Bipolar Transistor in Static (DC) Operation

1. **Structure and Operation of a Transistor**

1.1. Structure of a Bipolar Transistor (BJT):

A **Bipolar Junction Transistor (BJT)** consists of **three layers of extrinsic semiconductors** (Silicon or Germanium), forming **two opposing PN junctions**. There are **two types**: **NPN** and **PNP**.

The three terminals are:

- **Base (B):** Controls the current through the transistor; very thin (a few microns).
- **Collector (C):** Terminal through which current enters the transistor.
- **Emitter (E):** Terminal through which current and output signal exit the transistor.

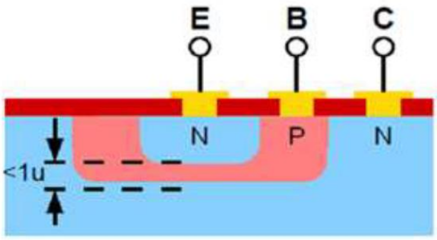


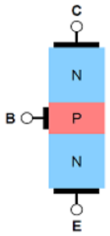
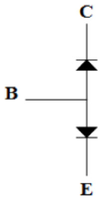
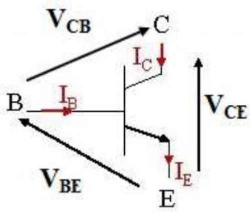
Figure 4.1: Structure of an NPN Transistor

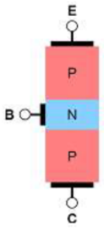
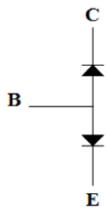
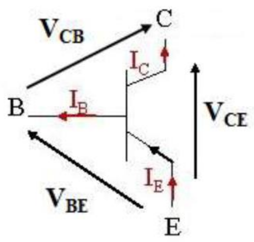
An **NPN (or PNP) transistor** is composed of:

- A **heavily doped N (or P) layer → Emitter (E)**
- A **very thin, lightly doped P (or N) layer → Base (B)**
- A **lightly doped N (or P) layer → Collector (C)**

The table below provides a **schematic representation** and the **standard symbols** for both types of bipolar transistors.

Table 4.1: Pinout and Electrical Schematic of a Bipolar Transistor

Transistor type	Order of the layers	Static schematic	Symbol
NPN			

PNP			

The term **“bipolar”** refers to the conduction of current by both **electrons and holes**. **NPN transistors** are more widely used because the main current is carried by electrons, making them **faster** and suitable for **higher operating frequencies**. Physically, **NPN and PNP transistors operate in the same way**; for a PNP transistor, it is sufficient to **interchange the roles of electrons and holes**.

1.2.Operating Principle of a Transistor (Transistor Effect)

A. Experimental Study (Common-Base Configuration in Normal Operation)

Apply a DC voltage (V_{BE}}) of about **1 V** between the emitter and the base so that the **emitter–base N–P junction is forward-biased** ((V_{BE} > 0)). Also apply a voltage (V_{BC}) of several volts between the base and the collector so that the **base–collector junction is reverse-biased** ((V_{BC} < 0)) (Figure 4.2).

In this configuration, the **base serves as the common reference** for both the input circuit (emitter–base circuit) and the output circuit (collector–base circuit). This configuration is called the **common-base** arrangement.

B. Definition of the Transistor Effect

With a **small base–emitter voltage** ($V_{BE} = 1$), a transistor injects an **emitter current** into a **low-resistance circuit** (forward-polarization emitter–base junction) and transfers this current to a **high-resistance circuit** (reverse-polarization base–collector junction). This phenomenon is called the **transistor effect**.

In summary, a transistor obeys the relation ($I_C = \beta I_B$), which shows that a **small base current** can control a **much larger collector current**, making the transistor widely used for **signal amplification**.

1.3. Equations of an NPN Transistor

Considering an **NPN transistor** and its symbol, its behavior can be described by the following equations:

1) **Voltage equations (from Kirchhoff’s Voltage Law):**

$$V_{CE} = V_{CB} + V_{BE}$$

- $V_{CE} = V_C - V_E$: voltage between collector and emitter.

- $V_{BE} = V_B - V_E$: voltage between base and emitter.
- $V_{CB} = V_C - V_B$: voltage between collector and base.

2) **Current equations (from Kirchhoff's Current Law):**

$$I_E = I_B + I_C$$
$$I_E = I_B + \beta I_B = (1+\beta) I_B$$

- I_B: base current (input).
- I_C: collector current (output).
- I_E**:** Emitter current, used as a reference.

The parameter α is called the **conduction efficiency**, defined as:

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

3) Equation of the conducting base–emitter junction: $I_B = I_{SB} e^{\frac{V_{BE}}{V_T}}$

where $V_T = \frac{K_B T}{q} = 0.026\ V$ at $T = 300\ °K$ is the **thermal voltage**, and I_{SB} is the **reverse saturation current** of the BE junction.

4) Collector current equations:

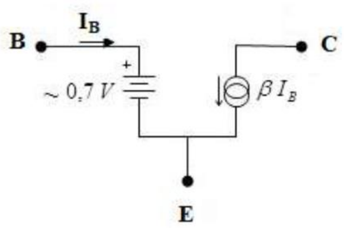
$$I_C = \beta I_{SB}\left(1 + \frac{V_{CE}}{V_A}\right) e^{\frac{V_{BE}}{V_T}} = \beta\left(1 + \frac{V_{CE}}{V_A}\right) I_B \cong \beta I_B$$

where V_A is the **Early voltage** and β is the **DC current gain** of the transistor.

Operating Modes of an NPN Transistor:

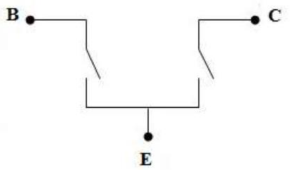
The bipolar transistor has two operating modes: **linear mode (amplification)** and **cutoff/saturation mode**.

Linear mode:



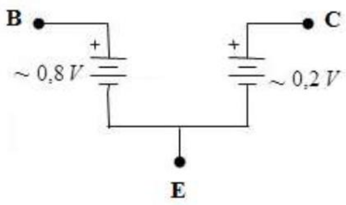
$$I_C = \beta I_B$$
$$V_{CE} > 1\,V$$
$$V_{BE} = 0{,}7\,V$$

Cut off mode:



$$I_B = I_C = I_E = 0$$
$$V_{BE} < V_{BESat} = 0{,}7\,V$$

Saturation Mode:



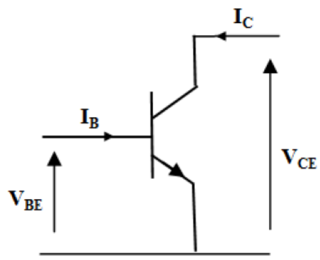
$$I_C = I_{CSat} < \beta I_B$$
$$V_{CE} = V_{CESat} = 0{,}2 \text{ à } 0{,}4\ V$$
$$En\ pratique : V_{CESat} = 0\ V$$
$$V_{BE} = V_{BESat} = 0{,}6 \text{ à } 0{,}7\ V$$

1.4. Basic Transistor Configurations

A transistor can be considered a **two-port network**. When connecting a transistor, one terminal is made **common to both the input and the output**. There are three basic transistor configurations: **Common Emitter**, **Common Collector**, and **Common Base**.

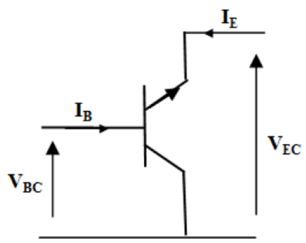
A. Common Emitter (CE):

Used at **low frequencies (AF)** to **amplify a signal**.



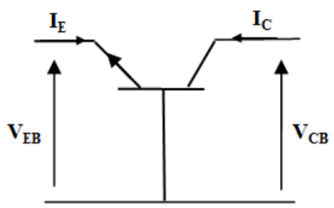
B. Common Collector (CC):

Used as an **impedance adapter (buffer)**.



C. Common Base (CB):

Used at **high frequencies (HF)**.



1.5. NPN Transistor Characteristic Networks

The characteristics are curves showing the relationships between the **currents and voltages** of a transistor. They are used to define the **operating regions**, determine the **optimal operating point**, and extract transistor parameters.

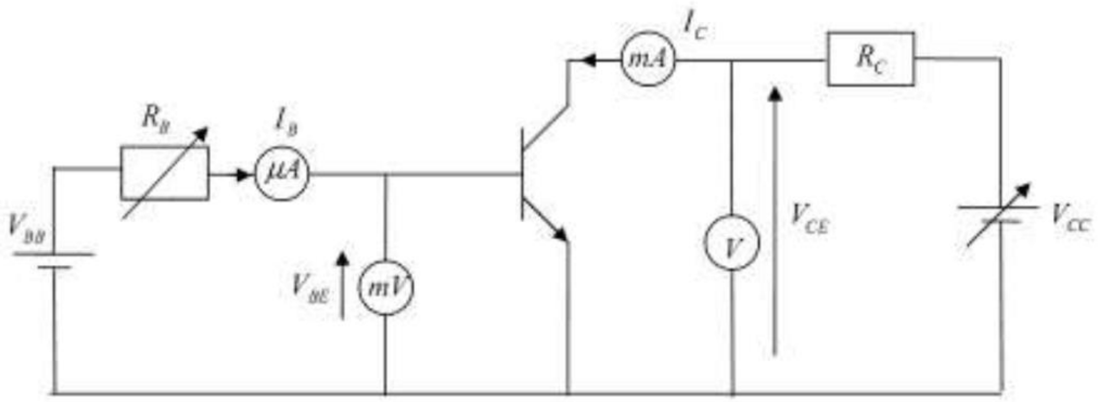
Determining the operating state of a bipolar transistor requires six variables:

- **Three currents:** $\boldsymbol{I_B}$, I_E , I_C
- **Three voltages:** $\boldsymbol{V_{CE}, V_{BE}, V_{CB}}$

To plot these characteristics, the **common-emitter configuration** is most commonly used.

Normal operating conditions:

- ($V_{BE} > 0$): base–emitter junction forward-biased.
- ($V_{BC} < 0$): base–collector junction reverse-biased.



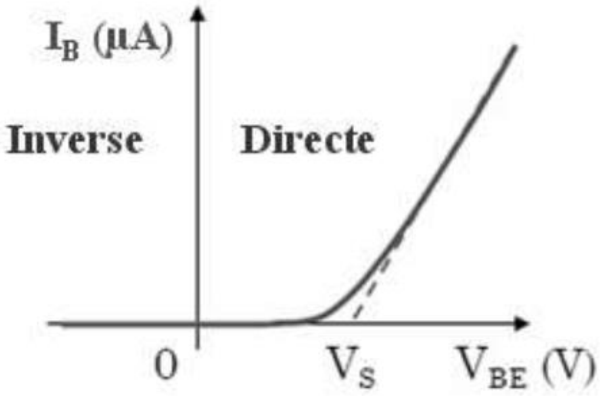
In this configuration

- The **base–emitter junction** is forward-biased using the voltage source (V_{BB}) through the resistor (R_B), which is much larger than the transistor's input resistance. For a **silicon transistor**, (V_{BE}) is approximately **0.7 V**.
- The **collector** is biased by the resistor (R_C) using the voltage source (V_{CC}), so that the **collector voltage is higher than the base voltage**, ensuring the **base–collector junction is reverse-biased**.

A. Input Characteristics ($I_B = f(V_{BE})$)

The **input characteristic** of a transistor is given by the relation ($I_B = f(V_{BE})$) with (V_{CE}) kept constant. It is practically the same as the **forward-biased diode characteristic** and depends very little on (V_{CE}). Therefore, it is usually plotted for a **single value of (V_{CE})**.

In normal operation, (V_{BE}) is about **0.7 V** for a **silicon transistor**, and the base current (I_B) is generally **less than 1 mA**.

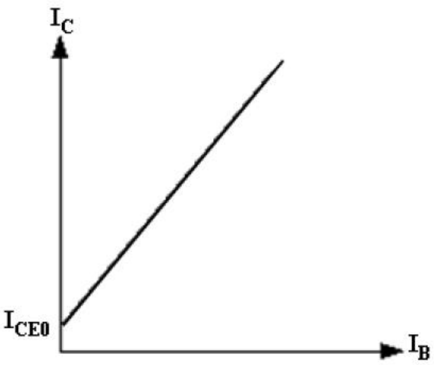


B. Current Transfer Characteristics ($I_C = f(I_B)$)

The **current transfer characteristic** of a transistor is defined by the relation ($I_C = f(I_B)$) with (V_{CE}) kept constant. A bipolar transistor acts as a **current amplifier**, characterized by the relationship between the output current (I_C) and the input current (I_B) through the **current gain $\boldsymbol{\beta}$**:

$$I_C = \beta I_B$$

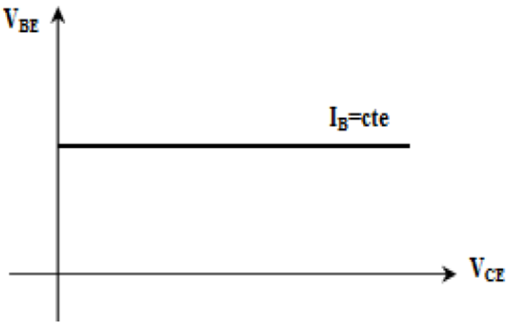
The value of β depends on the **type of transistor**.



C. Current transfer characteristics $\boldsymbol{V_{BE} = f(V_{CE})}$:

They are given by the relation $V_{BE} = f(V_{CE})$ with I_B constant. Due to the weak influence of the output voltage V_{CE} on the input voltage V_{BE} , the voltage transfer characteristics are almost horizontal.

This characteristic is often ignored by manufacturers

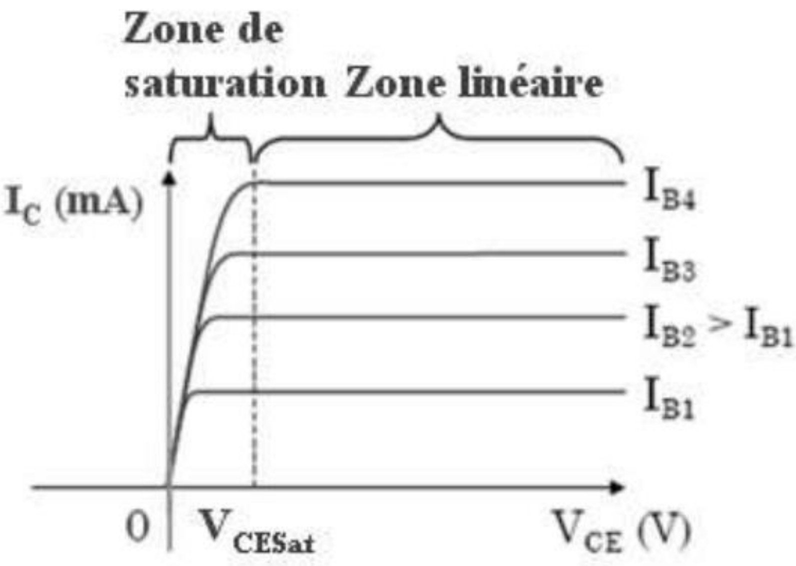


D. Output characteristics $I_C = f(V_{CE})$:

The transistor's output characteristic is defined by the relation $I_C = f(V_{CE})$ with I_B constant. In practice, a set of characteristics is provided for several values of I_B.

Three regions can be distinguished:

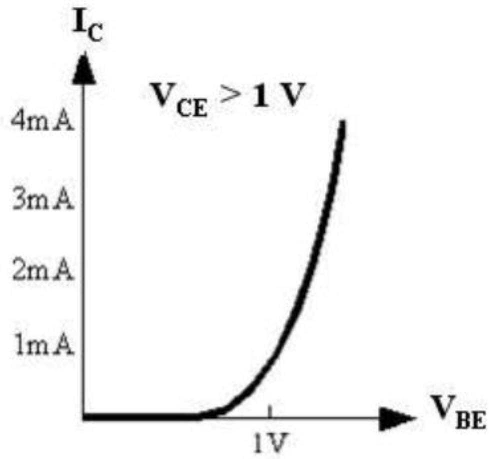
- An important region where the current I_C depends on I_B ($I_C \approx \beta I_B$) and varies very little with V_{CE}. This characteristic corresponds to a current source (with very high internal resistance) used as a load.
- The low V_{CE} voltage region (0 to a few volts), called the saturation region. When the C-B voltage decreases to become very low, the C-B junction is no longer reverse-biased, and the transistor effect rapidly diminishes. At the limit, the C-B junction becomes forward-biased: the transistor is equivalent to two diodes in parallel.



E. Characteristics $I_C = f(V_{BE})$:

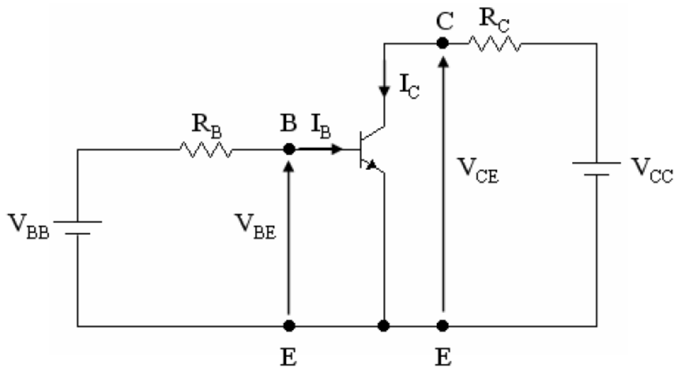
The $I_C = f(V_{BE})$: curve shows that, for a transistor operating in the saturation region, the V_{BE} voltage varies very little. Below $V_{BE} = 0.7\ V$, the transistor does not conduct. When this value, called the threshold voltage, is exceeded, the collector current increases exponentially.

In practice, V_{BE} is generally between 0.7 V (for I_C of a few mA) and 1 V (for power transistors carrying a large I_C)



1.6. Transistor polarization

It is now necessary to set the transistor's operating mode (cut-off, saturation, or linear). That is, the values of I_B, I_C, V_{BE}, and V_{CE} must be fixed. These quantities are determined by the external components connected to the transistor (Figure 4.4). Depending on the values of I_B, I_C, V_{BE}, and V_{CE}, the transistor will operate in the linear, cut-off, or saturation region.



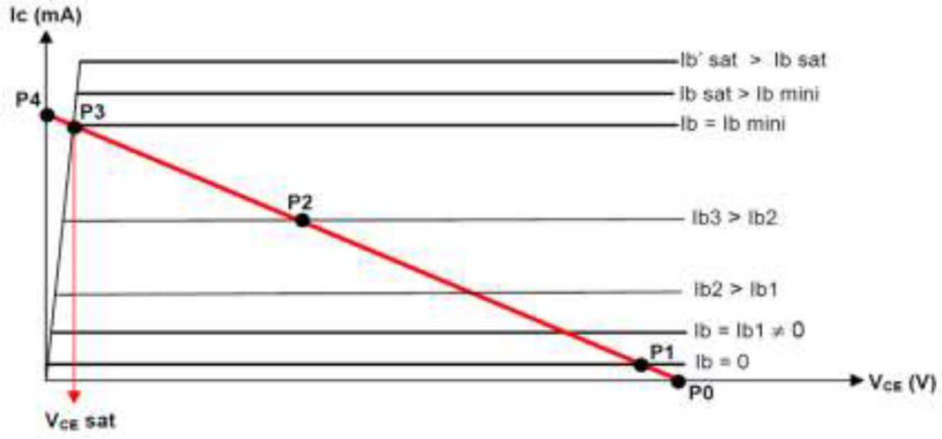
A. Static Load Line and Input Line:

On the $I_C = f(V_{CE})$ characteristic of the transistor at constant I_B, the static load line is drawn, given by the equation:

$$V_{CE} = V_{CC} - R_{CC} \cdot I_C$$

Similarly, the line $V_B = V_{BB} - R_{BB} \cdot I_B$ can be drawn on the input characteristic, then called the input line.

The intersection point between the static load line and the transistor's output characteristic gives the operating point $P_0, P_2, or\ P_3$ of the circuit.

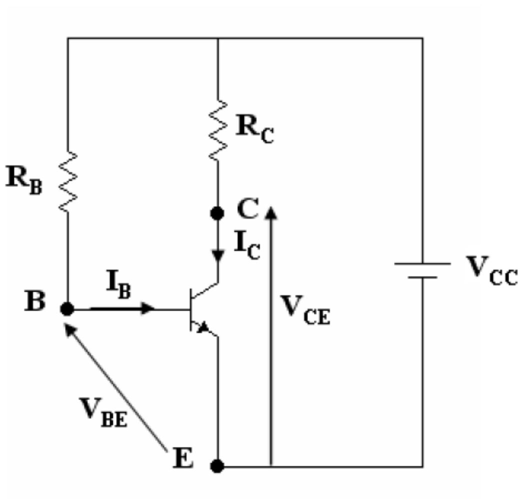


- If the operating point is at P_0, the transistor is in cut-off.
- If the operating point is at P_2, the transistor operates in the linear region.
- If the operating point is at P_3, the transistor is saturated.

B. Types of polarization Circuits for an NPN Transistor:

polarization of a transistor means making it conduct using a DC power supply and by adding external active or passive components (resistors, inductors, diodes), in order to set the operating point. The biasing configurations for a bipolar transistor are varied, such as:

- **Base-resistor Polarization**



The line of static charge:

$$V_{CC} = R_C I_C + V_{CE}$$

$$I_C = \frac{V_{CC} - V_{CE}}{R_C}$$

With,

$$I_C = \beta I_B$$

The line of static attack :

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

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

With,

$$V_{BE} = 0.7\ V$$

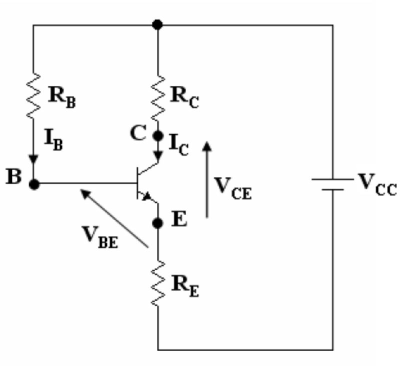
Characteristics:

- Few in number.
- β-dependent.
- Base current defined.

Applications:

- Switches.
- Digital circuits.

➢ **Emitter-feedback polarization**



The line of static charge:

$$V_{CE} - V_{CC} + R_E I_E + R_C I_C = 0$$

$$I_C = \frac{V_{CC} - V_{CE}}{R_C + R_E}$$

The line of static attack:

$$V_{BE} - V_{CC} + R_B I_B + R_E I_E = 0$$

$$I_E \cong I_C \text{ and } I_C = \beta I_B$$

$$I_B = \frac{V_{CC} - V_{BE}}{R_B + \beta R_E}$$

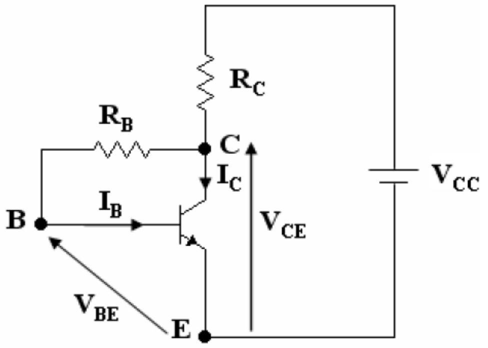
Characteristics:

- Emitter current defined.
- β-dependent.

Applications:

- Driving integrated circuits.
- Amplifiers.

➢ **Collector-feedback polarization**



The line of static charge,

$$V_{CE} - V_{CC} + R_C I_C = 0$$

$$I_C = \frac{V_{CC} - V_{CE}}{R_C}$$

The line of static attack:

$$V_{BE} - V_{CC} + R_B I_B + R_C(I_C + I_B) = 0$$

With,

$$I_C = \beta I_B$$

$$I_B = \frac{V_{CC} - V_{BE}}{R_B + \beta R_C}$$

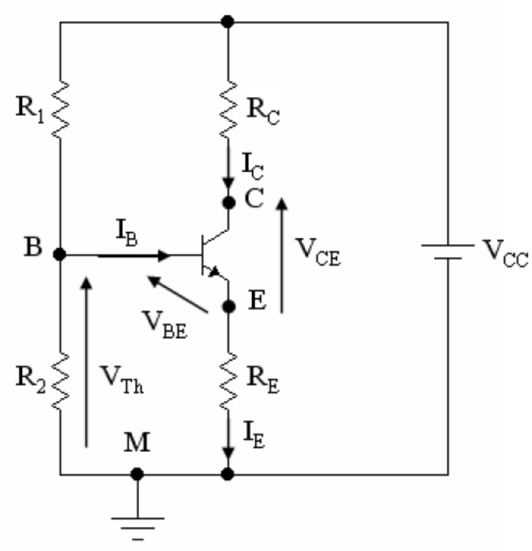
Characteristics:

- This configuration prevents transistor saturation.
- β is involved in setting the quiescent current.

Applications:

- Amplifiers.

➢ **Voltage-divider polarization**



The voltage of Thevenin and the resistor of Thevenin :

$$V_{Th} = \frac{R_2}{R_1 + R_2} V_{CC}$$

$$R_{Th} = R_1 // R_2 = \frac{R_1 R_2}{R_1 + R_2}$$

The line of static charge

$$V_{CC} = R_C I_C + V_{CE} + R_E I_E$$

With,

$$I_E \approx I_C$$

$$I_C = \frac{V_{CE} - V_{CC}}{R_C + R_E}$$

The line of static attack

$$V_{Th} = (R_1 // R_2 + \beta R_E) I_B + V_{BE}$$

Characteristics:

- Requires more resistors.
- β-independent.
- Uses only one power supply.

Applications:

- Amplifiers.

1.7. Applications of the Bipolar Transistor:

The bipolar transistor is used in many areas, such as: alternating flasher, alarm system, fan, NTC thermistor, sliding door, flashlight, continuity tester, refrigerator lighting, 3-story elevator, radio, television, satellite, traffic lights.