

## TOPIC 19: DIGITAL ELECTRONICS

By the end of this chapter, you will be able to:

- Examine the performance of semiconductor diodes in different devices.
- Analyze the operation and application of transistors in various situations.

### 19.1 REVIEW OF DIGITAL CONCEPTS

#### LOGIC GATES

A logic gate is a device that acts as a building block for digital circuits. Logic gates perform basic logical functions fundamental to digital

Most logic gates have two inputs and one output. At any moment, every terminal is in one of the two binary conditions: true (high) or false (low). False is represented as 0 and true as 1.

#### The AND gate

The AND gate gives a "true" (or 1) output **only if all** its inputs are "true" (1). If any input is "false" (0), the output will be "false" (0).

Input 1	Input 2	Output
0	0	0
0	1	0
1	0	0
1	1	1



**Analogy:** Think of a series circuit with two switches controlling a light bulb. The light will only turn ON if **both** Switch A AND Switch B are ON.

#### The OR gate

The OR gate gives a "true" (1) output if **at least one** of its inputs is "true" (1). It's only "false" (0) if all inputs are "false" (0).

Input 1	Input 2	Output
0	0	0
0	1	1
1	0	1
1	1	1



**Analogy:** Imagine a door that can be opened by either of two keys. The door will open if Key A OR Key B (or both) are used. It only stays closed if neither key is used.

### The NOT gate (Inverter)

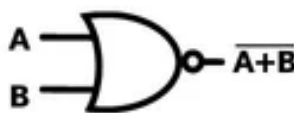
The NOT gate is the simplest. It has only one input and its output is always the **opposite** of the input. If the input is "true" (1), the output is "false" (0), and vice-versa.

Input 1	Output
1	0
0	1

### The NOR gate

The NOR gate is like an OR gate followed by a NOT gate. It gives a "true" (1) output **only if all** its inputs are "false" (0). Otherwise, the output is "false" (0). It's the opposite of an OR gate.

Input 1	Input 2	Output
0	0	1
0	1	0
1	0	0
1	1	0



**Analogy:** Imagine a security system that sounds an alarm (output is 0 or "false" meaning problem) if either Door A is open OR Window B is open. The alarm is silent (output is 1 or "true" meaning no problem) **only if both** the door and the window are closed (both inputs are 0).

### The NAND gate

The NAND gate is like an AND gate followed by a NOT gate. It gives a "false" (0) output **only if all** its inputs are "true" (1). Otherwise, the output is "true" (1). It's the opposite of an AND gate.

Input 1	Input 2	Output
0	0	1
0	1	1
1	0	1
1	1	0



**Analogy:** Using our series circuit light bulb example: The light is normally ON, but it turns OFF **only if both** Switch A AND Switch B are ON.

## Where are logic gates used in real life?

Arrays of logic gates are found in digital Integrated Circuits (ICs) to perform basic logical functions that all digital operations rely on, regardless of device type. These functions occur at high speeds, enabling fast data processing and transfer in electronic devices. These ICs appear in a wide, growing range of digital devices, including laptops, tablets, smartphones, memory devices, digital clocks and televisions. As IC technology advances, the physical volume required for individual logic gates decreases, and digital devices can perform more complicated operations faster.

## BISTABLE SWITCHES

The "bi" in bistable means **two**, and "stable" means it likes to stay put. So, a bistable switch is a type of switch that has **two stable states** (like ON or OFF) and will remain in one of those states without needing any continuous power or signal. It only changes its state when it receives a specific trigger or input.

Let us think of it like this:

**It "remembers" its last position.** If you set it to ON, it stays ON. If you set it to OFF, it stays OFF, until you actively change it.

**It doesn't need power to hold its state.** This is a key feature. Once switched, it's locked in that position mechanically or electronically until the next trigger.



## Applications of Bistable switches

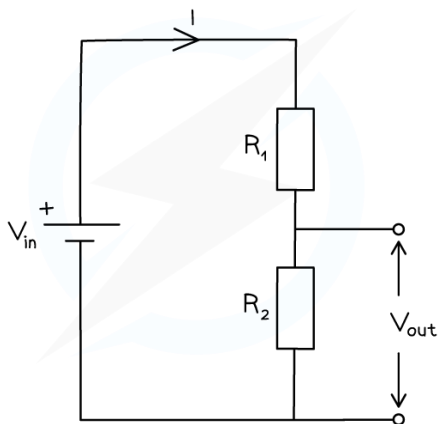
Bistable switches are commonly used in automatic door opening and closing systems. Solutions of this type are used, among others. In commercial buildings and public facilities. Another application is public transportation vehicles, where an automatic door opening and closing system has been implemented.

They are also commonly used in automatic door opening and closing systems. Solutions of this type are used, among others. In commercial buildings and public facilities. Another application is

public transportation vehicles, where an automatic door opening and closing system has been implemented.

### POTENTIAL DIVIDERS

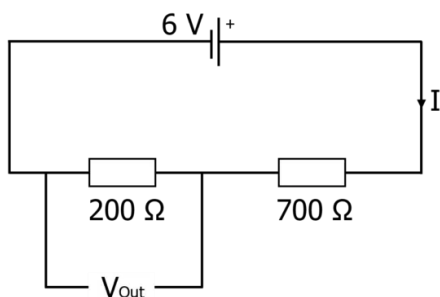
How can we get an output of 3.0 V from a battery of e.m.f. 6.0 V? Sometimes we want to use only part of the e.m.f. of a supply. To do this, we use an arrangement of resistors called a potential divider circuit.



The output voltage  $V_{out}$  depends on the relative values of  $R_1$  and  $R_2$ . You can calculate the value of  $V_{out}$  using the following potential divider equation.

$$V_{out} = \frac{R_2}{R_1 + R_2} V_{in}$$

**Example:** Calculate the voltage output across the  $200\Omega$  resistor



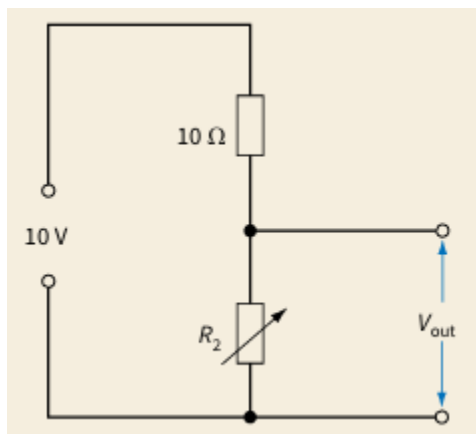
$$V_{out} = \frac{R_2}{R_1 + R_2} V_{in}$$

$$V_{out} = \frac{200\Omega}{200\Omega + 700\Omega} 6V$$

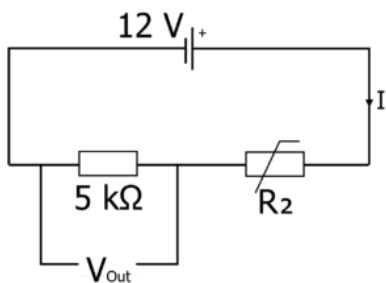
$$V_{out} = 1.33V$$

### Try this

Determine the range of  $V_{out}$  for the circuit in Figure below as the variable resistor  $R_2$  is adjusted over its full range from  $0\ \Omega$  to  $40\ \Omega$ . (Assume the supply of e.m.f.  $10\ \text{V}$  has negligible internal resistance.)



The potential divider circuit is used in a room which varies in temperature between  $25^\circ\text{C}$  and  $50^\circ\text{C}$ . At  $25^\circ\text{C}$ , the resistance of the thermistor is  $10\ \text{k}\Omega$  which decreases to  $800\ \Omega$  at  $50^\circ\text{C}$ . What is the minimum and maximum output voltage from this circuit?



## 19.2 CONDUCTORS, SEMICONDUCTORS, AND INSULATORS

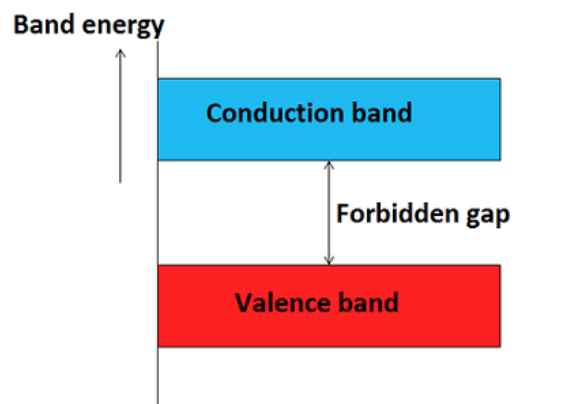
Conductors, semiconductors, and insulators, the trio forms the most popular set of substances in electricity and its conductivity, and form one of the most exciting study in physics.

The basic difference among them is that conductors, semiconductors, and insulators is their conductivity levels of electricity. Conductors have a high conductivity, which implies they enable energy to flow easily through them, such as electricity, heat, or sound. Semiconductors allow for moderate flow, whereas insulators have poor conductivity.

### The Band Theory

One of the important ways in which the differences in conduction may be explained is Band theory. Since this uses the material 'band' to explain a variety of physical properties of conduction, it is called band theory.

In an individual atom, within the permissible energy levels, there are electrons that orbit its positive nucleus. Among the several atoms, the energy levels are reorganized in two bands, the valence band and the conduction band. The lower level of electrons is called the valence band while the conduction band refers to the higher level of electrons.



There is an energy gap occurring between the bands in which there is no existence of electrons commonly referred to as the forbidden gap. As and when the conduction occurs, these electrons get into motion, and this can be possible only when there are spaces in the energy bands for them electrons to enter and move.

### What is a Conductor?

A conductor allows an electron to move easily from one atom to another when the right voltage is applied, as there are no band gaps between the valence and conduction bands.



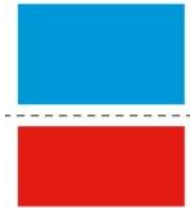
Some materials' conductor and valence bands overlap, allowing electrons to flow between the two overlapping bands. Because there is space for electrons to travel into the conduction band, one electron from the valence band moves into the other band, allowing conductivity.

Can we name on most popular conductor of electricity? Among several, silver is most likely the finest electrical conductor we come up with in daily life. Other metals with good conductivity include gold, copper, steel, aluminum, and brass. These materials can be found in ordinary electrical equipment, either as cables or etched onto circuit boards.

### What is a Semiconductor?

A semiconductor with moderate conductivity has a conductivity value between that of a conductor, such as silver, and an insulator. As a semiconductor's temperature rises, its resistance decreases. Semiconductors include elements or metalloids such as silicon (Si), germanium (Ge), and selenium (Se), as well as compounds such as gallium arsenide (GaAs) and indium antimonide (InSb), from which Silicon is the most commonly used semiconductor.

In a semiconductor, there is a gap between the valence and conduction bands, but it is tiny enough to allow electrons to flow at ambient temperature, allowing some conduction.



A semiconductor's conductivity increases as temperature rises because more electrons have enough energy to travel into the conduction band.

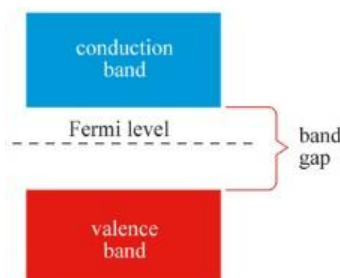
Because of the gap between atoms, gases are normally weak conductors. Gases, on the other hand, can be fair conductors and function as semiconductors under certain conditions, such as when they contain a significant number of ions.

### Insulators

An *insulator* has a large gap between the valence band and the conduction band.

The valence band is full as no electrons can move up to the conduction band. As a result, the conduction band is empty.

Only the electrons in a conduction band can move easily, so because there aren't any electrons in an insulator's conduction band, the material can't conduct.

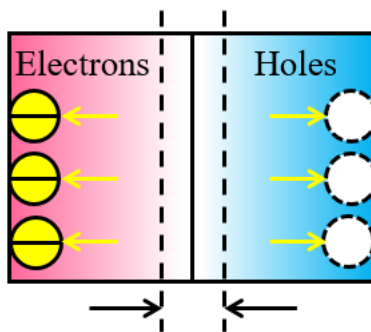


## Differences between Conductors, Semiconductors, and Insulators

Conductors	Semiconductors	Insulators
Materials that allow electricity or heat to flow through them.	Materials that moderately allow the flow of heat or electricity.	Materials that do not allow the passage of heat or electricity.
Aluminium, Silver, and iron are examples of conductors.	Silicon (Si), germanium (Ge), and selenium (Se) are some examples.	Paper, wood, and rubber are all examples of insulators.
Electrons are free to migrate throughout the conductor.	Electrons have low mobility due to the higher atomic force.	Electrons cannot easily migrate within the insulator.
On the surface, there is an electric field, yet it is zero on the inside.	The electric field is inside and outside.	There is no such thing as an electric field.

### 19.3 SEMICONDUCTORS AND DOPING

In Semiconductors the electric current is created due to electrons occupying states in the conduction band. However, moving an electron from the valence band to the conduction band leaves an **unoccupied state or hole** in the energy structure of the valence band, which a nearby electron can move into. As these holes are filled by other electrons, new holes are created. The electric current associated with this filling can be viewed as the collective motion of many negatively charged electrons or the motion of the positively charged electron holes.



In a Semiconductor the valence band is filled and the unfilled conduction band, and a relatively small energy gap between the bands. Excess electrons or holes can be introduced into the material by the substitution into the crystal lattice of an impurity atom, which is an atom of a slightly different valence number. This process is known as **doping**. For example, adding an arsenic atom to a crystal of silicon

While adding impurities, a small amount of suitable impurity is added to pure semiconductor material, increasing its conductivity by many times. The impurity modifies the electrical properties of the semiconductor and makes it more suitable for electronic devices such as diodes and transistors.

## Some Commonly Used Dopants

While doping tetravalent atoms such as Si or Ge, two types of dopants are used, and they are:

**Pentavalent atoms:** Atoms with valence 5; such as Arsenic (As), Phosphorous (Pi), Antimony (Sb), etc.

**Trivalent atoms:** Atoms with valence 3; such as Indium (In), Aluminium (Al), Boron (B), etc.

These dopants give rise to two types of semiconductors as follows:

- **n-type semiconductors**
- **p-type semiconductors**

### N-type Semiconductors (Excess Electrons)

"N" stands for Negative, referring to the negative charge of electrons, which are the majority charge carriers.

How they are made (Doping Process):

We start with a pure semiconductor material, most commonly silicon (Si). Silicon atoms have 4 valence electrons (electrons in their outermost shell available for bonding).

We then "dope" it with a small amount of an impurity element from Group 15 (V) of the periodic table, such as phosphorus (P), arsenic (As), or antimony (Sb). These elements are called donor impurities because they "donate" an electron.

Group 15 elements have 5 valence electrons. When one of these impurity atoms replaces a silicon atom in the crystal lattice, four of its valence electrons form covalent bonds with the four neighboring silicon atoms.

This leaves one extra electron from the impurity atom that is not involved in bonding. This extra electron is very loosely bound to the impurity atom and can easily break free and move around within the semiconductor material.

In N-type semiconductors, **electrons are the majority charge carriers**. They are free to move and carry electric current.

### P-type Semiconductors (Excess Holes)

"P" stands for Positive, referring to the positive "holes," which are the majority charge carriers.

How they are made (Doping Process):

Again, we start with a pure semiconductor material like silicon (Si).

We then "dope" it with a small amount of an impurity element from Group 13 (III) of the periodic table, such as boron (B), aluminum (Al), or gallium (Ga). These elements are called acceptor impurities because they "accept" an electron.

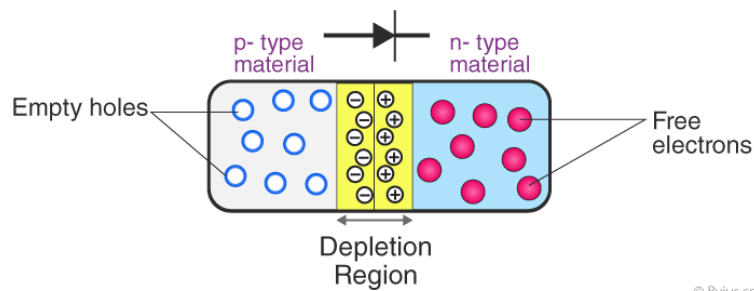
Group 13 elements have 3 valence electrons. When one of these impurity atoms replaces a silicon atom in the crystal lattice, it can only form three covalent bonds with its three neighboring silicon atoms.

This leaves a "missing electron" or a "vacancy" in one of the covalent bonds. This vacancy is called a hole.

In p-type semiconductors, holes are the majority charge carriers. When an electron from a neighboring atom moves to fill this hole, it leaves behind a new hole in its original position. This makes it appear as if the "hole" itself is moving, carrying a positive charge

### **P-N Junction diodes**

A p-n junction diode is a semiconductor device made by joining a p-type semiconductor with an n-type semiconductor. It allows current to flow easily in one direction (forward bias) but blocks it in the other (reverse bias). This behavior is due to the creation of a depletion region at the junction where charge carriers are separated. The holes from the p-side diffuse to the n-side, and the electrons from the n-side diffuse to the p-side. These give rise to a diffusion current across the junction.



The depletion region is a region where mobile charge carriers (electrons and holes) have been removed, leaving behind a region of fixed, ionized dopant atoms.

### **Biasing Conditions for the P-N Junction Diode**

There are two operating regions in the P-N junction diode:

P-type

N-type

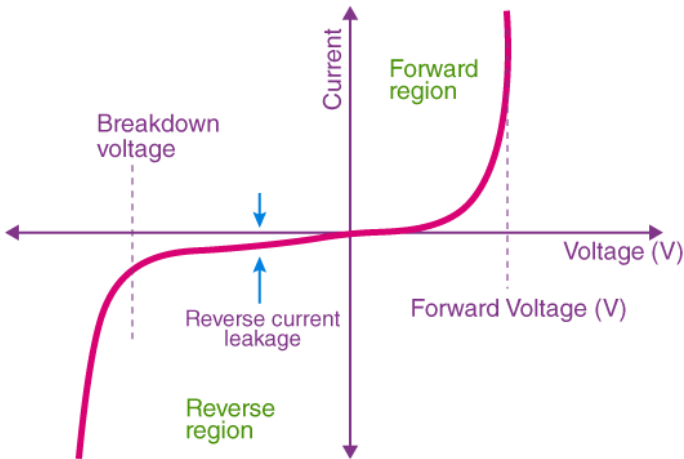
There are three biasing conditions for the P-N junction diode, and this is based on the voltage applied:

Zero bias: No external voltage is applied to the P-N junction diode.

Forward bias: The positive terminal of the voltage potential is connected to the p-type while the negative terminal is connected to the n-type.

Reverse bias: The negative terminal of the voltage potential is connected to the p-type and the positive is connected to the n-type.

### I-V Characteristics of a PN Junction diode



During **Forward Bias**, The p-type side of the diode is connected to the positive terminal of a voltage source, and the n-type side is connected to the negative terminal. Initially, a very small current flows. As the forward voltage increases, it opposes and eventually overcomes the diode's internal potential barrier (also called forward voltage). For silicon diodes, this is typically around 0.7V, and for germanium, it's about 0.3V. Once the applied voltage exceeds this threshold, the current increases rapidly and exponentially with only a small increase in voltage. This indicates that the diode offers very low resistance to current flow in this region.

Reverse Bias Region, the p-type side is connected to the negative terminal of the voltage source, and the n-type side is connected to the positive terminal. This arrangement widens the depletion region, effectively preventing the majority charge carriers from crossing the junction. When the reverse bias voltage is continuously increased beyond a certain critical point known as the breakdown voltage, the diode suddenly begins to conduct heavily in the reverse direction. This is due to phenomena like avalanche breakdown or Zener breakdown, where the strong electric field causes a rapid increase in current.

### 19.4 APPLICATIONS OF PN JUNCTION DIODE

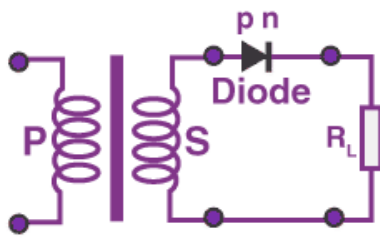
The main application of p-n junction diode is in rectification circuits. These circuits are used to describe the conversion of A.C signals to D.C. in power supplies.

There are two primary methods of diode rectification:

- Half Wave Rectifier
- Full Wave Rectifier

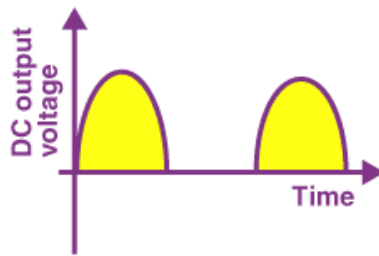
## Half Wave Rectifier

In a half-wave rectifier, one half of each A.C input cycle is rectified. When the p-n junction diode is forward biased, it gives little resistance and when it is reversed biased it provides high resistance.



### Operation

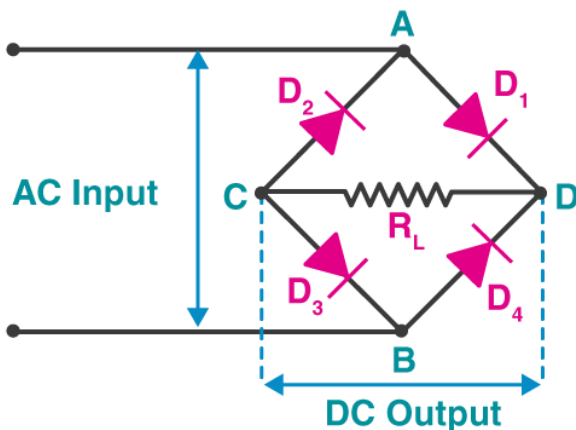
The diode allows current to flow in only one direction. During the positive half-cycle of the AC input, the diode is forward-biased and conducts, allowing that portion of the waveform to pass through to the output. During the negative half-cycle, the diode is reverse-biased and blocks the current.



The result is a pulsating DC waveform, where only half of the original AC cycle is present, while the other half is cut off (zero). This leads to a less efficient conversion and a significant "ripple" (variations in the DC output).

## Full Wave Rectifier

Full-wave rectifier circuits are used for producing an output voltage or output current which is purely DC. The main advantage of a full-wave rectifier over half-wave rectifier is that such as the average output voltage is higher in full-wave rectifier, there is less ripple produced in full-wave rectifier when compared to the half-wave rectifier.

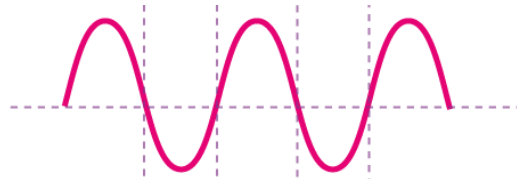


When an AC signal is applied across the bridge rectifier, terminal A becomes positive during the positive half cycle while terminal B becomes negative. This results in diodes D<sub>1</sub> and D<sub>3</sub> becoming forward biased while D<sub>2</sub> and D<sub>4</sub> becoming reverse biased. The current flow during the positive half-cycle is in the direction D to C.

During the negative half-cycle, terminal B becomes positive while terminal A becomes negative. This causes diodes D<sub>2</sub> and D<sub>4</sub> to become forward biased and diodes D<sub>1</sub> and D<sub>3</sub> to

be reverse biased. The current flows in the same direction as before.

**AC Input**



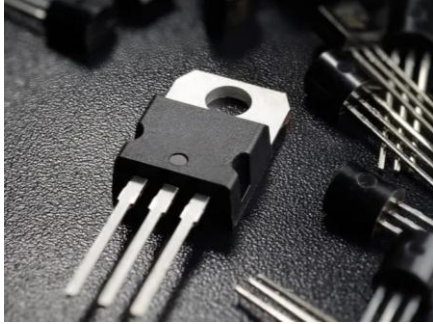
**DC output  
(pulsating  
form)**



The output is a pulsating DC waveform, but it includes both halves of the original AC cycle, with the negative half-cycle "flipped" to positive. This results in a much smoother DC output with less ripple and higher efficiency compared to a half-wave rectifier.

## 19.5 BI POLAR JUNCTION TRANSISTORS

The invention of the transistor in the 1940s was a major turning point in the history of electronics. Transistors replaced bulky and unreliable vacuum tubes, making it possible to build smaller, more powerful, and more efficient electronic devices.

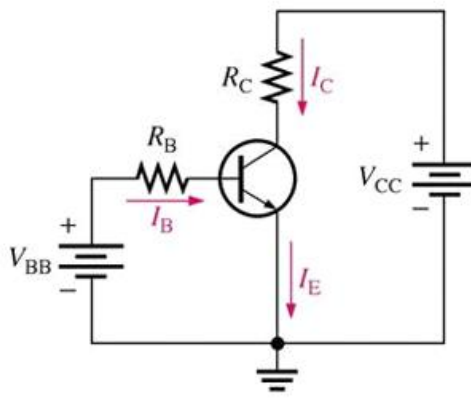


Transistors are made of semiconductor materials, which allows them to control the flow of electricity, making them ideal for amplifying and switching signals. **The transistor can be either a PNP type or an NPN type**, depending on the arrangement of the p-type and n-type semiconductors. Each type, made of three layers - emitter, base, and collector - operates differently. The base, notably thin, is sandwiched

between the other layers.

### NPN Transistor

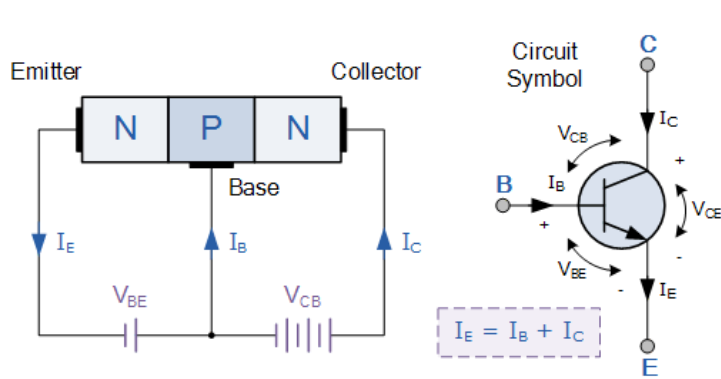
Consists of a thin layer of p-type semiconductor material (base) sandwiched between two n-type semiconductor layers (emitter and collector). The name NPN reflects this N-type, P-type, N-type arrangement. The Majority of the charge carriers are electrons.



### Operation

An NPN transistor functions by using a small positive voltage applied to its base (relative to the emitter) to initiate a small base current, which then allows a significantly larger flow of electrons (the majority carriers) to pass from the emitter, through the thin base, and into the collector, effectively controlling a large collector-emitter current with a small base current.

### PNP Transistor



Consists of a thin layer of n-type semiconductor material (base) sandwiched between two p-type semiconductor layers (emitter and collector). The name PNP reflects this **P**-type, **N**-type, **P**-type arrangement. The majority of the charge carriers are holes.

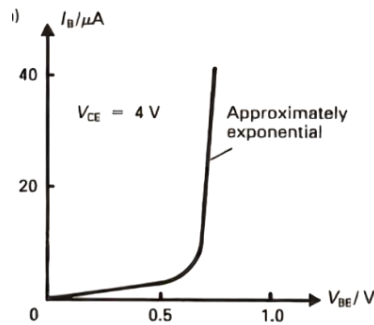
### Operation

A PNP transistor operates by applying a small negative voltage to its base (relative to the emitter), which draws a small current out of the base and allows a much larger flow of holes (the majority carriers) to pass from the emitter, through the thin base, and into the collector, thereby controlling a large emitter-collector current with a small base current.

## 19.6 BJTS - CHARACTERISTICS AND AMPLIFICATION

### Input (Base) Characteristics

This shows how the base current ( $I_b$ ) changes with the base-emitter voltage ( $V_{be}$ ) when the collector-emitter voltage ( $V_{ce}$ ) is kept constant.



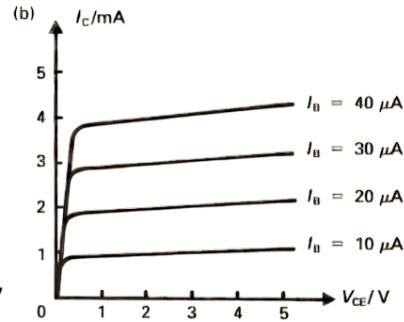
The curve resembles the forward bias characteristics of a diode. For silicon transistors, the base current remains nearly zero until  $V_{BE}$  reaches about 0.6-0.7V, after which  $I_B$  increases rapidly for a small change in voltage

$$\text{Input resistance} = \frac{\Delta V_{BE}}{\Delta I_B}$$

Typically, around  $1,000 \Omega$  ( $1 k\Omega$ )

## Output (Collector) Characteristics

This shows how collector current ( $I_C$ ) changes with collector-emitter voltage ( $V_{CE}$ ) for fixed base currents ( $I_b$ ).



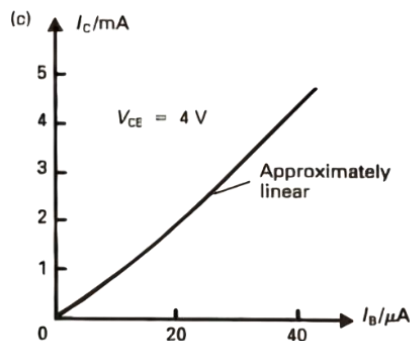
Beyond about 1V of  $V_{CE}$ , increasing  $V_{CE}$  doesn't affect  $I_C$  much — it stays nearly constant for a given  $I_b$ . So,  $I_C$  mainly depends on  $I_b$ .

$$\text{Output resistance } r_O = \frac{\Delta V_{CE}}{\Delta I_C}$$

Very high, often  $> 100 k\Omega$

## Transfer Characteristics

This relates the collector current ( $I_C$ ) to the base current ( $I_b$ ) at a fixed collector-emitter voltage.



$I_C$  is almost directly proportional to  $I_b$ . A small increase in  $I_b$  leads to a much larger increase in  $I_C$ .

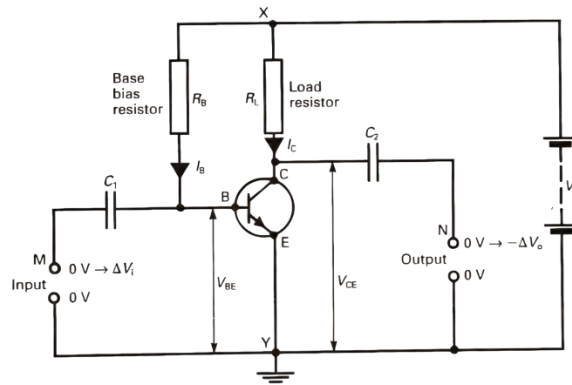
DC Current Gain ( $h_{FE}$  or  $\beta$ ):

$$\beta = \frac{I_C}{I_b}$$

## USING A TRANSISTOR AS AN AMPLIFIER (COMMON-EMITTER)

In the common-emitter configuration, a small input signal at the base leads to a much larger signal at the collector — hence, it amplifies.

### Example – Designing a Transistor Amplifier



#### Given:

$V_S = 9V$  (supply voltage)

Desired operating point:  $I_C = 2mA$ ,  $V_{CE} = 4V$

From graph, when  $I_C = 2mA$ ,  $I_B = 20\mu A$ ,  $V_{BE} = 0.8V$ .

Assume  $h_{FE} = 100$ ,  $r_i \approx 1000\Omega$

#### Calculate Load Resistor ( $R_L$ )

Using Kirchoff's Voltage Law (KVL):

$$V_S = I_C R_L + V_{CE}$$

$$9V = (2 \times 10^{-3}A) \cdot R_L + 4V$$

$$R_L = 2.5 \times 10^3 \Omega$$

#### Calculate Base Bias Resistor ( $R_B$ )

From the input side:

$$V_S = I_B R_B + V_{BE}$$

$$9 = (20 \times 10^{-6})R_B + 0.8$$

$$R_B = 4.1 \times 10^5 \Omega$$

## Voltage Amplification ( $A_V$ )

Let the signal source have internal resistance  $R_s$ . The voltage amplification is:

$$A_V = \frac{V_{out}}{V_{in}} = \frac{h_{FE} \cdot R_C}{R_i + R_s} A_V = \frac{100 \cdot 2500}{250} = 250$$

So the voltage is amplified 250 times

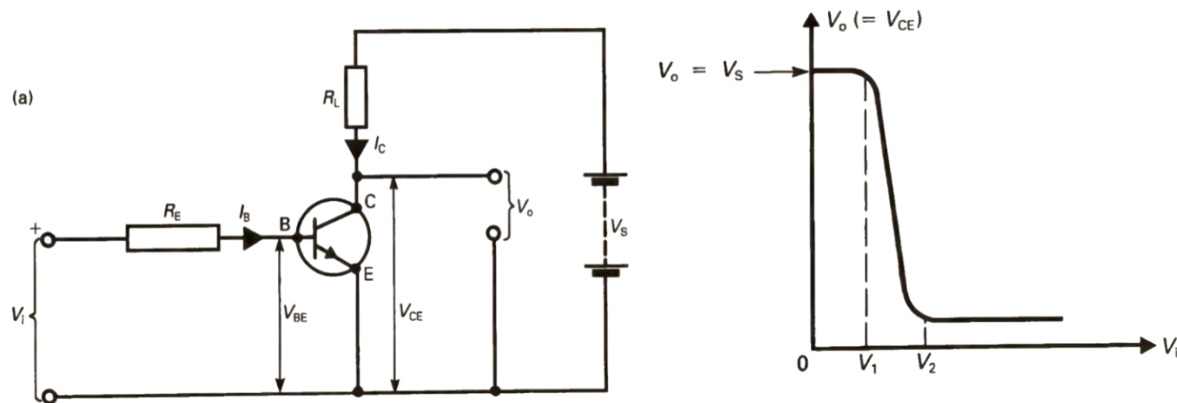
## Power Amplification

$$\text{Power Gain} = \text{Current Gain} \times \text{Voltage}$$

$$= 100 \times 250 = 25,000$$

## THE TRANSISTOR AS A SWITCH

The use of a transistor as a switch involves operating the transistor in two distinct regions: the cut-off region and the saturation region. This allows the transistor to act like an electronic switch that can turn a circuit on or off.



### How a Transistor Works as a Switch?

#### a) Cut-off Region (Switch OFF):

When the base-emitter voltage is below approximately 0.7 V (for a silicon transistor), the transistor is in the cut-off region. Both the base-emitter and base-collector junctions are reverse-biased, resulting in no base current ( $I_B \approx 0$ ) and no collector current ( $I_C \approx 0$ ). In this state, the transistor behaves like an open switch, preventing current flow through the collector-emitter path and keeping the connected load off.

#### b) Saturation Region (Switch ON):

When the base-emitter voltage exceeds about 0.7 V, the transistor enters saturation. Both junctions are forward-biased, allowing maximum collector current to flow. The transistor behaves like a closed switch with very low resistance between collector and emitter, turning the load on. The collector-emitter voltage ( $V_{CE}$ ) drops to a low value close to zero.

## Practical Application

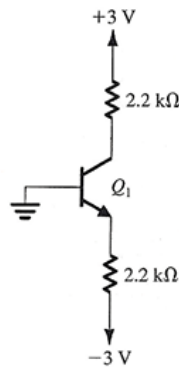
A small current at the base controls a much larger current through the collector-emitter path, enabling the transistor to switch high-power devices such as motors, lamps, or relays using low-power control signals.

This switching action is fundamental in digital electronics, where transistors serve as the building blocks of logic gates and microprocessors.

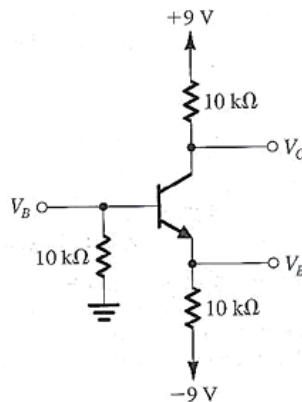
For example, in a circuit with an LED, the transistor switch can turn the LED on or off depending on the base current.

## SELF-ASSESSMENT

1. Why is the input resistance of a transistor typically much lower than the output resistance?
2. What does the "knee" of the output characteristic curve represent in a BJT?
3. Describe the function of a blocking capacitor in a common-emitter amplifier.
4. Explain why a transistor can act as an amplifier, even though the input current is very small.
5. From the figure show below, find the emitter, base and collector voltages and currents. Use  $\beta = 50$ , but assume  $|V_{BE}| = 0.8V$  independent of the current level



6. In the figure show below measurements indicate that  $V_B = -1.5V$ . Assuming  $V_{BE} = 0.7V$ ,



- a) Calculate  $V_E$ ,  $\beta$  and  $V_C$ .

b) If a transistor with  $\beta = \infty$  is used what values of  $V_B$ ,  $V_E$  and  $V_C$  result?