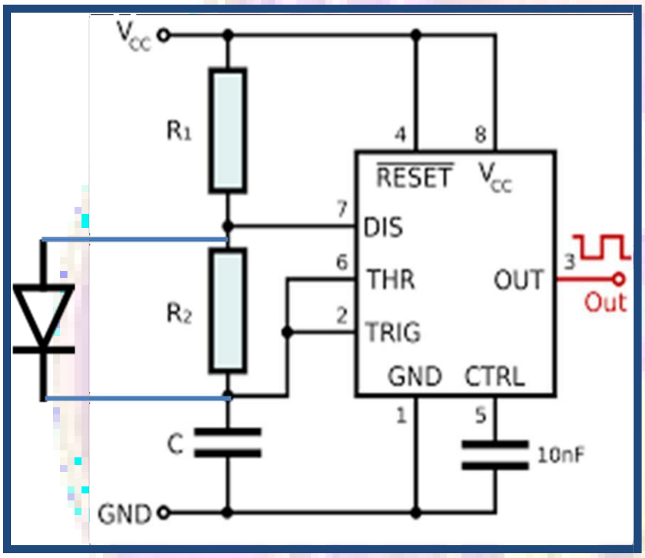


Figure 7: 555 timer IC in astable mode configured as a square wave generator

Figure 7 shows the 555 timer IC in astable mode configured as a square wave generator. It is pertinent to note that with values of both the resistors kept equal ($R_1 = R_2$) during charging, the current passes through R_1 but bypasses R_2 since the affixed diode being forward biased offers an easier path for it (ideal diode in forward bias offers zero resistance). During discharge of the capacitor only R_2 resistance comes into play since during this time the current cannot flow through the diode since it is reverse biased and offers a very high resistance.

6. 555 timer IC in Monostable mode (single shot / one shot)

As the name suggests monostable multivibrator (also known as one / single shot) has one stable state and it switches to its unstable state for a predetermined time period T when it is triggered. The time period (T) is pre-determined by the external resistor (R) and timing capacitor (C) whence the RC gives the time constant. in the circuit. The main application of the 555 timer IC in monostable mode is for generation of Pulse Width Modulated (PWM) waves and measurement of single events during data logging.

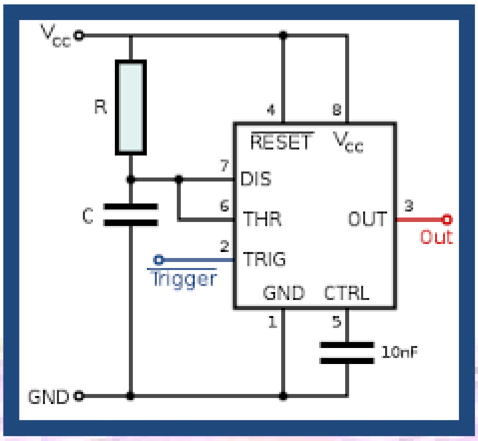


Figure 8: 555 timer IC configured in monostable mode

Figure 8 shows the 555 timer IC configured in monostable or single shot mode. It remains in its default low output state (stable state) until it is triggered. When a negative trigger (a negative going pulse) is applied to the TRIGGER (Pin # 2) of 555 Timer, the lower comparator (COMP 2) output goes HIGH and output of upper comparator (COMP1) goes LOW. HIGH output of the lower comparator makes the S input of the RS flip flop HIGH and R input LOW (since upper comparator output is R input). This makes the RS flip flop output (Q) HIGH and its complement output Q' LOW. Since Q' is connected to the base of the NPN BJT hence the discharge transistor turns OFF and the timing capacitor starts charging to Vcc (DC power supply) via the resistor R. It is assumed that the initial voltage on the timing capacitor is zero. After the negative pulse (trigger) which is momentary output of lower comparator (COMP 2) reverts to its LOW value and the upper comparator also remains LOW. This condition ensures that both the R and S inputs of the RS flip flop get fixed to LOW values and hence output does NOT change (Truth table of RS flip flop). The typical output characteristics of the 555 timer IC in monostable configuration are shown in Figure 9.

6.1 Timing calculations in 555 timer in monostable configuration

The time (t_p) during which the output of a monostable 555 timer remains high as shown in Figure 8 is given by

t_p = 1.1 RC (seconds)

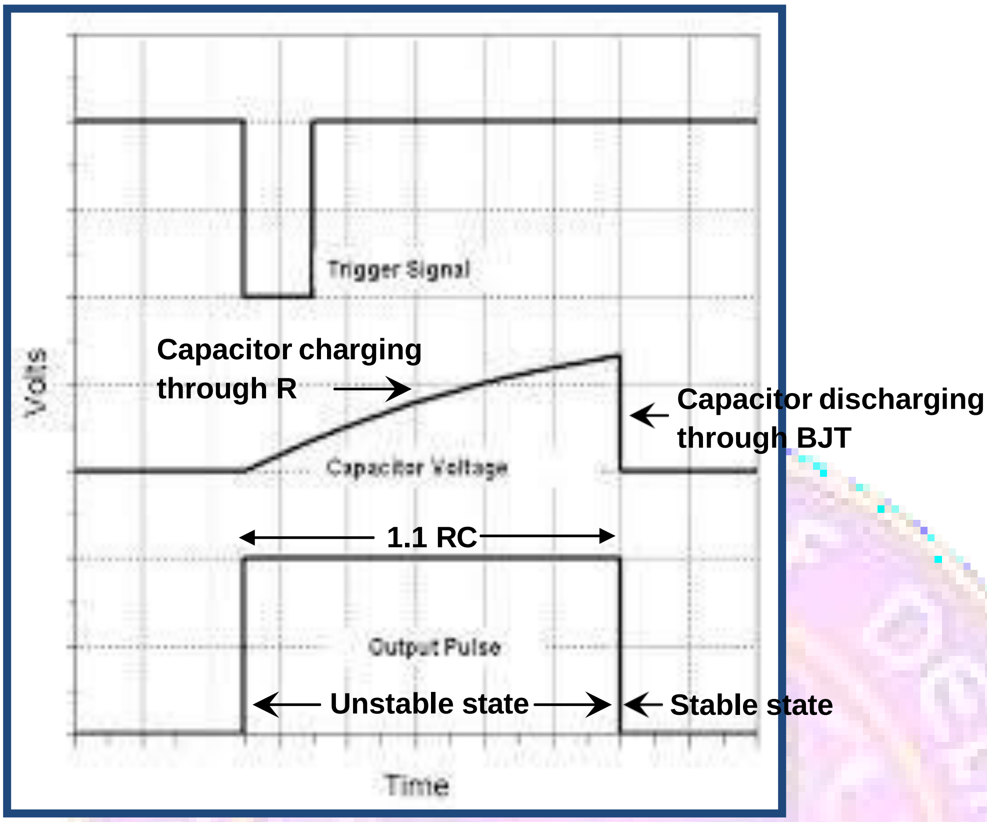


Figure 9: Typical output characteristics of the 555 timer IC in monostable configuration

ACTIVITY

How to realize 555 timer IC in monostable mode without using a CRO

In the 555 timer IC configured as a monostable multivibrator connect a Light Emitting Diode (LED) having a 100 Ω resistor in series between its output (Pin # 3) and ground. Choose the resistor (R) and timing capacitor (C) in such a way

Precaution

When choosing large capacitor values it is seen that most of them are electrolytic in nature. Electrolytic capacitors have polarities and one has to be careful while connecting them. An electrolytic capacitor when connected with reverse polarity beyond a particular voltage is prone to explode.

6.2 How to apply trigger to 555 timer IC in monostable mode

In order to trigger the 555 timer IC in monostable mode the TRIGGER (Pin #2) has to momentarily fall below 0.33 Vcc. The duration of the trigger pulse should be such that it must never be longer than the duration of the 555 timer output.

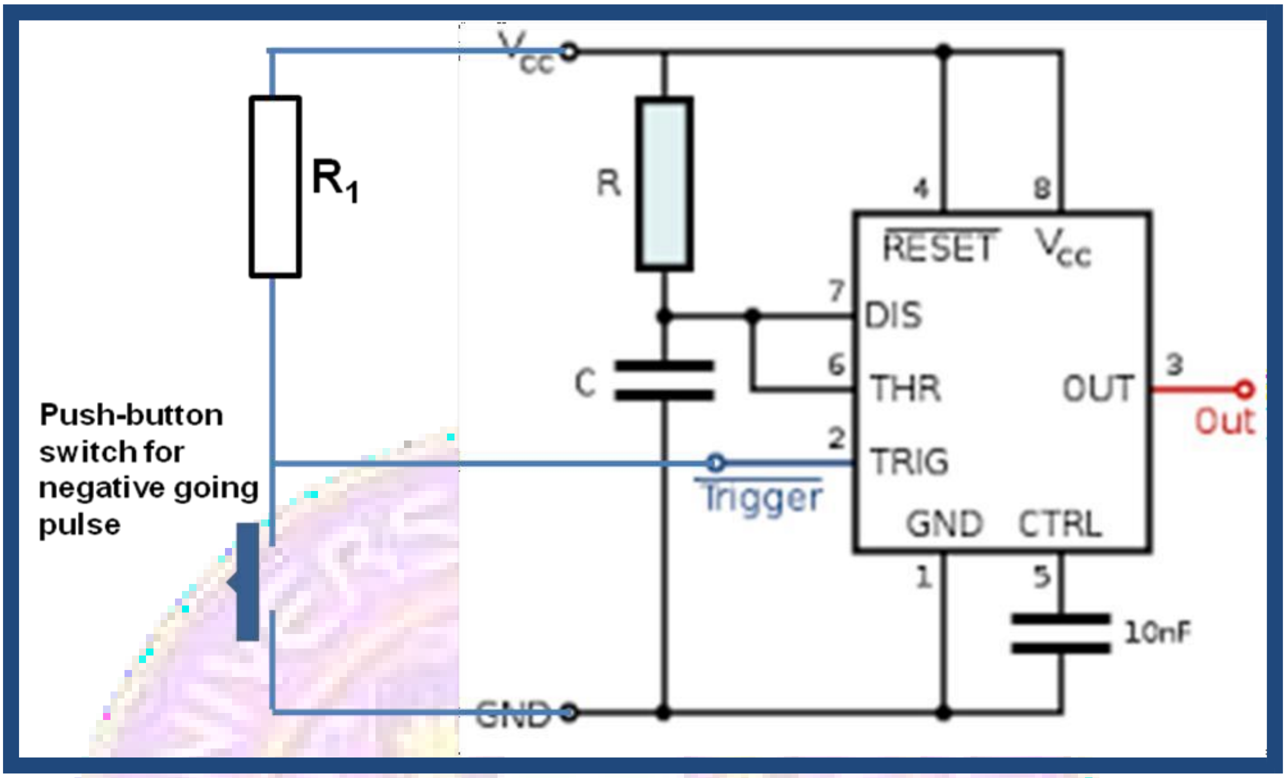


Figure 10: 555 timer IC configured in monostable mode with trigger circuit

Figure 10 shows the 555 timer IC configured in monostable mode with trigger circuit. The trigger circuit essentially consists of a resistor (R_1) connected between Vcc and TRIGGER (Pin #2). Further the TRIGGER is connected to the ground (GND) via a push-button switch. The value of resistor should be very high (> 1 MΩ) since it is used to prevent flow of high current during generation of the negative going pulse at Pin #2. This circuit for triggering is useful only for time-period in seconds. For triggering faster waveforms output of a 555 timer configured in astable mode can be used for triggering.

SUMMARY: After studying this chapter, you should be able to

- Explain and analyze the operation of 555 timer.
- Describe internal components of 555 timer and discuss their function
- Explain the function of various pins of 555 timer
- Explain working of 555 timer in Astable mode
- Explain working of 555 timer in Monostable mode
- Describe various output wave forms obtained

- Design timing circuits using 555 timer
- Understand limitations of 555 timer

EXERCISES

Question Number	Type of question
1	Multiple choice questions

1. In which decade did the 555 timer IC start being used commercially
(a) 1950 (b) 1970 (c) 1990 (d) 2010

2. Main use of the 555 IC is
(a) As an amplifier (b) As a voltage divider (c) As a timer (d) All of these

3. 555 timer has three resistors each having a value
(a) 5 K Ω (b) 5 M Ω (c) 5 Ω (d) None of these

4. In a 555 timer in astable mode, a square wave output can be achieved by
(a) using a diode across R_A (b) $R_A = 0\ \Omega$ (c) $R_B = 0\ \Omega$ (d) using a diode across R_B

5. Which configuration of 555 timer is not possible
(a) Astable (b) Bistable (c) Unstable (d) Monostable

6. The function of Pin 3 is:

a) Control Voltage b) Discharge c) Output d) Reset e) Threshold g) Trigger

7. The function of Pin 6 is:

a) Control Voltage b) Discharge c) Output d) Reset e) Threshold g) Trigger

8. The function of Pin 5 is:

a) Control Voltage b) Discharge c) Output d) Reset e) Threshold g) Trigger

9. The function of Pin 4 is:

a) Control Voltage b) Discharge c) Output d) Reset e) Threshold g) Trigger

10. What is the function of the Threshold pin?

a) To charge the capacitor "C"

b) To discharge the capacitor "C"

c) To detect when the capacitor is "HIGH"

d) To detect when the capacitor is "LOW"

11. What is the function of the Discharge pin?

a) To charge the capacitor "C"

b) To discharge capacitor "C"

14. The Discharge and Output are:

a) In phase with each other

b) 90 degree out of phase with each other

c) 180 degree out of phase with each other

d) None of these

15. What does pin 6 do?

a) Charges the capacitor "C"

b) Discharges the capacitor "C"

c) Detects the HIGH on capacitor "C"

d) Detects the LOW on capacitor "C"

16. What does pin 2 do?

a) Charges the capacitor "C"

b) Discharges the capacitor "C"

c) Detects the HIGH on capacitor "C"

d) Detects the LOW on capacitor "C"

KEY

(1) b	(2) c	(3) a	(4) d	(5) c
(6) c	(7) e	(8) a	(9) d	(10) c
(11) b	(12) d	(13) b	(14) a	(15) c
(16) d				

Question Number	Type of question
2	Subjective questions

1. Describe the working of a basic 555 timer IC

2. Describe the working of 555 timer in astable configuration

3. Explain in detail how would you obtain a square wave output in 555 timer in astable mode?

4. Describe the working of 555 timer in monostable configuration

5. Describe how can you obtain output from 555 timer in monostable configuration without using a cathode ray oscilloscope?

Question Number	Type of question
3	Numericals

1. In a 555 timer in monostable mode, if R = 5 KΩ and time for which output is high is = 10 ms then determine the value of C (Ans: 1 μF)

2. For a 555 timer in astable configuration if R_a = 2.2 KΩ and R_b = 3.9 KΩ and C = 0.1 μF then determine a) the positive pulse width b) the negative pulse width and c) free running frequency f_o (Ans: a) 0.421 ms, b) 0.269 ms and c) f_o = 1.45 KHz)

3. What is the pulse width for a 555 timer based monostable circuit with R = 2.2 KΩ and C = 0.01 μF? (Ans: 24.2 μs)

4. What is the frequency and duty cycle for a 555 timer based astable circuit with R_a = 2.2 KΩ, R_b = 4.7 KΩ and C = 0.022 μF? (Ans: 5.64 KHz and 59.5%)