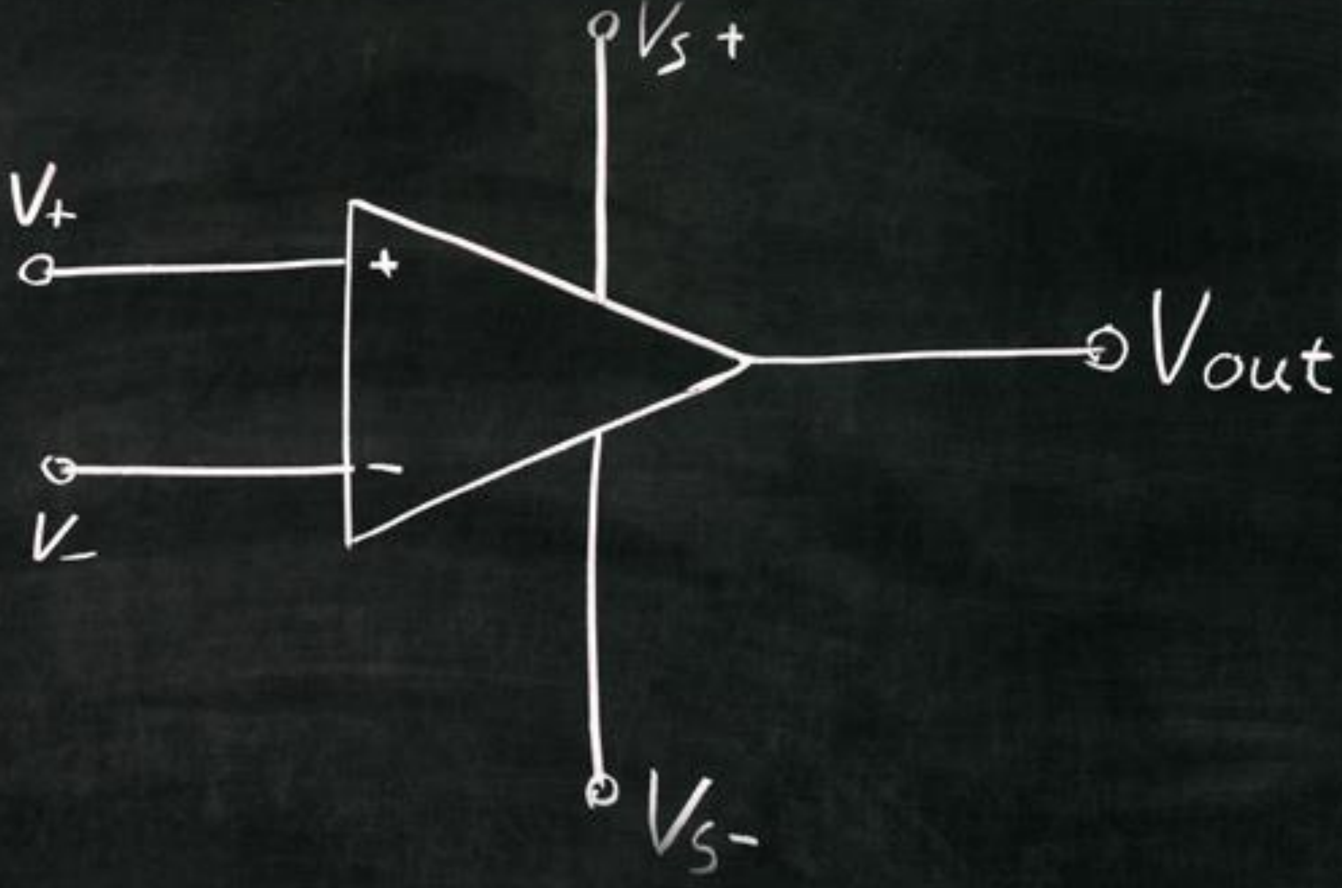

Amplifiers

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About the Tutorial

An electronic signal contains some information which cannot be utilized if doesn't have proper strength. The process of increasing the signal strength is called as **Amplification**. Almost all electronic equipment must include some means for amplifying the signals. We find the use of amplifiers in medical devices, scientific equipment, automation, military tools, communication devices, and even in household equipment.

In this tutorial, we will discuss all the important concepts from the introduction of transistors along with the amplifier action of transistor. In addition, we will cover all the topics related to all the major types of **transistor amplifiers** in detail.

Audience

This tutorial will suit all beginners who want to learn the fundamental concepts of transistors and transistor amplifier circuits.

Prerequisites

Though this tutorial is intended for beginners in the field of Electronics and Communications, we expect the readers to have some prior knowledge regarding the functioning of different electronic components. Therefore, we suggest that you first go through our tutorial on Basic Electronics.

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Table of Contents

1. MATERIALS – INTRODUCTION

Every **material** in nature has certain properties. These properties define the behavior of the materials. Material Science is a branch of electronics that deals with the study of flow of electrons in various materials or spaces, when they are subjected to various conditions.

Due to the intermixing of atoms in solids, instead of single energy levels, there will be bands of energy levels formed. These set of energy levels, which are closely packed are called as **Energy bands**.

Types of Materials

The energy band in which valence electrons are present is called **Valence band**, while the band in which conduction electrons are present is called **Conduction band**. The energy gap between these two bands is called as **Forbidden energy gap**.

Electronically, the materials are broadly classified as Insulators, Semiconductors, and Conductors.

- **Insulators** – Insulators are such materials in which the conduction cannot take place, due to the large forbidden gap. Examples: Wood, Rubber.
- **Semiconductors** – Semiconductors are such materials in which the forbidden energy gap is small and the conduction takes place if some external energy is applied. Examples: Silicon, Germanium.
- **Conductors** – Conductors are such materials in which the forbidden energy gap disappears as the valence band and conduction band become very close that they overlap. Examples: Copper, Aluminum.

Of all the three, insulators are used where resistivity to electricity is desired and conductors are used where the conduction has to be high. The semiconductors are the ones which give rise to a specific interest of how they are used.

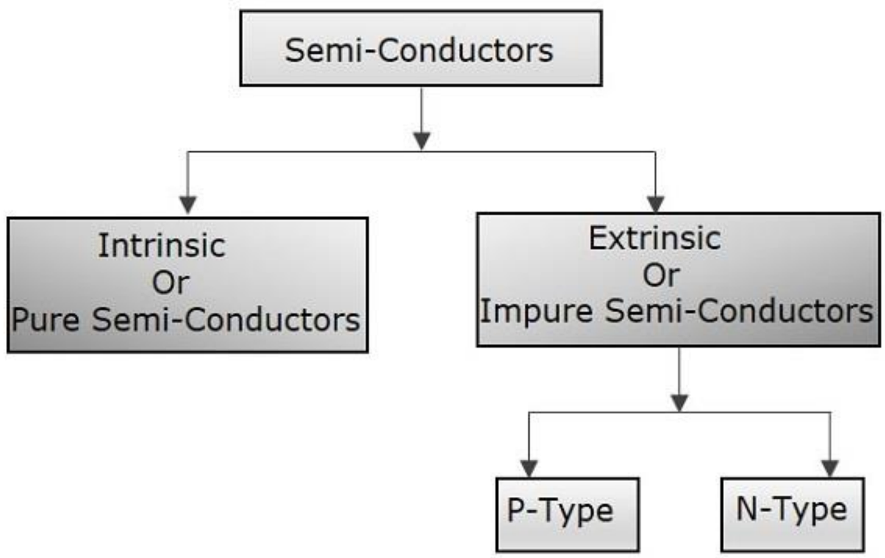
Semiconductors

A **Semiconductor** is a substance whose resistivity lies between the conductors and insulators. The property of resistivity is not the only one that decides a material as a semi-conductor, but it has few properties as follows.

- Semiconductors have the resistivity which is less than insulators and more than conductors.
- Semiconductors have negative temperature co-efficient. The resistance in semi-conductors, increases with the decrease in temperature and vice versa.

- The Conducting properties of a Semi-conductor changes, when a suitable metallic impurity is added to it, which is a very important property.

The Semiconductor devices are extensively used in the field of electronics. The transistor has replaced the bulky vacuum tubes, from which the size and cost of the devices got decreased and this revolution has kept on increasing its pace leading to the new inventions like integrated electronics. Semiconductors can be classified as shown below.



A semiconductor in its extremely pure form is said to be an **intrinsic semiconductor**. But the conduction capability of this pure form is too low. In order to increase the conduction capability of intrinsic semiconductor, it is better to add some impurities. This process of adding impurities is called as **Doping**. Now, this doped intrinsic semiconductor is called as an **Extrinsic Semiconductor**.

The impurities added, are generally **pentavalent** and **trivalent** impurities. Depending upon these types of impurities, another classification is done. When a **pentavalent** impurity is added to a pure semiconductor, it is called as **N-type extrinsic Semiconductor**. As well, when a **trivalent** impurity is added to a pure semiconductor, it is called as **P-type extrinsic Semiconductor**.

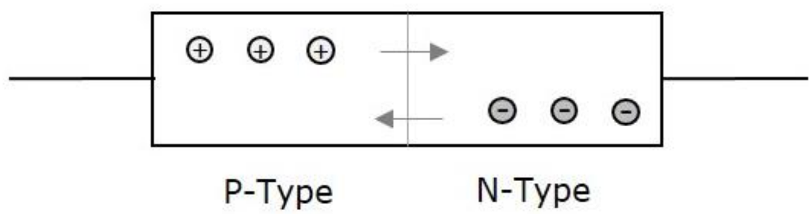
P-N Junction

When an electron moves from its place, a hole is said to be formed there. So, a hole is the absence of an electron. If an electron is said to be moved from negative to positive terminal, it means that a hole is being moved from positive to negative terminal.

The materials mentioned above are the basics of semiconductor technology. The **N-type** material formed by adding pentavalent impurities has **electrons as its majority carriers** and holes as minority carriers. While, the **P-type** material formed by adding trivalent impurities has **holes as its majority carriers** and electrons as minority carriers.

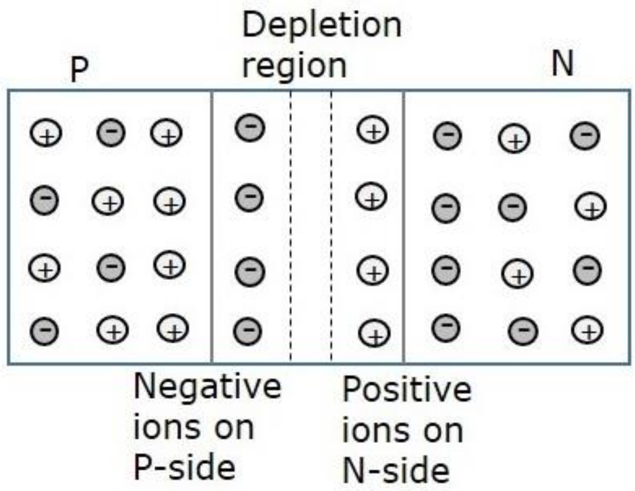
Let us try to understand what happens when the P and N materials are joined together.

If a P-type and an N-type material are brought close to each other, both of them join to form a junction, as shown in the figure below.



A P-type material has **holes** as the **majority carriers** and an N-type material has **electrons** as the **majority carriers**. As opposite charges attract, few holes in P-type tend to go to n-side, whereas few electrons in N-type tend to go to P-side.

As both of them travel towards the junction, holes and electrons recombine with each other to neutralize and forms ions. Now, in this junction, there exists a region where the positive and negative ions are formed, called as **PN junction** or junction barrier as shown in the figure.



The formation of negative ions on P-side and positive ions on N-side results in the formation of a narrow charged region on either side of the PN junction. This region is now free from movable charge carriers. The ions present here have been stationary and maintain a region of space between them without any charge carriers.

As this region acts as a barrier between P and N type materials, this is also called as **Barrier junction**. This has another name called as **Depletion region** meaning it depletes both the regions. There occurs a potential difference V_D due to the formation of ions, across the junction called as **Potential Barrier** as it prevents further movement of holes and electrons through the junction. This formation is called as a **Diode**.

Biasing of a Diode

When a diode or any two terminal components are connected in a circuit, it has two biased conditions with the given supply. They are **Forward biased** condition and **Reverse biased** condition.

Forward Biased Condition

When a diode is connected in a circuit, with its **anode to the positive** terminal and **cathode to the negative** terminal of the supply, then such a connection is said to be **forward biased** condition.

This kind of connection makes the circuit more and more forward biased and helps in more conduction. A diode conducts well in forward biased condition.

Reverse Biased Condition

When a diode is connected in a circuit, with its **anode to the negative** terminal and **cathode to the positive** terminal of the supply, then such a connection is said to be **Reverse biased** condition.

This kind of connection makes the circuit more and more reverse biased and helps in minimizing and preventing the conduction. A diode cannot conduct in reverse biased condition.

With the above information, we now have a good idea of what a PN junction is. With this knowledge, let us move on and learn about transistors in the next chapter.

Part 1: Transistors

2. TRANSISTORS – OVERVIEW

After knowing the details about a single PN junction, or simply a diode, let us try to go for the two PN junction connection. If another P-type material or N-type material is added to a single PN junction, another junction will be formed. Such a formation is simply called as a **Transistor**.

A **Transistor** is a three terminal semiconductor device that regulates current or voltage flow and acts as a switch or gate for signals.

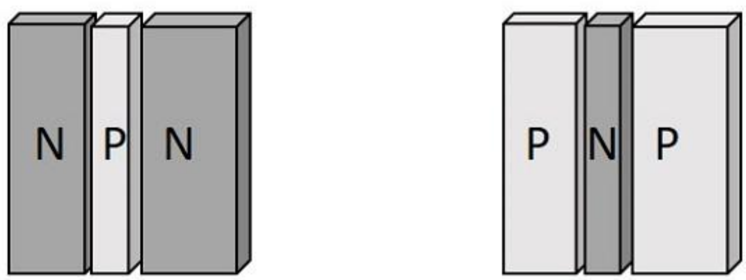
Uses of a transistor

- A transistor acts as **an Amplifier**, where the signal strength has to be increased.
- A transistor also acts as a **switch** to choose between available options.
- It also **regulates** the incoming **current and voltage** of the signals.

Constructional Details of a Transistor

The Transistor is a three terminal solid state device which is formed by connecting two diodes back to back. Hence it has got **two PN junctions**. Three terminals are drawn out of the three semiconductor materials present in it. This type of connection offers two types of transistors. They are **PNP** and **NPN** which means an N-type material between two P-types and the other is a P-type material between two N-types respectively.

The following illustration shows the basic construction of transistors



Construction of PNP & NPN Transistors

The three terminals drawn from the transistor indicate **Emitter**, **Base** and **Collector** terminals. They have their functionality as discussed below.

Emitter

- The left-hand side of the above shown structure can be understood as **Emitter**.

- This has a **moderate size** and is **heavily doped** as its main function is to **supply** a number of **majority carriers**, i.e. either electrons or holes.
- As this emits electrons, it is called as an Emitter.
- This is simply indicated with the letter **E**.

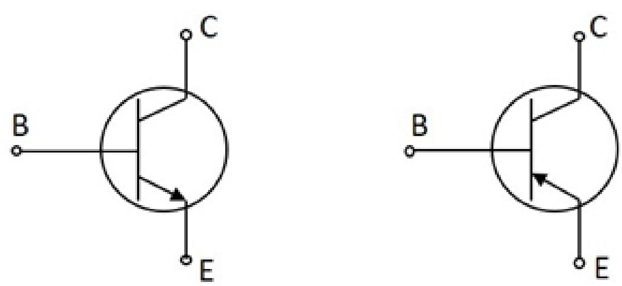
Base

- The middle material in the above figure is the **Base**.
- This is **thin** and **lightly doped**.
- Its main function is to **pass** the majority carriers from the emitter to the collector.
- This is indicated by the letter **B**.

Collector

- The right side material in the above figure can be understood as a **Collector**.
- Its name implies its function of **collecting the carriers**.
- This is **a bit larger** in size than emitter and base. It is **moderately doped**.
- This is indicated by the letter **C**.

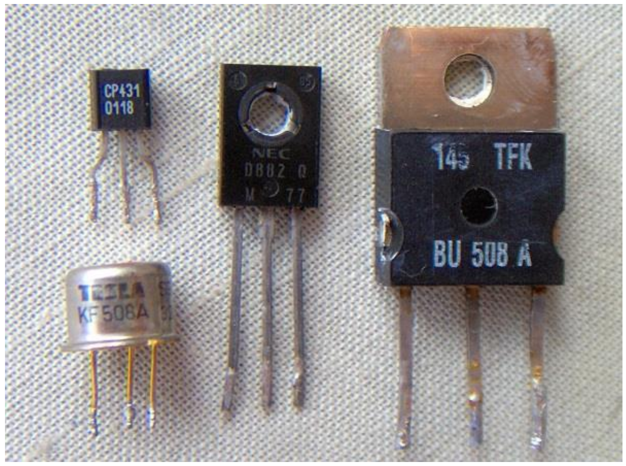
The symbols of PNP and NPN transistors are as shown below.



NPN transistor PNP transistor

The **arrow-head** in the above figures indicated the **emitter** of a transistor. As the collector of a transistor has to dissipate much greater power, it is made large. Due to the specific functions of emitter and collector, they are **not interchangeable**. Hence the terminals are always to be kept in mind while using a transistor.

In a Practical transistor, there is a notch present near the emitter lead for identification. The PNP and NPN transistors can be differentiated using a Multimeter. The following image shows how different practical transistors look like.

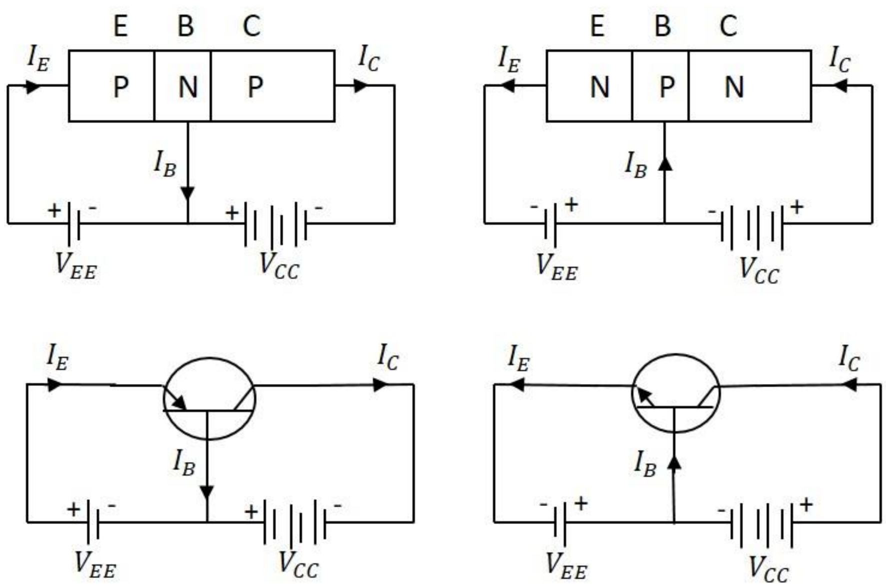


We have so far discussed the constructional details of a transistor, but to understand the operation of a transistor, first we need to know about the biasing.

Transistor Biasing

As we know that a transistor is a combination of two diodes, we have two junctions here. As one junction is between the emitter and base, that is called as **Emitter-Base junction** and likewise, the other is **Collector-Base junction**.

Biasing is controlling the operation of the circuit by providing power supply. The function of both the PN junctions is controlled by providing bias to the circuit through some dc supply. The figure below shows how a transistor is biased.



P-N-P Transistor biasing

N-P-N Transistor biasing

By having a look at the above figure, it is understood that

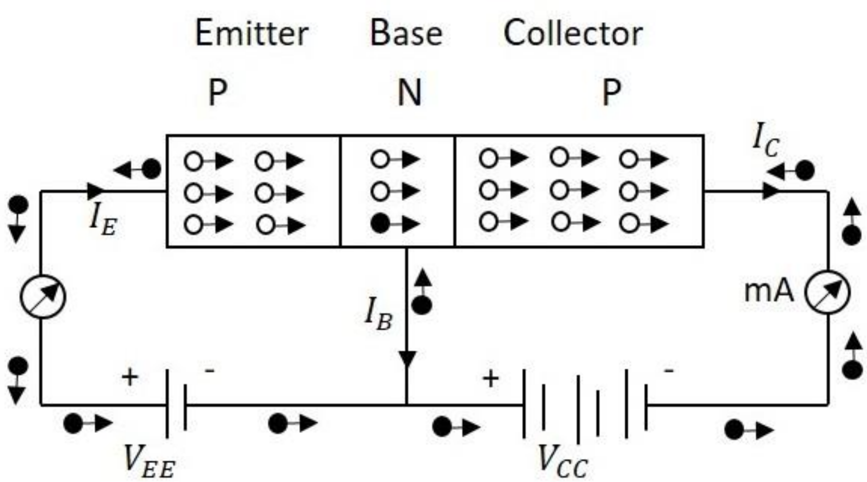
- The N-type material is provided negative supply and P-type material is given positive supply to make the circuit **Forward bias**.
- The N-type material is provided positive supply and P-type material is given negative supply to make the circuit **Reverse bias**.

By applying the power, the **emitter base junction** is always **forward biased** as the emitter resistance is very small. The **collector base junction** is **reverse biased** and its resistance is a bit higher. A small forward bias is sufficient at the emitter junction whereas a high reverse bias has to be applied at the collector junction.

The direction of current indicated in the circuits above, also called as the **Conventional Current**, is the movement of hole current which is **opposite to the electron current**.

Operation of PNP Transistor

The operation of a PNP transistor can be explained by having a look at the following figure, in which emitter-base junction is forward biased and collector-base junction is reverse biased.



Operation of a PNP transistor

The voltage **V_{EE}** provides a positive potential at the emitter which repels the holes in the P-type material and these holes cross the emitter-base junction, to reach the base region. There a very low percent of holes re-combine with free electrons of N-region. This provides very low current which constitutes the base current **I_B**. The remaining holes cross the collector-base junction, to constitute collector current **I_C**, which is the hole current.

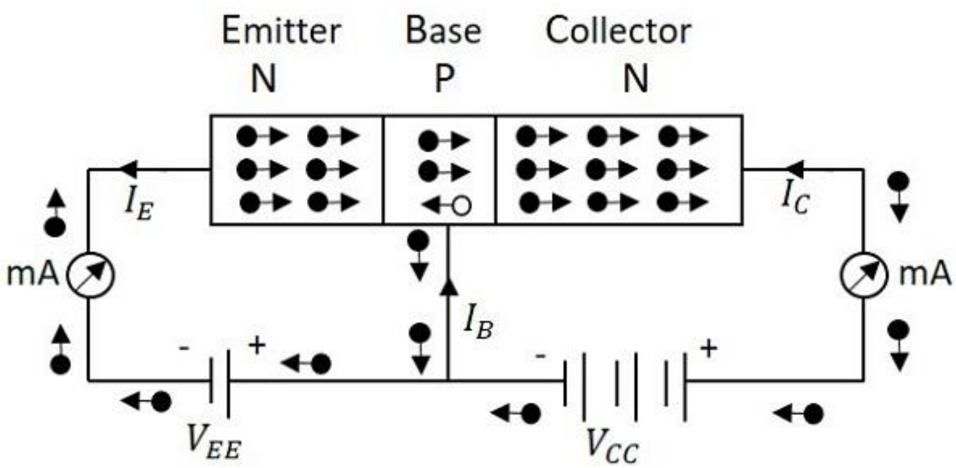
As a hole reaches the collector terminal, an electron from the battery negative terminal fills the space in the collector. This flow slowly increases and the electron minority current flows through the emitter, where each electron entering the positive terminal of V_{EE}, is replaced by a hole by moving towards the emitter junction. This constitutes emitter current I_E.

Hence we can understand that—

- The conduction in a PNP transistor takes place through holes.
- The collector current is slightly less than the emitter current.
- The increase or decrease in the emitter current affects the collector current.

Operation of NPN Transistor

The operation of an NPN transistor can be explained by having a look at the following figure, in which emitter-base junction is forward biased and collector-base junction is reverse biased.



Operation of a NPN transistor

The voltage V_{EE} provides a negative potential at the emitter which repels the electrons in the N-type material and these electrons cross the emitter-base junction, to reach the base region. There, a very low percent of electrons re-combine with free holes of P-region. This provides very low current which constitutes the base current I_B. The remaining holes cross the collector-base junction, to constitute the collector current I_C.

As an electron reaches out of the collector terminal, and enters the positive terminal of the battery, an electron from the negative terminal of the battery V_{EE} enters the emitter region. This flow slowly increases and the electron current flows through the transistor.

Hence we can understand that—

- The conduction in a NPN transistor takes place through electrons.
- The collector current is higher than the emitter current.
- The increase or decrease in the emitter current affects the collector current.

Advantages of Transistors

There are many advantages of using a transistor, such as—

- High voltage gain.
- Lower supply voltage is sufficient.
- Most suitable for low power applications.
- Smaller and lighter in weight.
- Mechanically stronger than vacuum tubes.
- No external heating required like vacuum tubes.
- Very suitable to integrate with resistors and diodes to produce ICs.

There are few disadvantages such as they cannot be used for high power applications due to lower power dissipation. They have lower input impedance and they are temperature dependent.

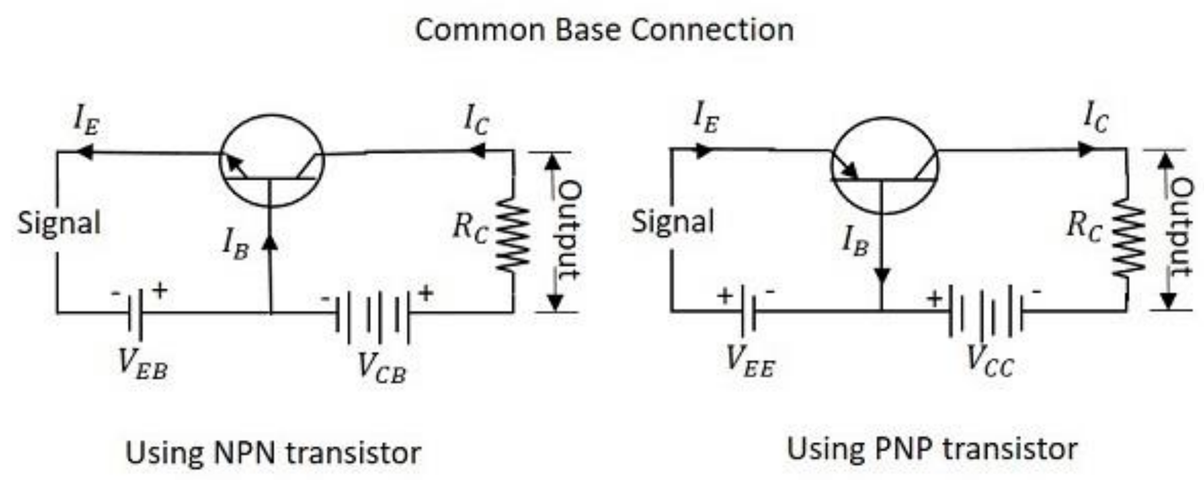
3. TRANSISTOR CONFIGURATIONS

Any transistor has three terminals, the **emitter**, the **base**, and the **collector**. Using these 3 terminals the transistor can be connected in a circuit with one terminal common to both input and output in three different possible configurations.

The three types of configurations are **Common Base**, **Common Emitter** and **Common Collector** configurations. In every configuration, the emitter junction is forward biased and the collector junction is reverse biased.

Common Base (CB) Configuration

The name itself implies that the **Base** terminal is taken as common terminal for both input and output of the transistor. The common base connection for both NPN and PNP transistors is as shown in the following figure.



For the sake of understanding, let us consider NPN transistor in CB configuration. When the emitter voltage is applied, as it is forward biased, the electrons from the negative terminal repel the emitter electrons and current flows through the emitter and base to the collector to contribute collector current. The collector voltage V_{CB} is kept constant throughout this.

In the CB configuration, the input current is the emitter current $\mathbf{I_E}$ and the output current is the collector current $\mathbf{I_C}$.

Current Amplification Factor (α)

The ratio of change in collector current (ΔI_C) to the change in emitter current (ΔI_E) when collector voltage V_{CB} is kept constant, is called as **Current amplification factor**. It is denoted by $\boldsymbol{\alpha}$.

$$\alpha = \frac{\Delta\, I_C}{\Delta I_E} \text{ at constant } V_{CB}$$

Expression for Collector current

With the above idea, let us try to draw some expression for collector current.

Along with the emitter current flowing, there is some amount of base current $\mathbf{I_B}$ which flows through the base terminal due to electron hole recombination. As collector-base junction is reverse biased, there is another current which is flown due to minority charge carriers. This is the leakage current which can be understood as $\mathbf{I_{leakage}}$. This is due to minority charge carriers and hence very small.

The emitter current that reaches the collector terminal is

$$\boldsymbol{\alpha\, I_E}$$

Total collector current

$$I_C = \alpha\, I_E + I_{leakage}$$

If the emitter-base voltage V_{EB} = 0, even then, there flows a small leakage current, which can be termed as I_{CBO} (collector-base current with output open).

The collector current therefore can be expressed as

$$I_C = \alpha I_E + I_{CBO}$$

$$I_E = I_C + I_B$$

$$I_C = \alpha\, (I_C + I_B) + I_{CBO}$$

$$I_C\, (1 - \alpha) = \alpha I_B + I_{CBO}$$

$$I_C = \frac{\alpha}{1-\alpha}\, I_B + \frac{I_{CBO}}{1-\alpha}$$

$$I_C = \left(\frac{\alpha}{1-\alpha}\right) I_B + \left(\frac{1}{1-\alpha}\right) I_{CBO}$$

Hence the above derived is the expression for collector current. The value of collector current depends on base current and leakage current along with the current amplification factor of that transistor in use.

Characteristics of CB configuration

- This configuration provides voltage gain but no current gain.
- Being V_{CB} constant, with a small increase in the Emitter-base voltage V_{EB}, Emitter current I_E gets increased.

- Emitter Current I_E is independent of Collector voltage V_{CB}.
- Collector Voltage V_{CB} can affect the collector current I_C only at low voltages, when V_{EB} is kept constant.
- The input resistance **r_i** is the ratio of change in emitter-base voltage (ΔV_{EB}) to the change in emitter current (ΔI_E) at constant collector base voltage V_{CB}.

$$r_i = \frac{\Delta V_{EB}}{\Delta I_E} \text{ at constant } V_{CB}$$

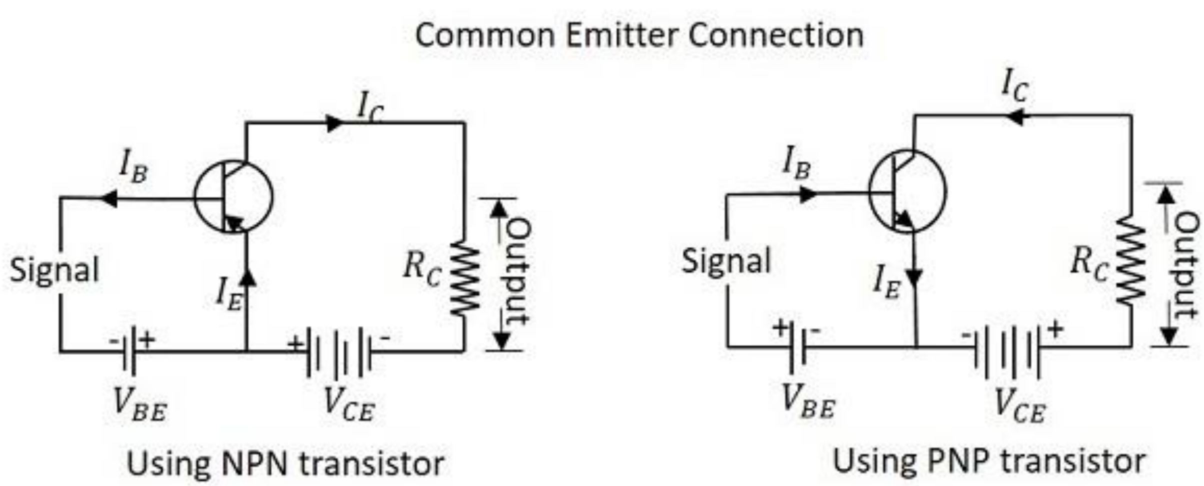
- As the input resistance is of very low value, a small value of V_{EB} is enough to produce a large current flow of emitter current I_E.
- The output resistance **r_o** is the ratio of change in the collector base voltage (ΔV_{CB}) to the change in collector current (ΔI_C) at constant emitter current I_E.

$$r_o = \frac{\Delta V_{CB}}{\Delta I_C} \text{ at constant } I_E$$

- As the output resistance is of very high value, a large change in V_{CB} produces a very little change in collector current I_C.
- This Configuration provides good stability against increase in temperature.
- The CB configuration is used for high frequency applications.

Common Emitter (CE) Configuration

The name itself implies that the **Emitter** terminal is taken as common terminal for both input and output of the transistor. The common emitter connection for both NPN and PNP transistors is as shown in the following figure.



Just as in CB configuration, the emitter junction is forward biased and the collector junction is reverse biased. The flow of electrons is controlled in the same manner. The input current is the base current $\mathbf{I_B}$ and the output current is the collector current $\mathbf{I_C}$ here.

Base Current Amplification factor ($\boldsymbol{\beta}$)

The ratio of change in collector current (ΔI_C) to the change in base current (ΔI_B) is known as **Base Current Amplification Factor**. It is denoted by β

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

Relation between β and α

Let us try to derive the relation between base current amplification factor and emitter current amplification factor.

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

$$\alpha = \frac{\Delta I_C}{\Delta I_E}$$

$$I_E = I_B + I_C$$

$$\Delta I_E = \Delta I_B + \Delta I_C$$

$$\Delta I_B = \Delta I_E - \Delta I_C$$

We can write

$$\beta = \frac{\Delta I_C}{\Delta I_E - \Delta I_C}$$

Dividing by ΔI_E

$$\beta = \frac{\Delta I_C / \Delta I_E}{\frac{\Delta I_E}{\Delta I_E} - \frac{\Delta I_C}{\Delta I_E}}$$

We have

$$\alpha = \Delta I_C / \Delta I_E$$

Therefore,

$$\beta = \frac{\alpha}{1 - \alpha}$$

From the above equation, it is evident that, as α approaches 1, β reaches infinity.

Hence, **the current gain in Common Emitter connection is very high**. This is the reason this circuit connection is mostly used in all transistor applications.

Expression for Collector Current

In the Common Emitter configuration, I_B is the input current and I_C is the output current.

We know

$$I_E = I_B + I_C$$

And

$$I_C = \alpha I_E + I_{CBO}$$

$$= \alpha (I_B + I_C) + I_{CBO}$$

$$I_C(1 - \alpha) = \alpha I_B + I_{CBO}$$

$$I_C = \frac{\alpha}{1 - \alpha} I_B + \frac{1}{1 - \alpha} I_{CBO}$$