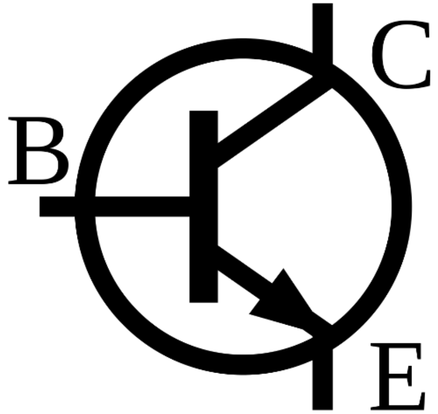
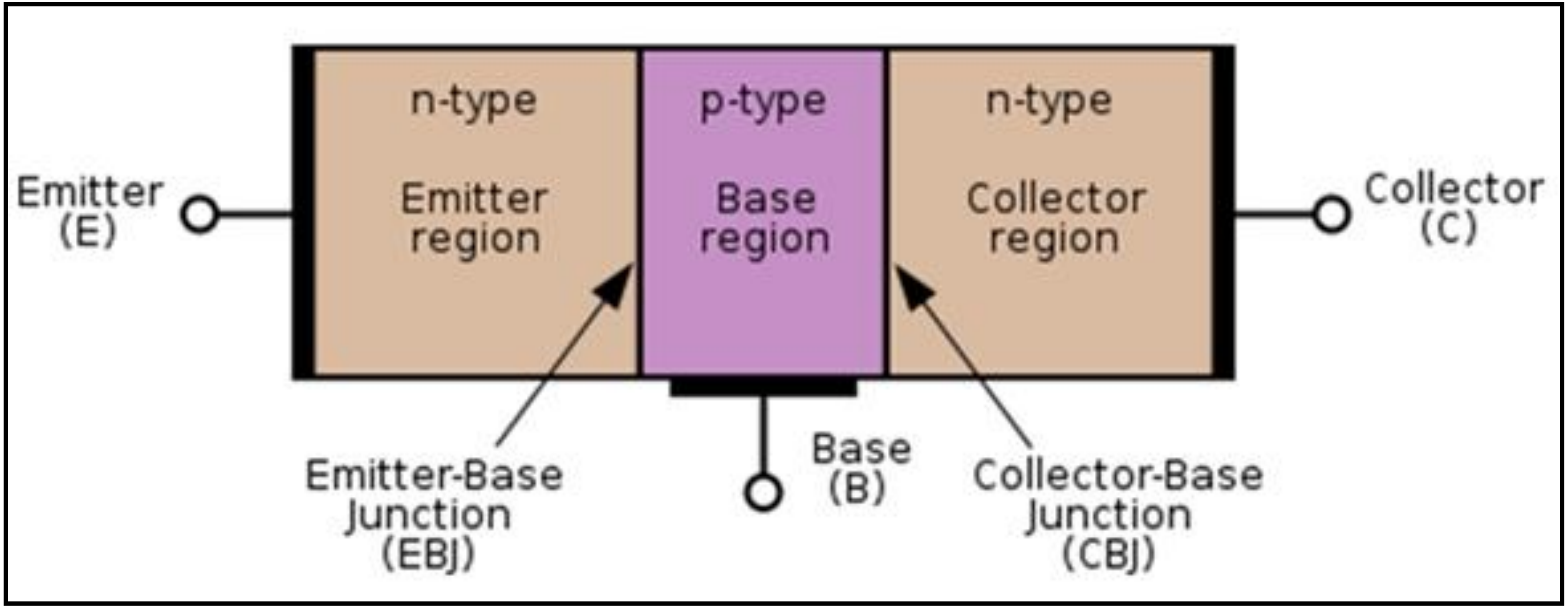
Unit: III
Bipolar Junction Transistor
(BJT)



Bipolar transistors are still used for amplification of signals, switching, and in digital circuits.

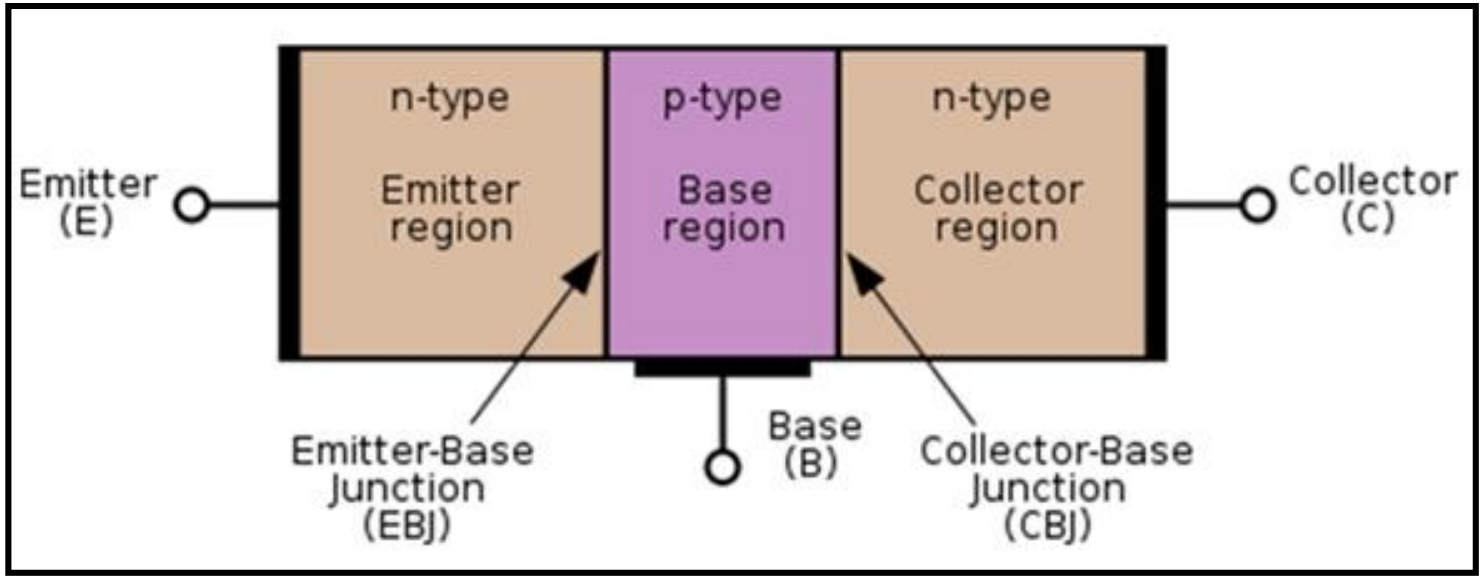
Unit III: **TRANSISTORS**

- Construction and characteristics of bipolar junction transistors (BJT’s)-
- Comm. Base, Comm. emitter, Comm. Collector configuration,
- Transistor biasing and bias stabilization: -
    - the operating point,
    - stability factor,
- analysis of
    - fixed base bias,
    - collector to base bias,
    - Emitter resistance bias circuit and
    - self bias circuit.

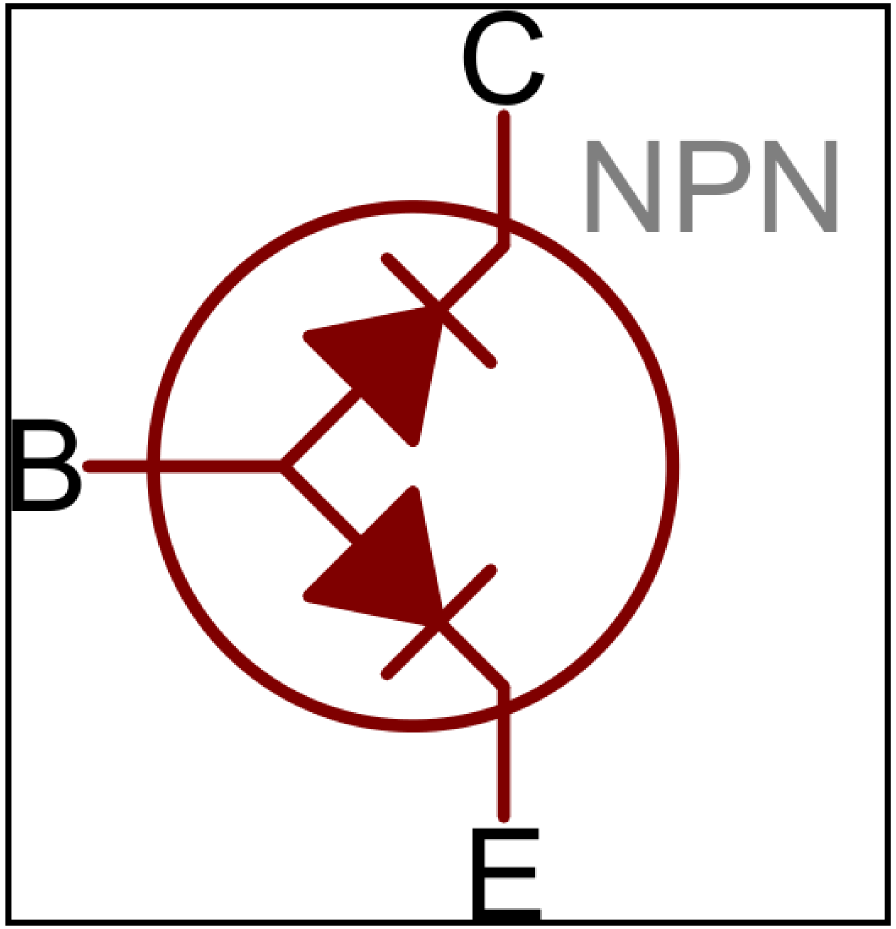


A **bipolar junction transistor** (**bipolar transistor** or **BJT**) is a type of transistor that uses both electrons and holes as charge carriers.

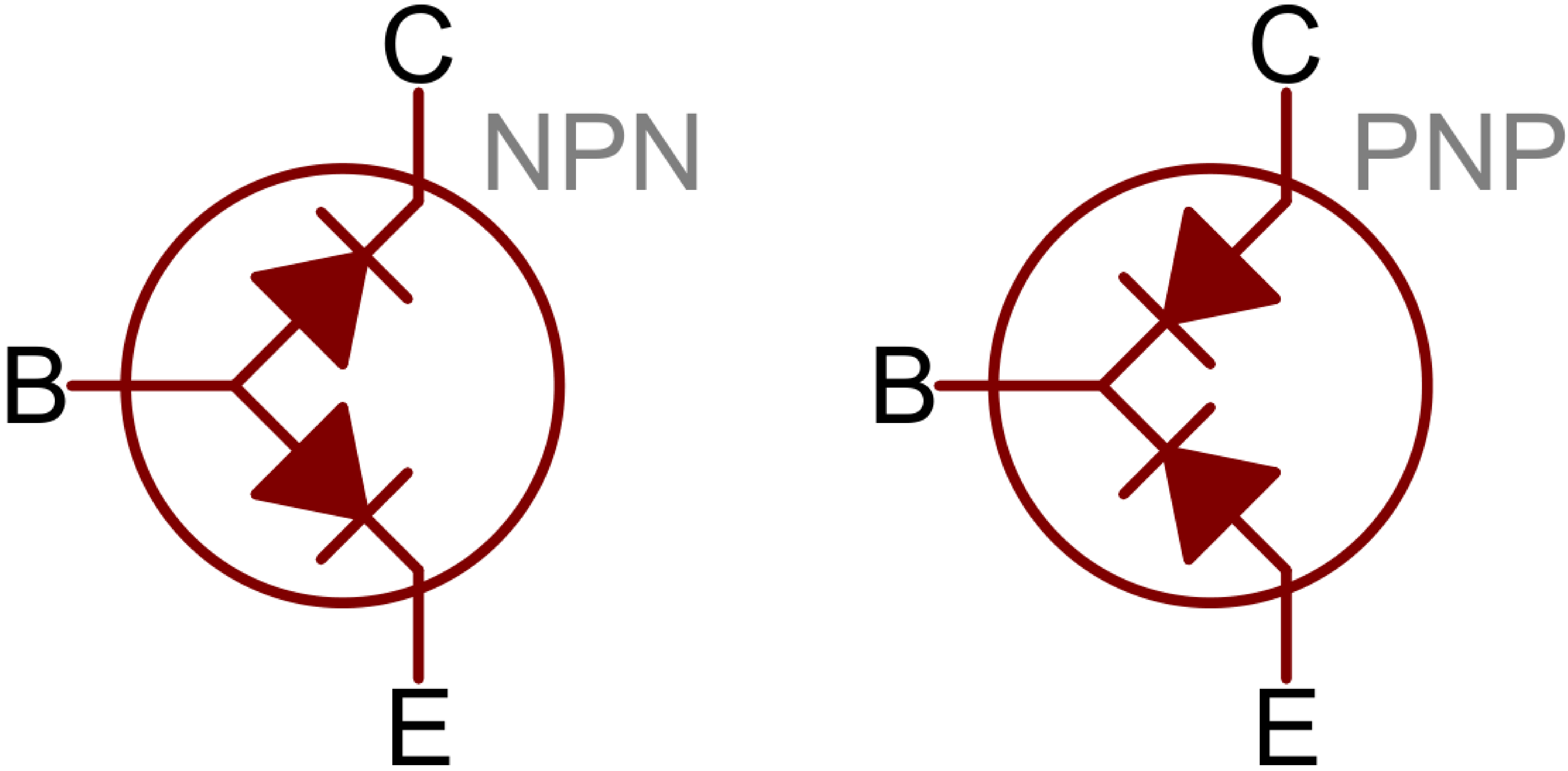
BJTs use two junctions between two semiconductor types, n-type and p-type.
The junctions can be made in several different ways, such as changing the Doping of the semiconductor material or by diffusion of n -type and p-type doping substances into the crystal.

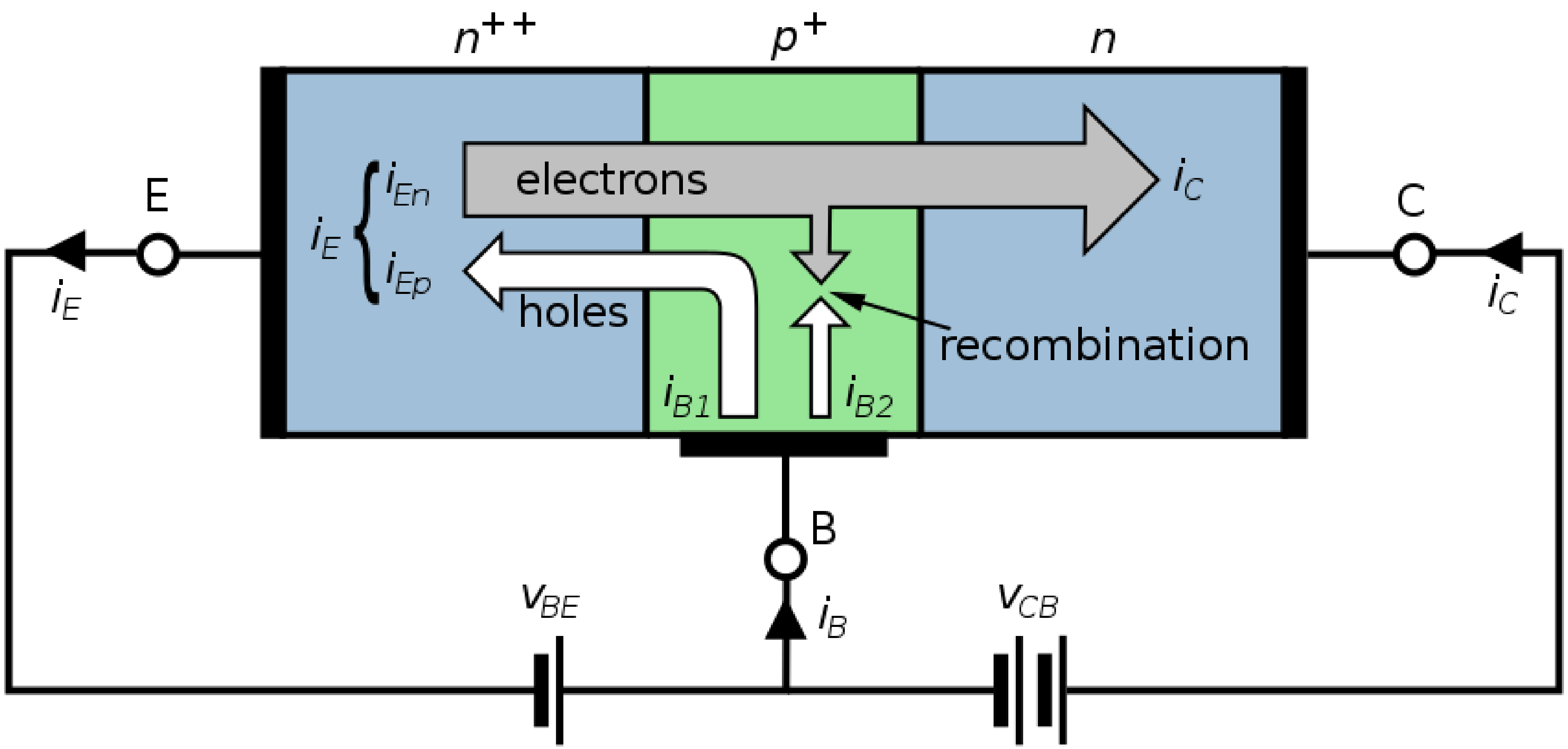


n-type
p-type
n-type
Emitter
(E)
Emitter
region
Base
region
Collector
region
Collector
(C)
Base
(B)
Emitter-Base
Junction
(EBJ)
Collector-Base
Junction
(CBJ)



C
NPN
B
E


C
NPN
B
E
C
PNP
B
E



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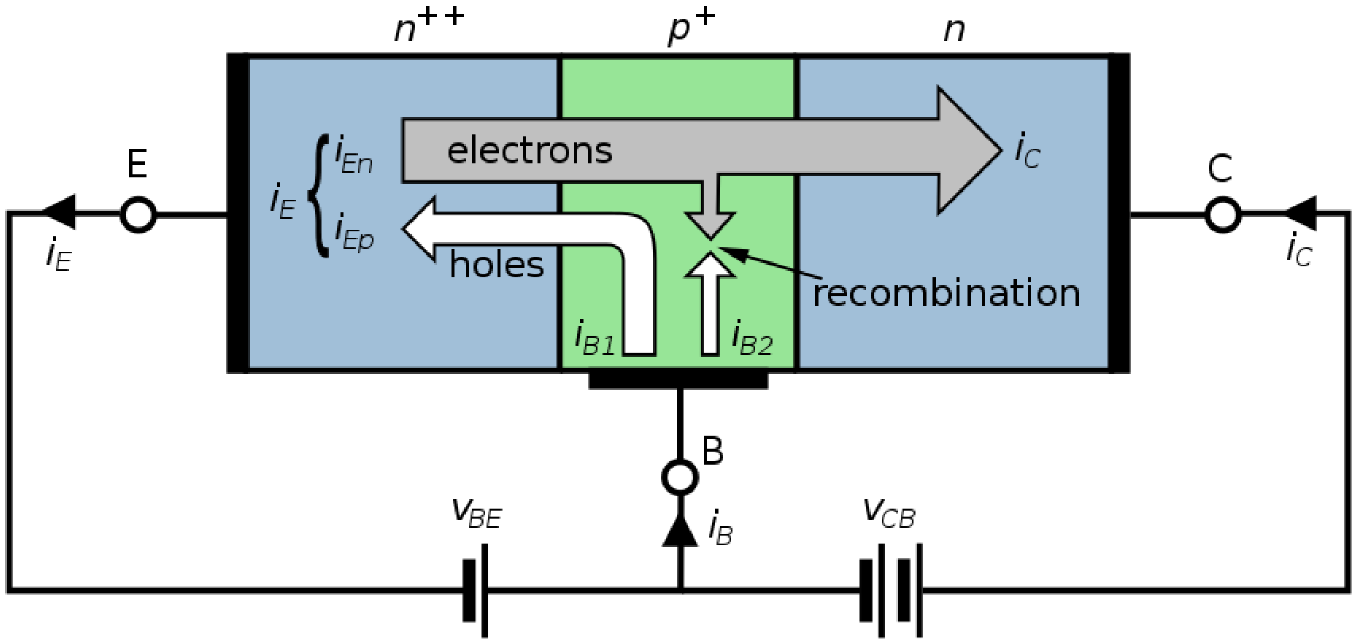
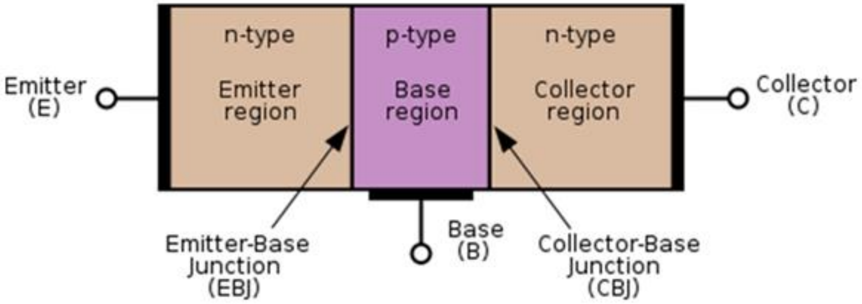
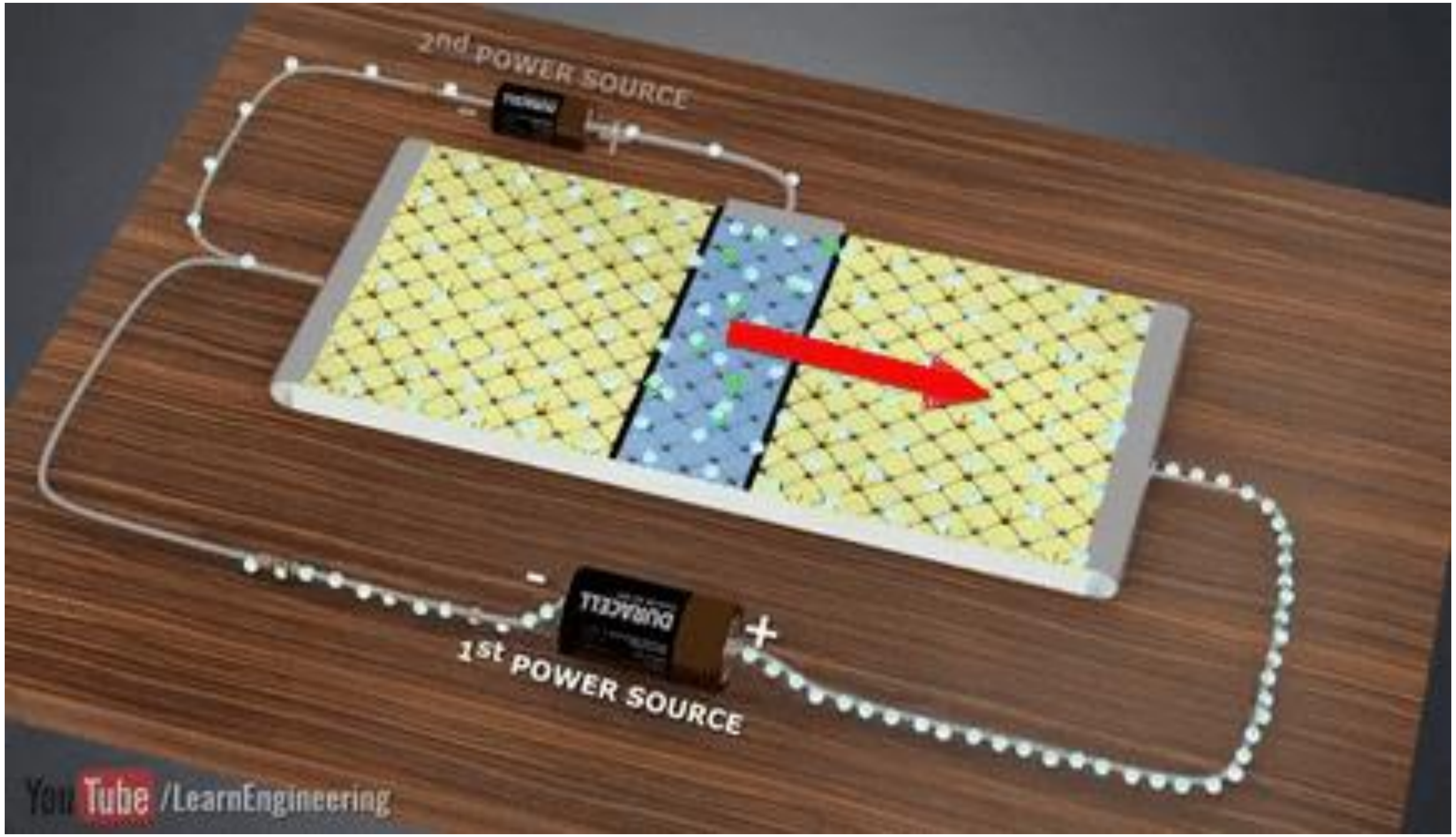
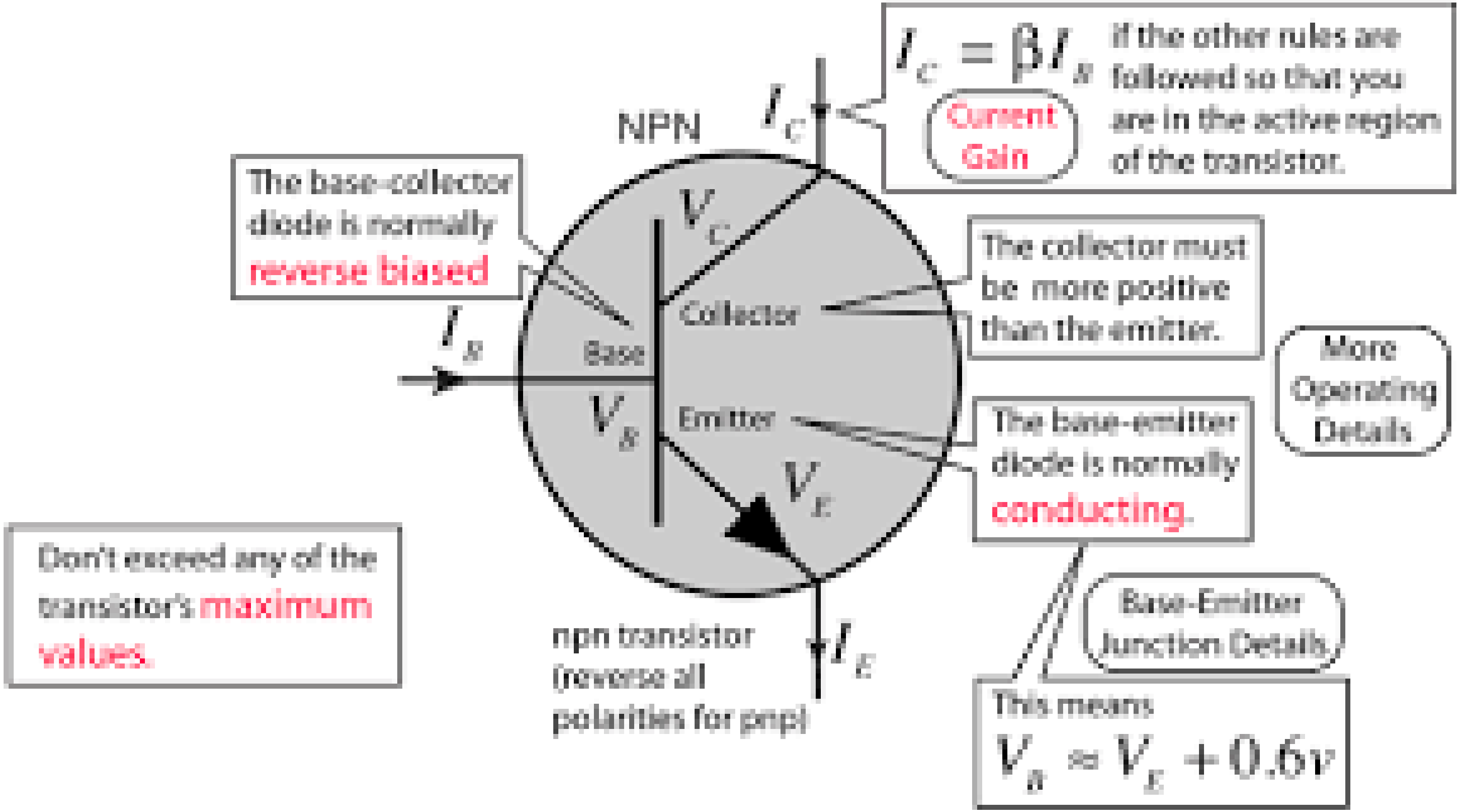


- ✓ By convention, the direction of current on diagrams is shown as the direction that a positive charge would move. This is called conventional current.
- ✓ However, current in many metal conductors is due to the flow of electrons. Because electrons carry a negative charge, they move in the direction opposite to conventional current.
- ✓ On the other hand, inside a bipolar transistor, currents can be composed of both positively charged holes and negatively charged electrons.
- ✓ In this Figure, current arrows are shown in the conventional direction, but labels for the movement of holes and electrons show their actual direction inside the transistor.
- ✓ The arrow on the symbol for bipolar transistors indicates the PN junction between base and emitter and points in the direction in which conventional current travels.





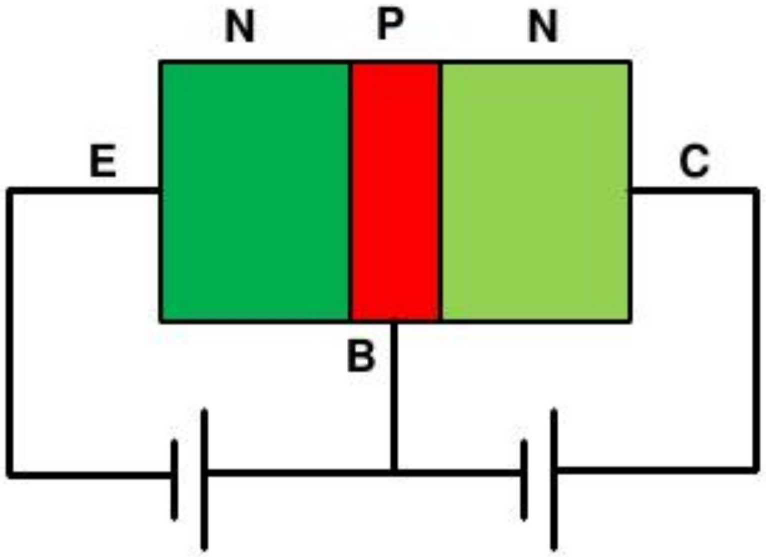
A bipolar junction transistor is a three-terminal semiconductor device that consists of two p-n junctions which are able to amplify or magnify a signal. It is a current controlled device. The three terminals of the BJT are the base, the collector and the emitter.

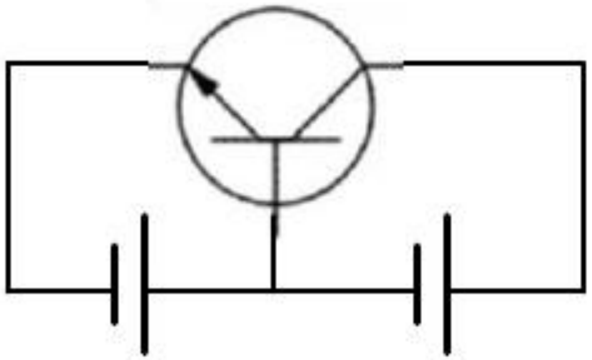


NPN
$I_C = \beta I_B$
Current Gain
If the other rules are followed so that you are in the active region of the transistor.
I_C
The base-collector diode is normally reverse biased
V_C
Collector
Base
I_B
V_B
Emitter
V_E
The collector must be more positive than the emitter.
More Operating Details
The base-emitter diode is normally conducting.
Base-Emitter Junction Details
This means
$V_B \approx V_E + 0.6v$
I_E
npn transistor (reverse all polarities for pnp)
Don't exceed any of the transistor's maximum values.

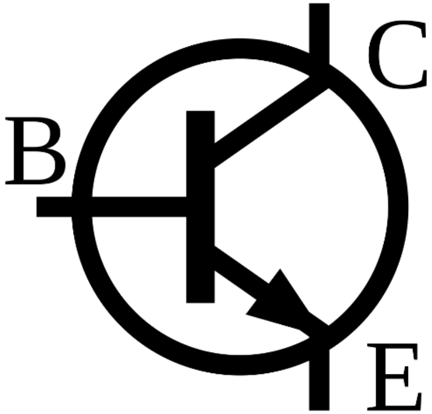
Transient Operation (V_{BE} ↑)

- Base to emitter junction is forward biased
  - Low resistance, so small ↑ in V_{BE} causes a large ↑ in I_E
- The base is thin and lightly doped
  - Few current carriers recombine to form more base current
  - I_B ↑ only slightly
- The rest of the current carriers are swept across the base to collector



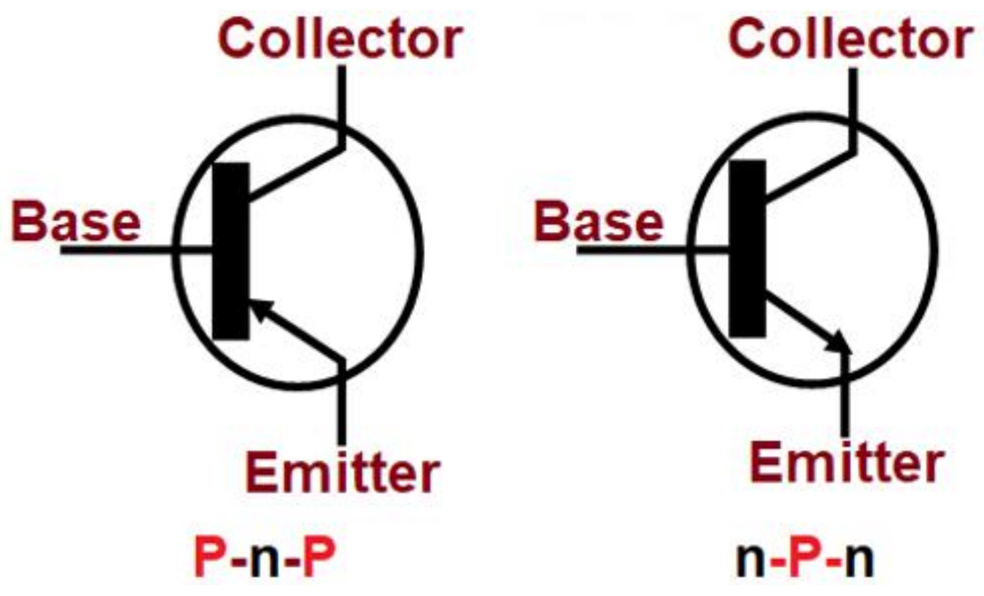


Unit: III
Bipolar Junction Transistor (BJT)



Construction and Working

Symbol of BJT Transistors



- ✓ The **difference between the PNP and NPN transistors** is that the arrow mark at the emitter end
- ✓ if you have noticed, the arrow in the PNP transistor is mentioned as moving from the emitter to the base
- ✓ whereas in the NPN transistor the arrow will be moving from the base to the emitter.
- ✓ The Direction of the arrow represents the direction of current flow in the transistor,
- ✓ in PNP the current will be flowing from emitter to base,
- ✓ similarly in the NPN transistor current will be flowing from the base to emitter.

Construction of Bipolar Junction Transistor

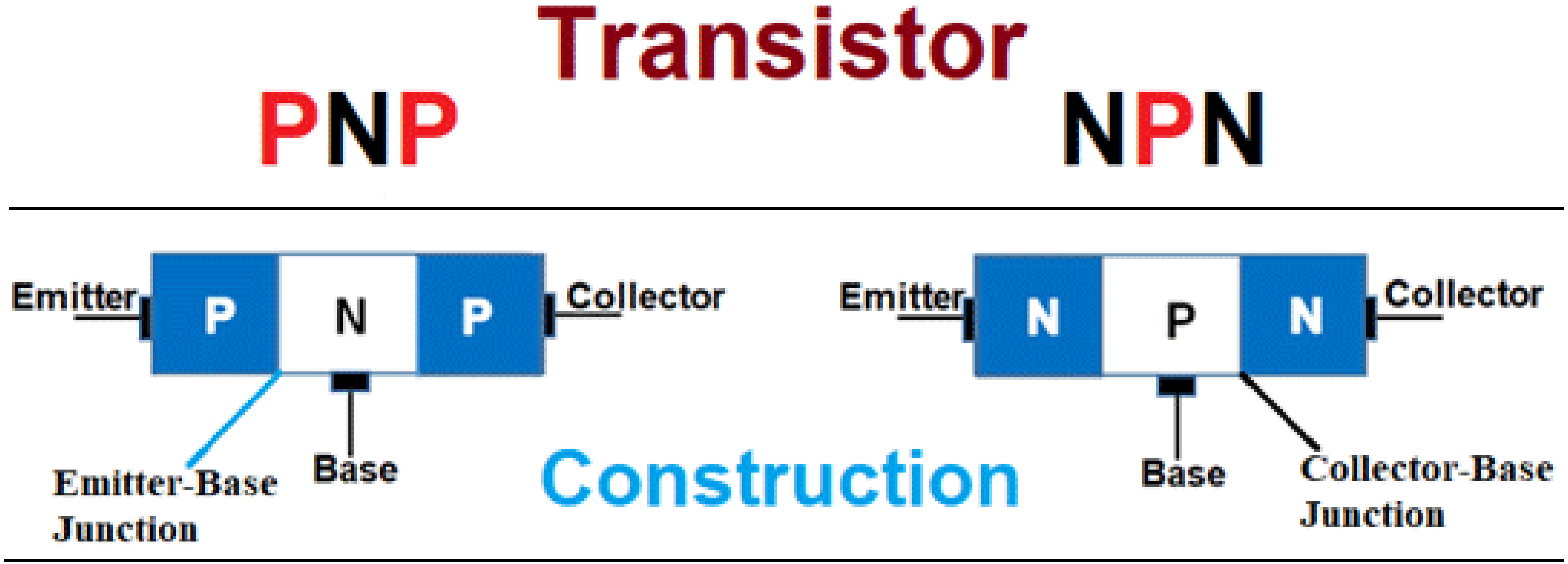
The BJT is formed by three layers of semiconductor materials,

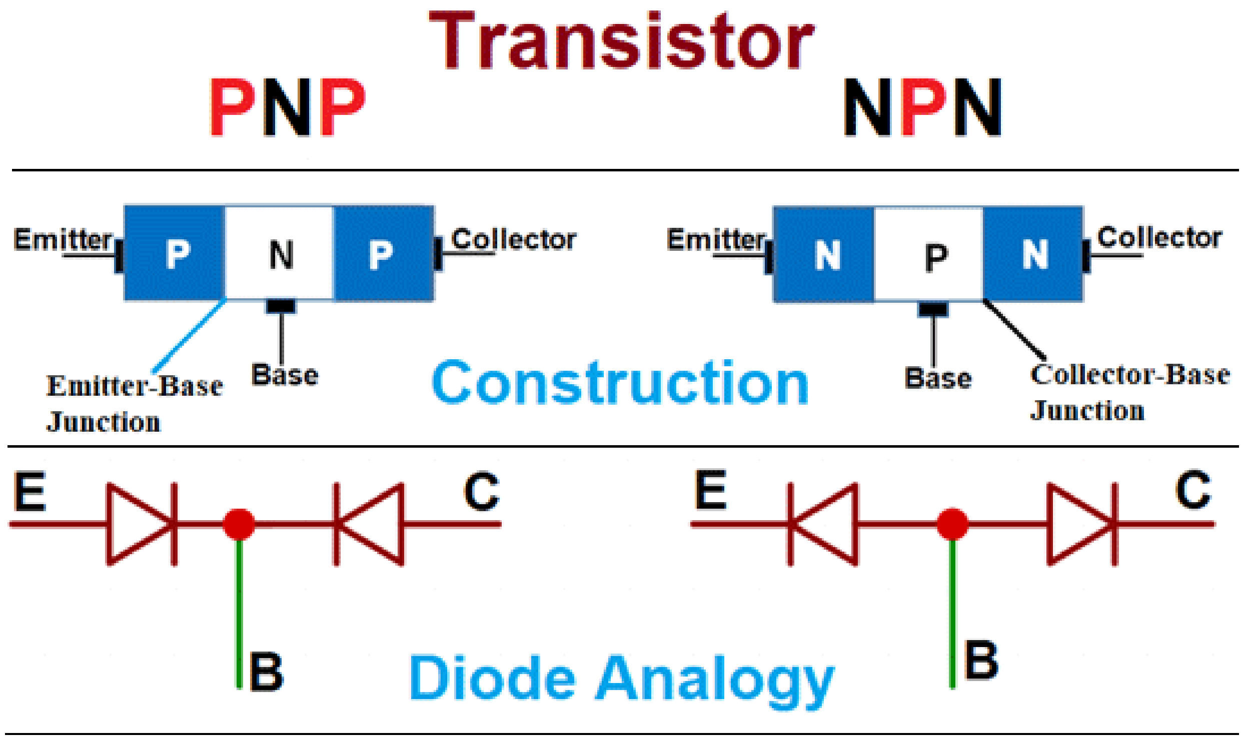
If it is a PNP transistor, it will have two P-type regions and one N-type region,

Likewise, if it is an NPN transistor, it will have two N-type regions and one P-type region.

The two outer layers are where the collector and emitter terminals are fixed and

The base terminal is fixed at the centre layer.

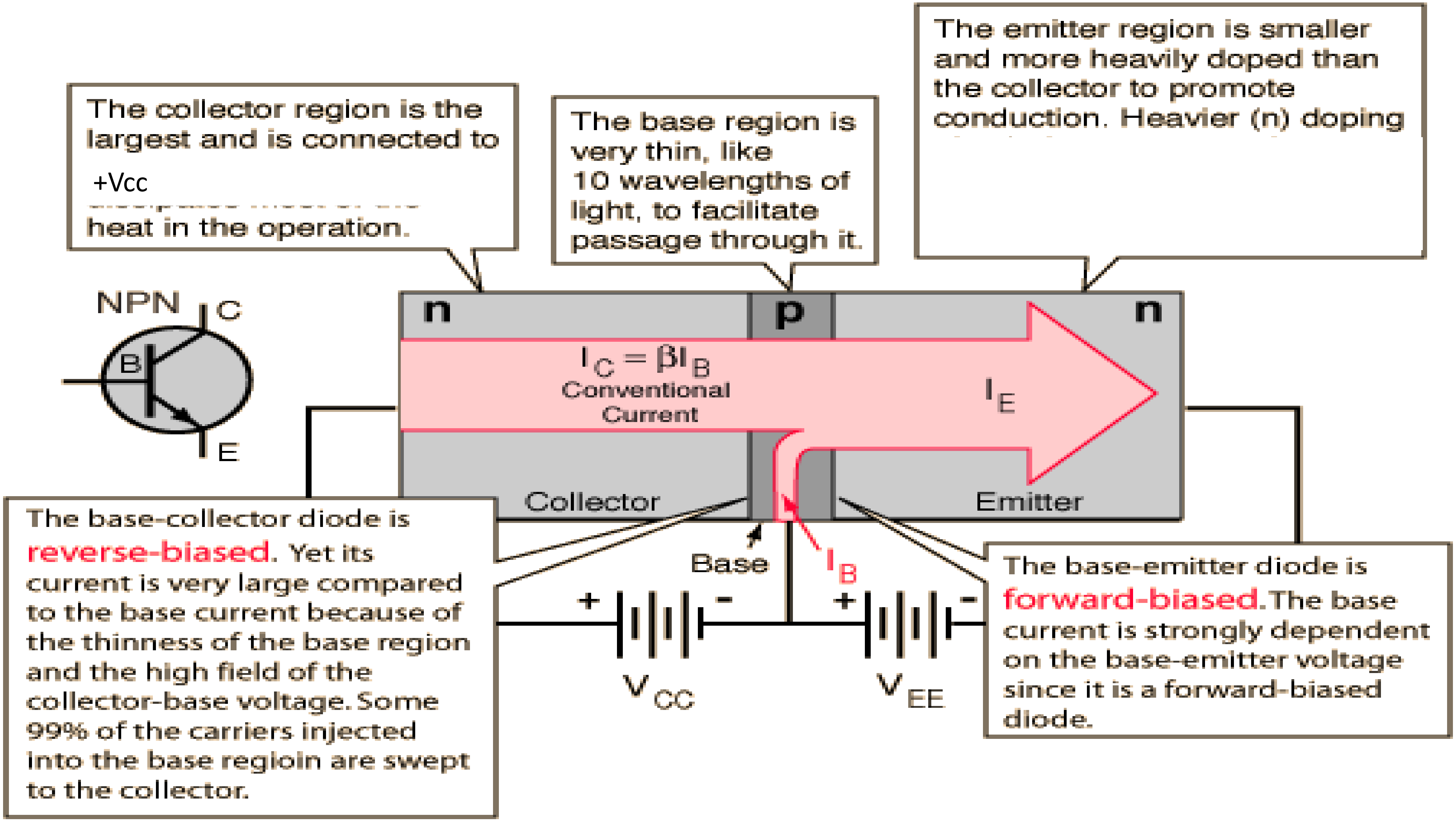


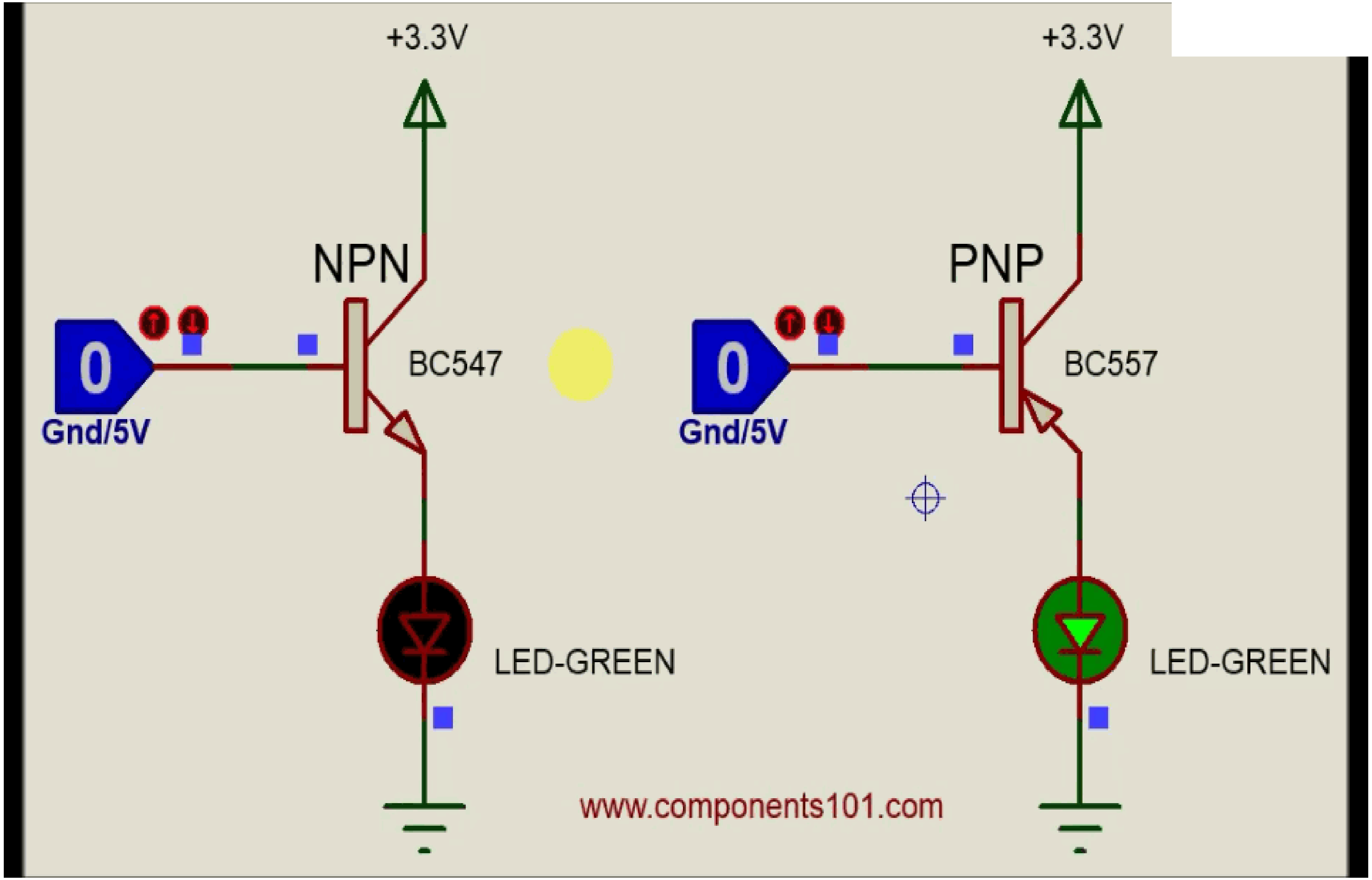


The construction can simply be explained with a **two diode analogy for transistor** as shown in the above image.

Consider the two diodes connected with each other using the cathode, then the meeting point can be extended to form the base terminal and the two anodes end acts as the collector and emitter of a PNP transistor.

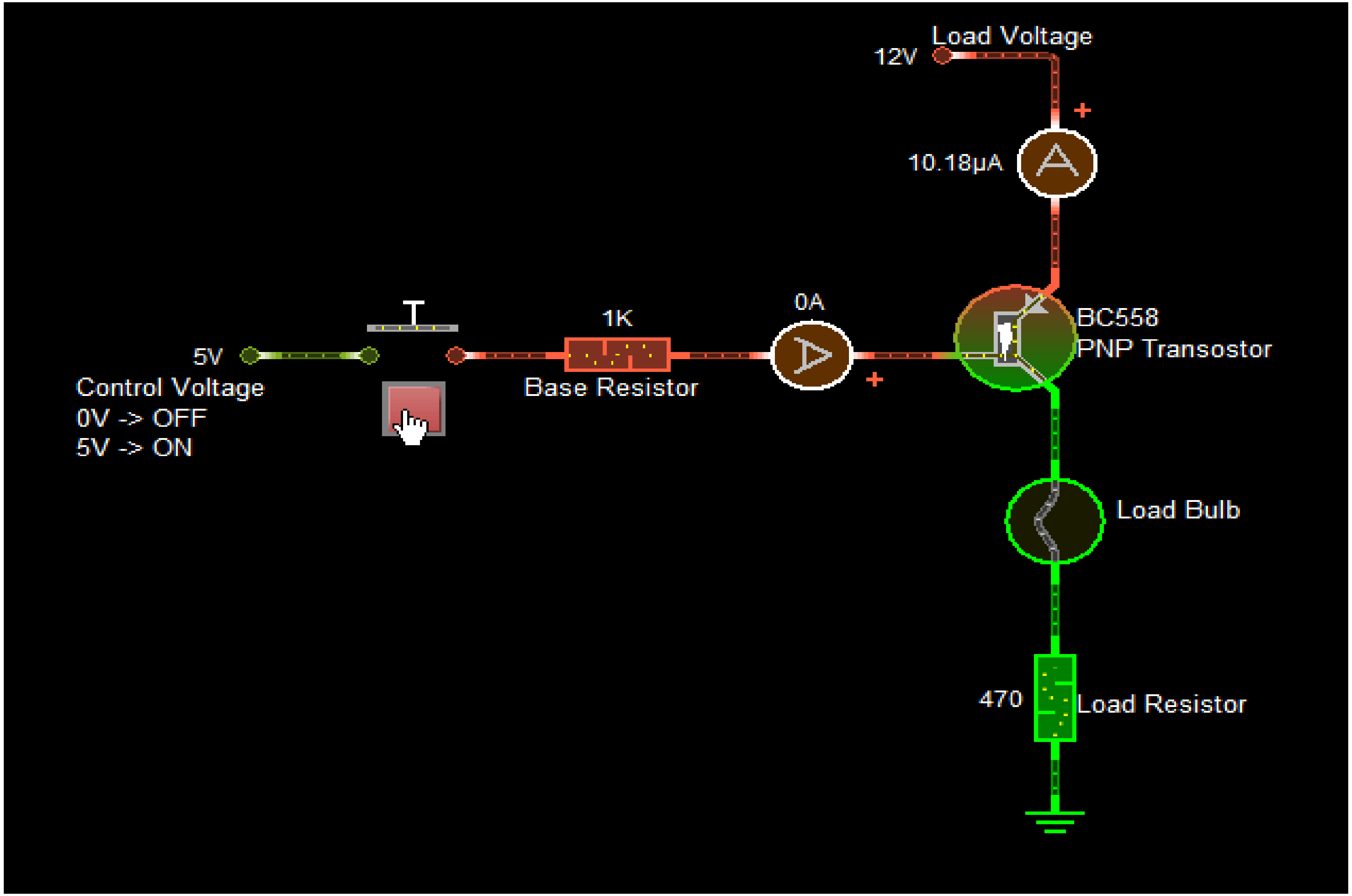
Similarly, if you connect the anode ends of the Diode then the meeting point of the anodes can be extended to for the base terminal and the two cathode ends act as the collector and emitter of the NPN transistor.


The collector region is the largest and is connected to
+Vcc
heat in the operation.
The base region is very thin, like 10 wavelengths of light, to facilitate passage through it.
The emitter region is smaller and more heavily doped than the collector to promote conduction. Heavier (n) doping
NPN
C
B
E
n
p
n
$I_C = \beta I_B$
Conventional Current
I_E
Collector
Emitter
Base
I_B
+
-
+
-
V_{CC}
V_{EE}
The base-collector diode is reverse-biased. Yet its current is very large compared to the base current because of the thinness of the base region and the high field of the collector-base voltage. Some 99% of the carriers injected into the base regioin are swept to the collector.
The base-emitter diode is forward-biased. The base current is strongly dependent on the base-emitter voltage since it is a forward-biased diode.



- ✓ Another important difference is that an NPN transistor remains open until it receives a signal on the base pin
- ✓ while a PNP transistor remains closed until a control signal is provided to the base pin as shown in the above GIF file.

Working of Transistor (BJT)



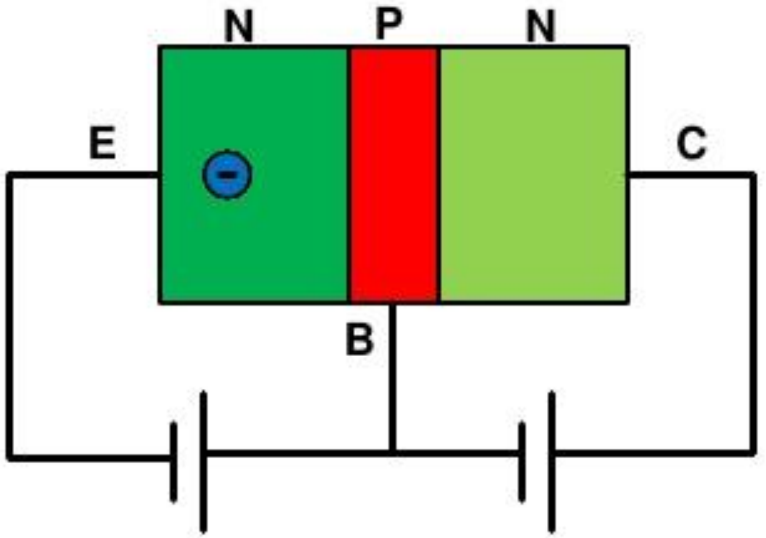
As can be seen when a control voltage is provided to the base pin, the required base current (I_B) flows into the base pin which is controlled by a base resistor.

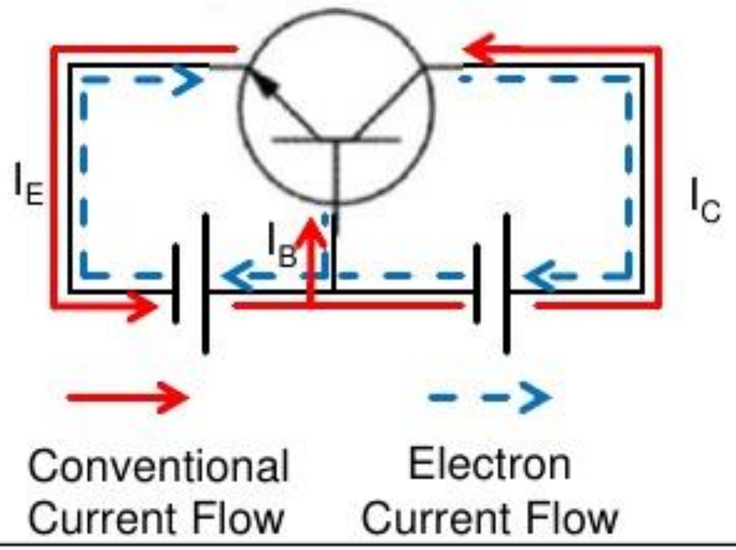
This current turns on the transistor (switch is closed) and allows the current to flow from collector to emitter.

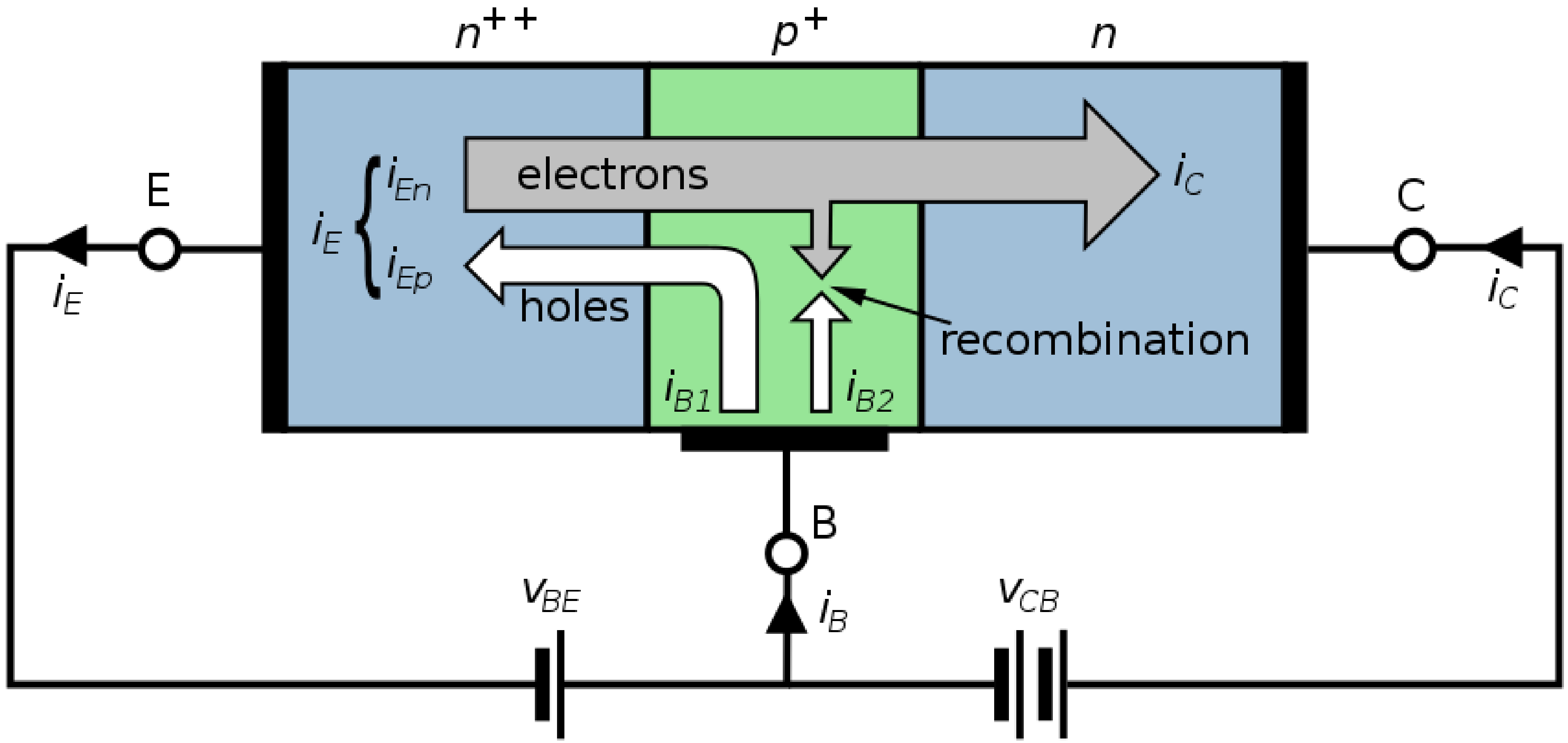
This current is called the collector current (I_C) and the voltage across the collector and emitter is called V_{BE}.

Steady-State Operation

- With the Base to Emitter Junction forward biased, majority current carriers flow from emitter to base, where they become minority carriers
  - This is emitter current (I_E)
- Since the base is thin and lightly doped, very few current carriers recombine in the base
  - This is base current (I_B)
- The rest of the current carriers are swept across the base to collector

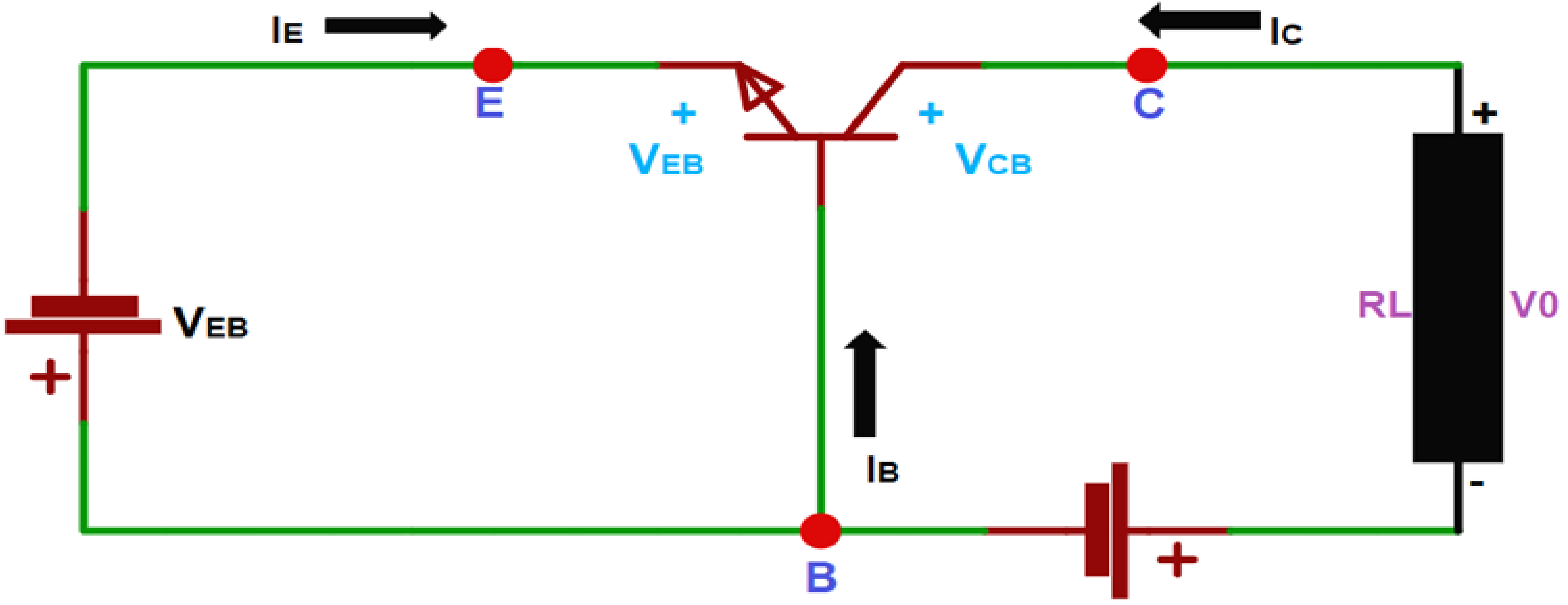






n++
p+
n
electrons
holes
recombination
E
C
B
iE
iEn
iEp
iC
iB1
iB2
iB
vBE
vCB

- ✓ Now for the theory, consider an NPN transistor, the BE junction is **forward biased** and the CB junction is **reverse biased**.
- ✓ The width of the depletion region at the Junction CB is higher when compared with the depletion region of the Junction BE.
- ✓ When the BE junction is forward biased it decreases the barrier potential, hence the electrons start flowing from the emitter to the base.
- ✓ The base region is very thin and it is lightly doped when compared with other regions, hence it consists of a very small number of holes, the electrons that are flowing from the emitter will recombine with the holes present in the base region and start to flow out of the base region in the form of the base current.
- ✓ A large number of electrons that are left will move across the reverse bias collector junction in the form of the collector current.



Based on the **Kirchoff's Current Law**, we can frame the current equation as

$$\mathbf{I_E = I_B + I_C}$$

Where, I_E, I_B, and I_C are the emitter, base, and collector current respectively. Here the base current will be very small when compared with emitter and collector current, therefore, $\mathbf{I_E \sim I_C}$

Similarly, the PNP Transistor, operates in the same way as the NPN transistor, but in NPN transistors the majority charge carriers are holes (Positively charged particle) but in the NPN transistor the charge carriers are the electrons (negatively charged particle).

Bipolar Junction Transistors

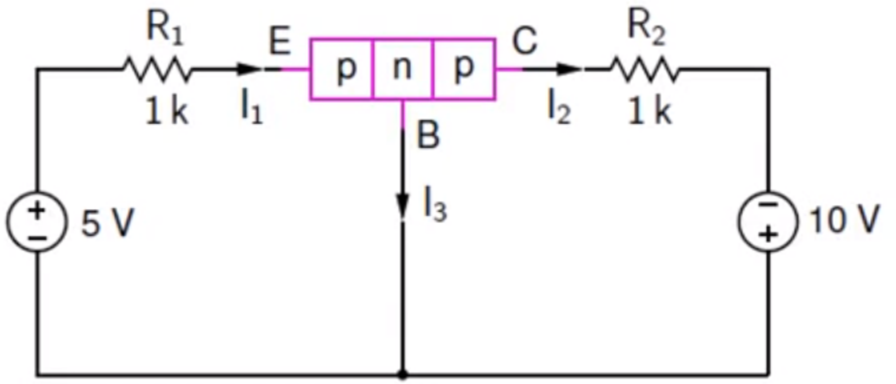
- Bipolar: both electrons and holes contribute to conduction
- Junction: device includes two *p*-*n* junctions (as opposed to a "point-contact" transistor, the first transistor)
- Transistor: "transfer resistor"

  When Bell Labs had an informal contest to name their new invention, one engineer pointed out that it acts like a resistor, but a resistor where the voltage is transferred across the device to control the resulting current.

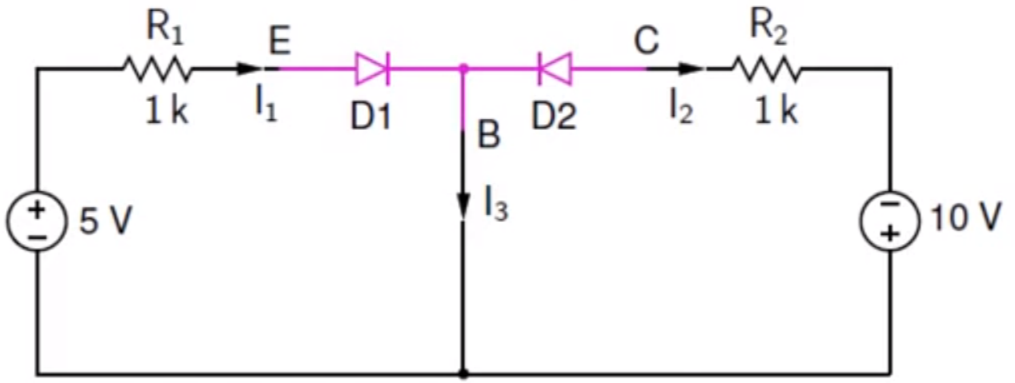
  (http://amasci.com/amateur/trshort.html)
- invented in 1947 by Shockley, Bardeen, and Brattain at Bell Laboratories.
- BJT is still used extensively, and anyone interested in electronics must have at least a working knowledge of this device.
- "A BJT is two diodes connected back-to-back."
  WRONG! Let us see why.

Bipolar Junction Transistors

Consider a *pnp* BJT in the following circuit:



If the transistor is replaced with two diodes connected back-to-back, we get



Assuming $V_{on} = 0.7\ V$ for D1, we get

$I_1 = \dfrac{5\ V - 0.7\ V}{R_1} = 4.3\ mA$,

$I_2 = 0$ (since D2 is reverse biased), and $I_3 \approx I_1 = 4.3\ mA$.

Bipolar Junction Transistors

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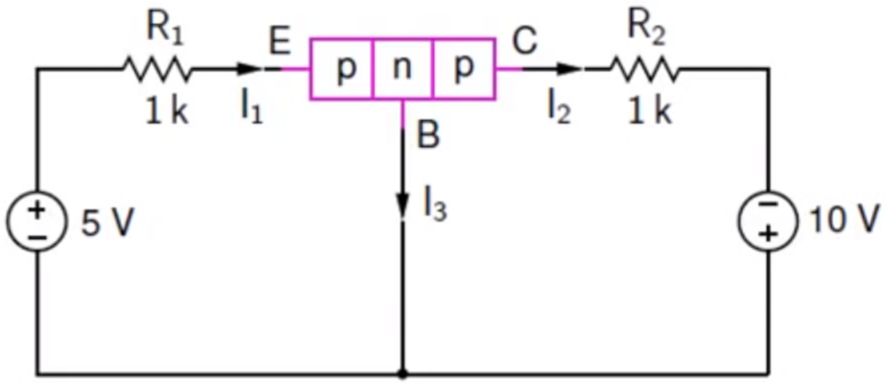

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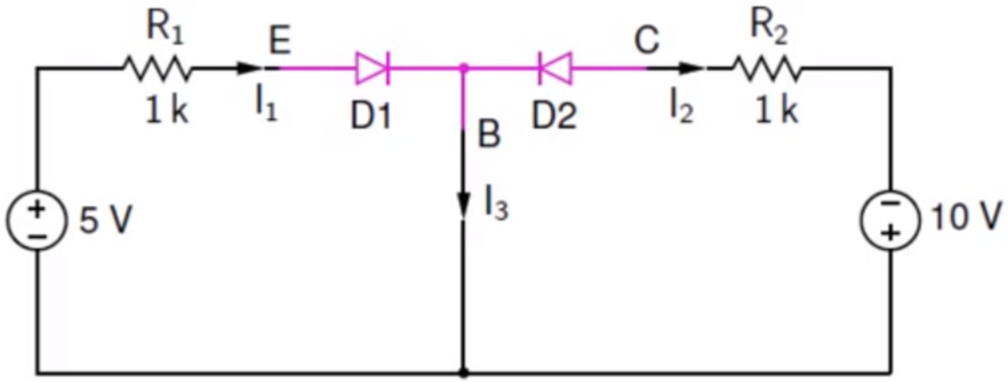

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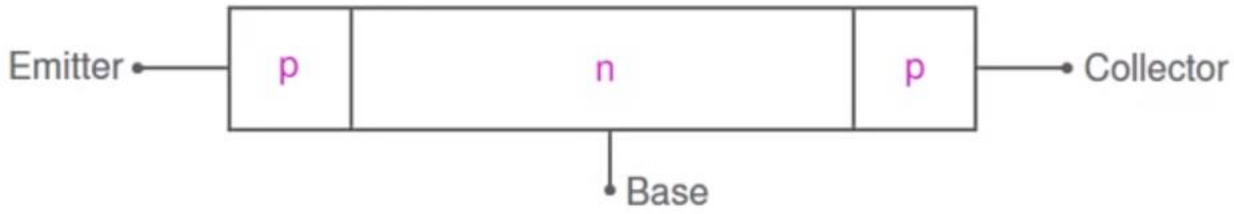
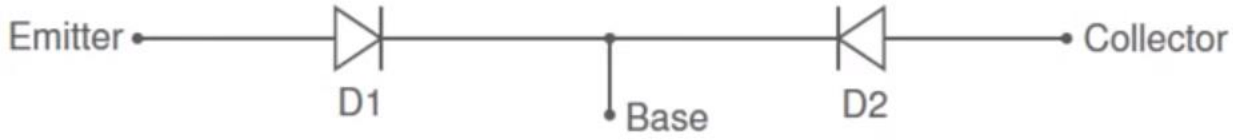
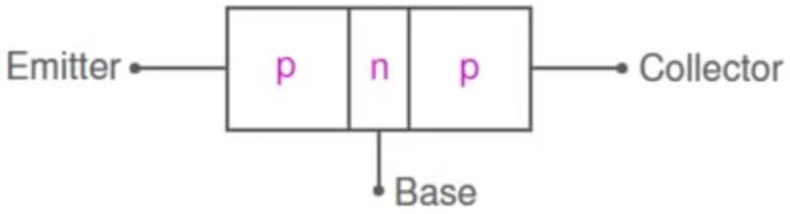
What is wrong with the two-diode model of a BJT?

* When we replace a BJT with two diodes, we assume that there is no interaction between the two diodes, which may be expected if they are "far apart."

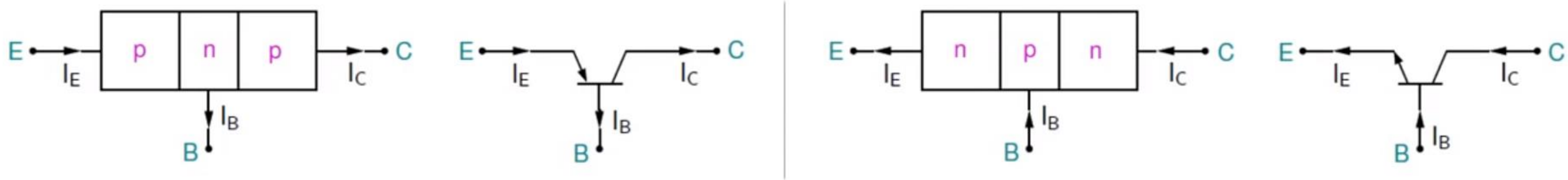




* However, in a BJT, exactly the opposite is true. For a higher performance, the base region is made as short as possible, and the two diodes cannot be treated as independent devices.

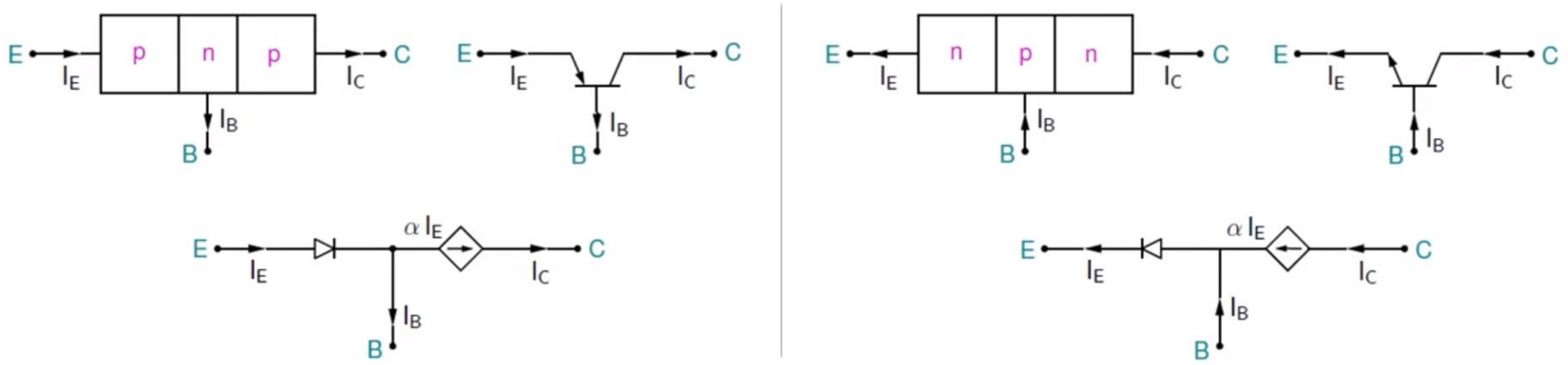


BJT in active mode



* In the active mode of a BJT, the B-E junction is under forward bias, and the B-C junction is under reverse bias.
  - For a *pnp* transistor, $V_{EB} > 0\ V$, and $V_{CB} < 0\ V$.
  - For an *npn* transistor, $V_{BE} > 0\ V$, and $V_{BC} < 0\ V$.
* Since the B-E junction is under forward bias, the voltage (magnitude) is typically 0.6 to 0.75 V.
* The B-C voltage can be several Volts (or even hundreds of Volts), and is limited by the breakdown voltage of the B-C junction.
* The symbol for a BJT includes an arrow for the emitter terminal, its direction indicating the current direction when the transistor is in active mode.
* Analog circuits, including amplifiers, are generally designed to ensure that the BJTs are operating in the active mode.

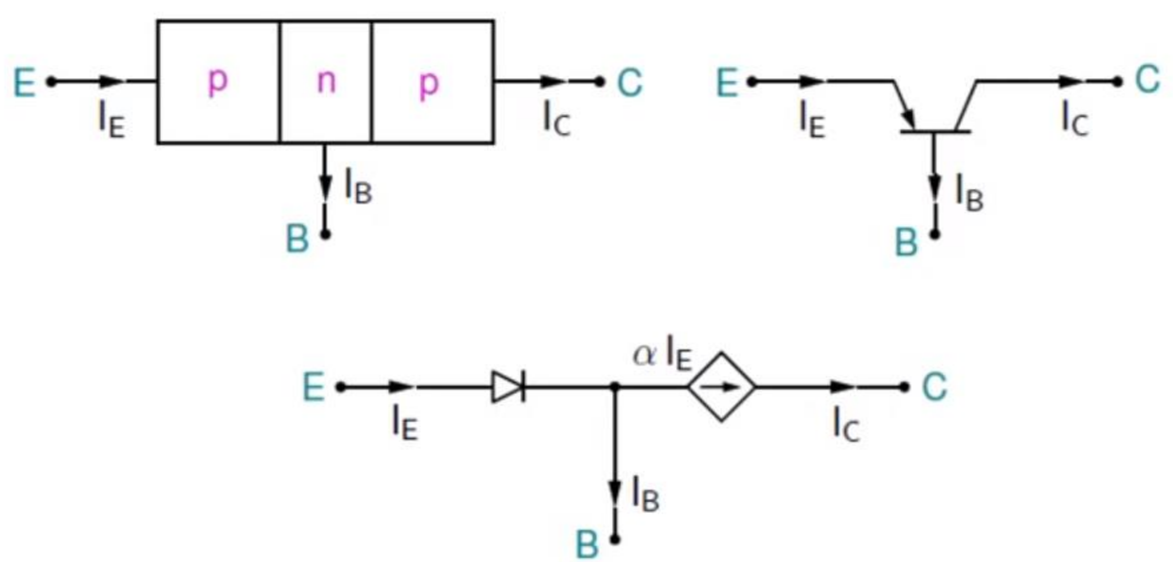
BJT in active mode

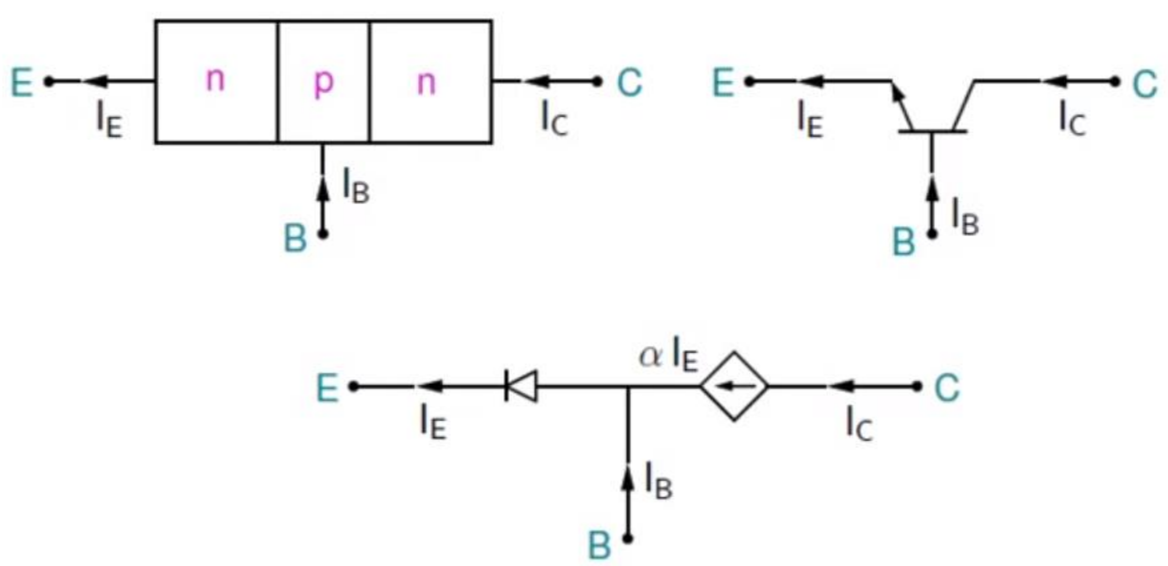


* In the active mode, $I_C = \alpha\, I_E$, $\alpha \approx 1$ (slightly less than 1).
* $I_B = I_E - I_C = I_E\,(1-\alpha)$.
* The ratio I_C/I_B is defined as the current gain β of the transistor.

  $$\beta = \frac{I_C}{I_B} = \frac{\alpha}{1-\alpha}\,.$$
* β is a function of I_C and temperature. However, we will generally treat it as a constant, a useful approximation to simplify things and still get a good insight.

BJT in active mode



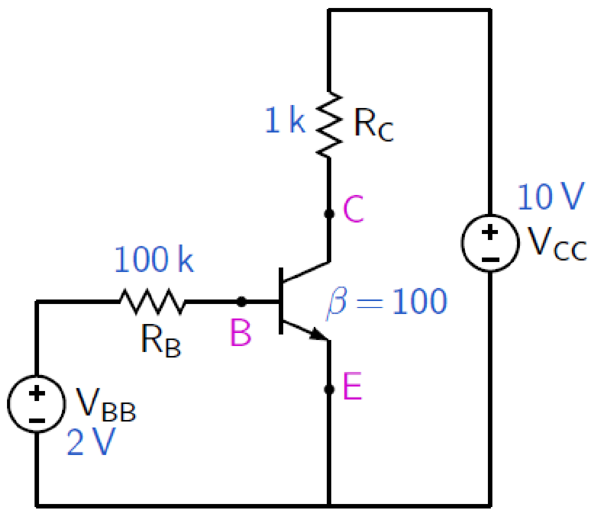


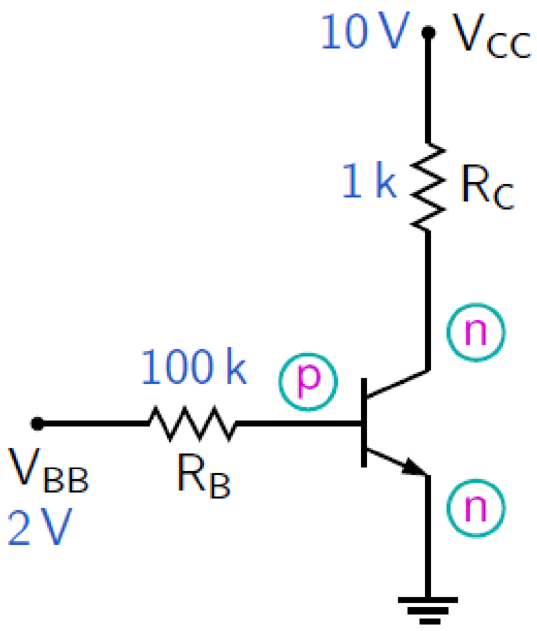
$$\beta = \frac{I_C}{I_B} = \frac{\alpha}{1-\alpha}$$

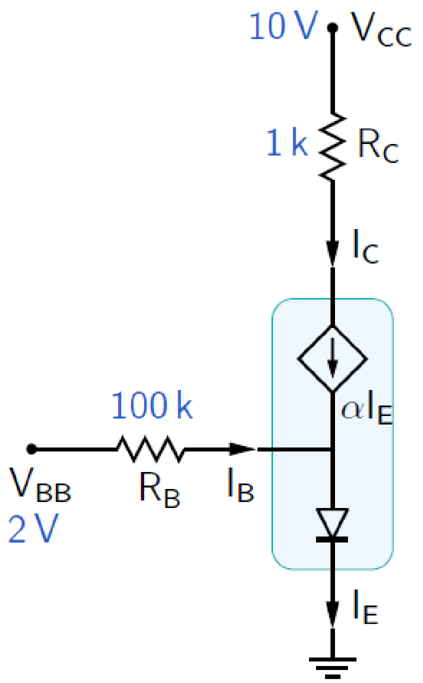
α	β
0.9	9
0.95	19
0.99	99
0.995	199

* β increases substantially as $\alpha \to 1$.
* Transistors are generally designed to get a high value of β (typically 100 to 250, but can be as high as 2000 for "super-β" transistors).
* A large $\beta \Rightarrow I_B \ll I_C$ or I_E when the transistor is in the active mode.

A simple BJT circuit







Assume the BJT to be in the active mode : **V_{BE} = 07 V and $I_C = \alpha I_E = \beta\ I_B$.**

$$I_B = \frac{V_{BB} - V_{BE}}{R_B} = \frac{2\ V - 0.7\ V}{100\ \text{k}} = 13\ \mu A.$$

$$I_C = \beta \times I_B = 100 \times 13\,\mu A = 1.3\,\text{m}A.$$

$$V_C = V_{CC} - I_C R_C = 10\ V - 1.3\,\text{m}A \times 1\,\text{k} = 8.7\ V.$$

Let us check whether our assumption of active mode is correct. We need to check whether the B-C junction is under reverse bias.

$$V_{BC} = V_B - V_C = 0.7\ V - 8.7\ V = -8.0\ V\ ,$$

i.e., the B-C junction is indeed under reverse bias.

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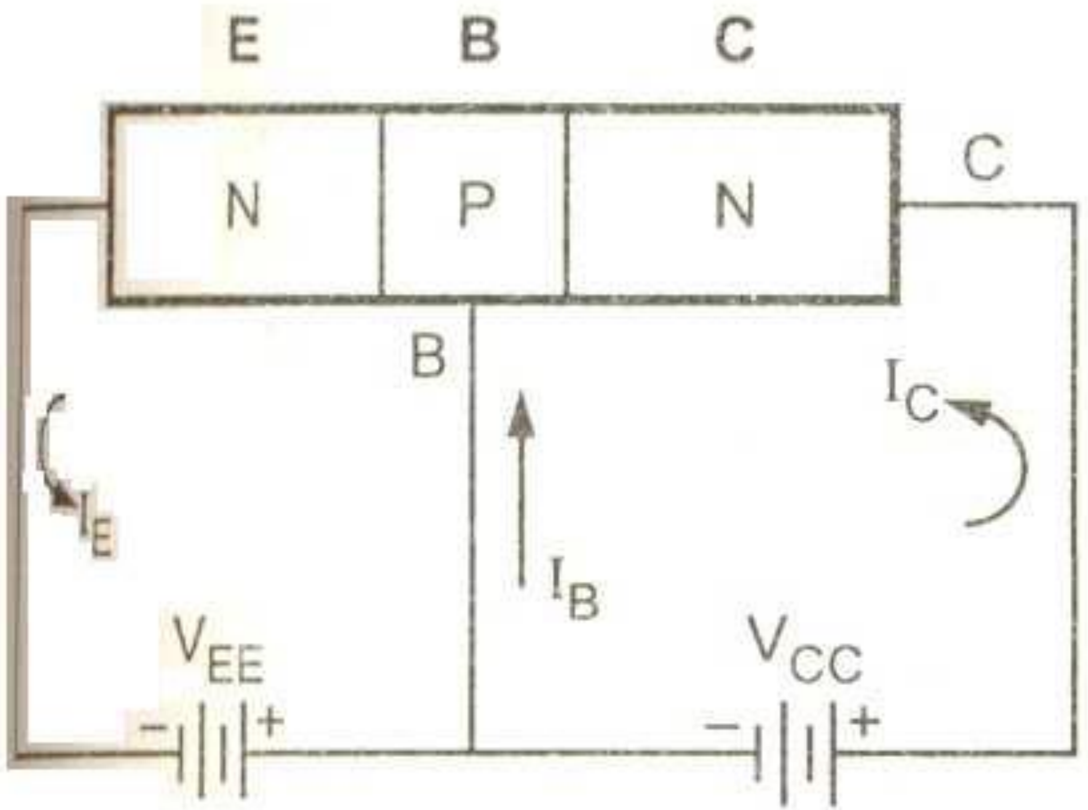


E
B
C
N
P
N
C
B
I_C
I_E
I_B
V_{EE}
V_{CC}
−
+
−
+

Table of Contents

Different Configurations of Transistors

There are three different configurations of Transistors possible with BJTs.

As we know that generally the transistor has three terminals – emitter (E), base (B) and collector. But in the circuit connections we need four terminals, two terminals for input and another two terminals for output. To overcome these problems we use one terminal as common for both input and output actions.

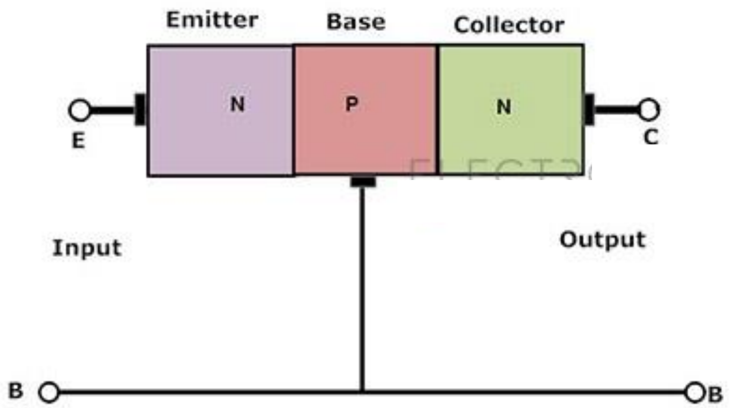
Using this property we construct the circuits and these structures are called transistor configurations.
Generally there are three different configurations of transistors and they are :
common base (CB) configuration,
common emitter (CE) configuration
common collector (CC) configuration and

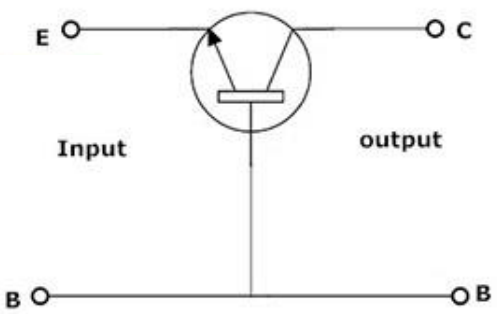
The behaviour of these three different configurations of transistors with respect to gain is given below.

- ✓ **Common Base (CB) Configuration**: no current gain but voltage gain
- ✓ **Common Collector (CC) Configuration**: current gain but no voltage gain
- ✓ **Common Emitter (CE) Configuration**: current gain and voltage gain

Now we discuss about these three different configurations of transistors with their input and output characteristics

Common Base Configuration

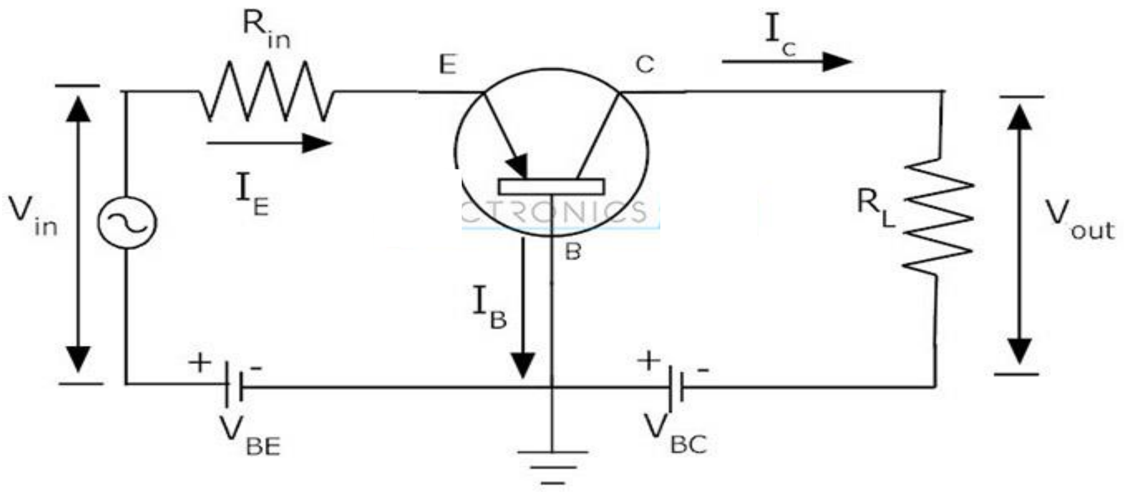


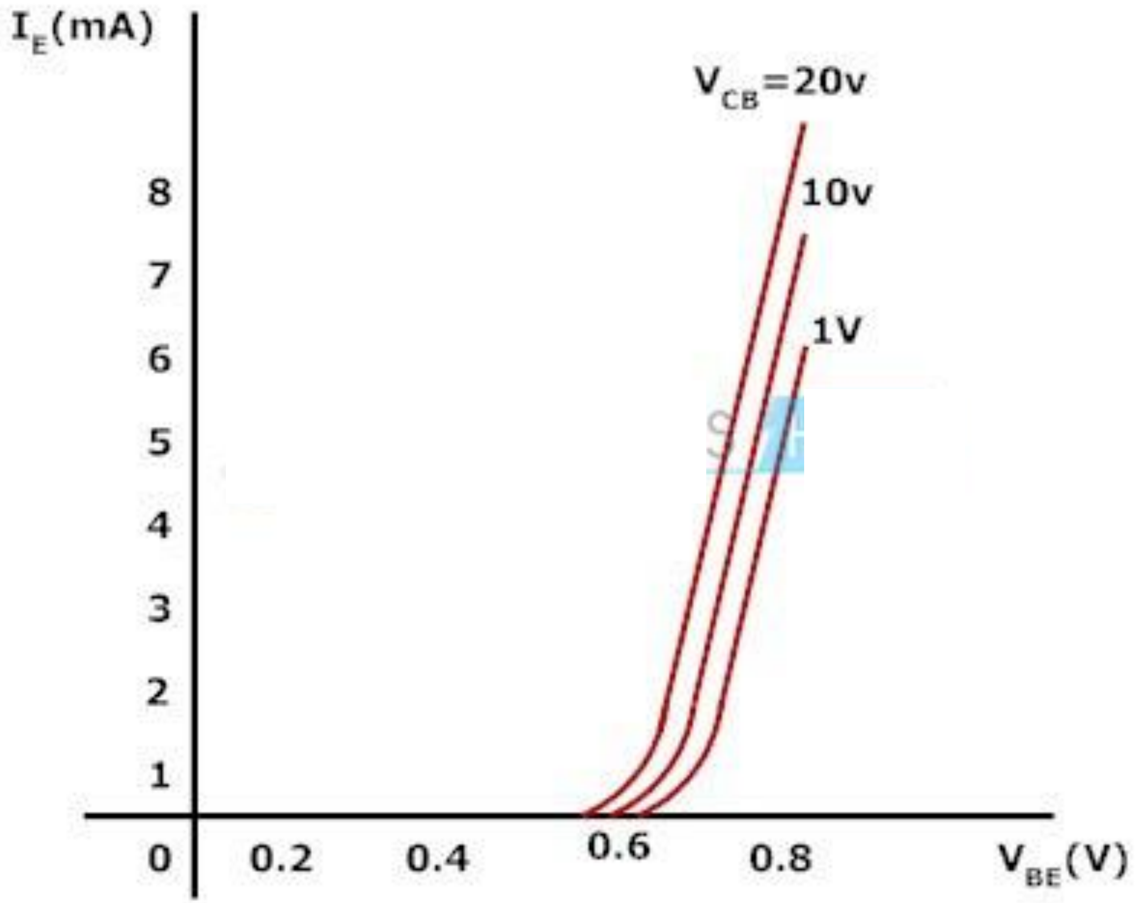


- ✓ In this configuration we use base as common terminal for both input and output signals.
- ✓ The configuration name itself indicates the common terminal.
- ✓ Here the input is applied between the base and emitter terminals and the corresponding output signal is taken between the base and collector terminals with the base terminal grounded.
- ✓ Here the input parameters are V_{EB} and I_E and the output parameters are V_{CB} and I_C.
- ✓ The input current flowing into the emitter terminal must be higher than the base current and collector current to operate the transistor, therefore the output collector current is less than the input emitter current.
- ✓ The current gain is generally equal or less than to unity for this type of configuration.
- ✓ Current gain in common base configuration is given as
- ✓ α = Output current/Input current
- ✓ $\alpha = I_C/I_E$

Input Characteristics

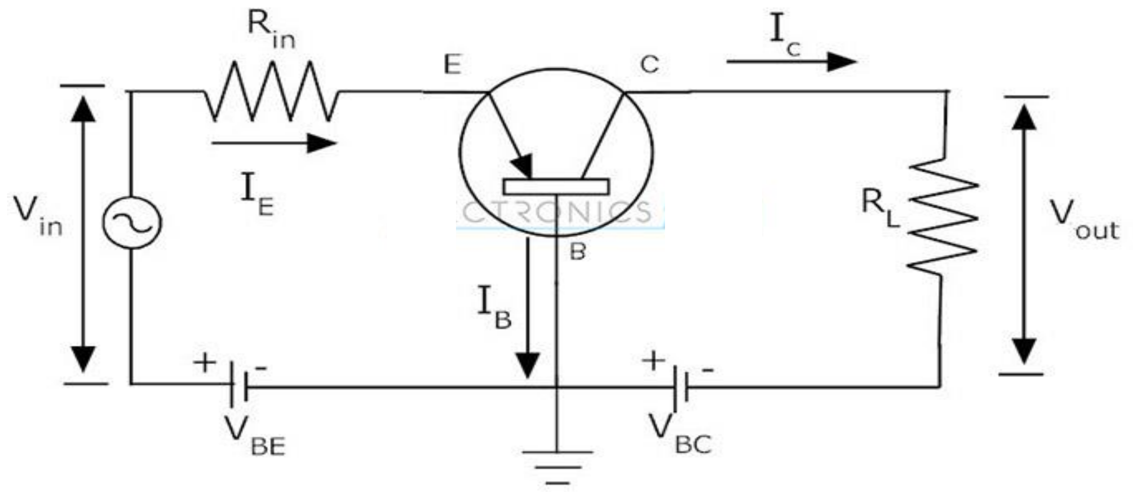
- ✓ Input characteristics are obtained between input current and input voltage with constant output voltage.
- ✓ First keep the output voltage V_{CB} constant and vary the input voltage V_{EB} for different points then at each point record the input current I_E value.
- ✓ Repeat the same process at different output voltage levels.
- ✓ Now with these values we need to plot the graph between I_E and V_{EB} parameters.
- ✓ The figure show the input characteristics of common base configuration.
- ✓ The equation to calculate the input resistance R_{in} value is given below.
- ✓ $R_{in} = V_{EB} / I_E$ (when V_{CB} is constant)

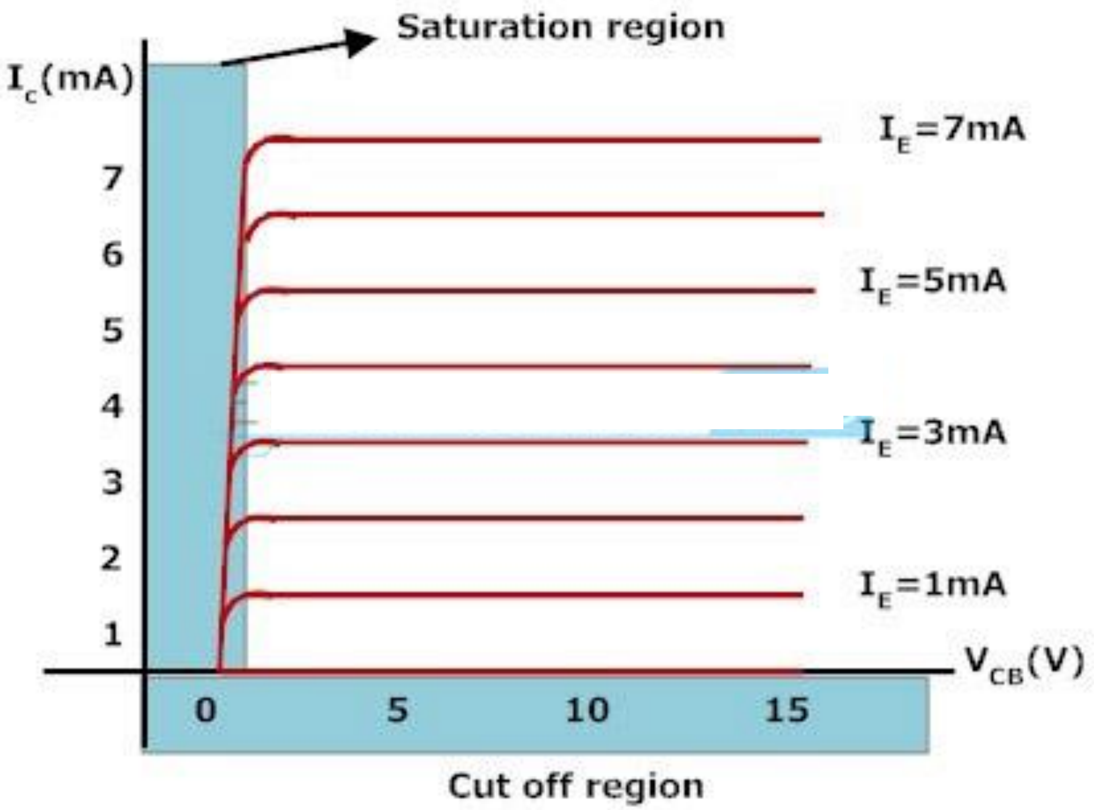




Output Characteristics

- ✓ The output characteristics of common base configuration are obtained between output current and output voltage with constant input current.
- ✓ First keep the emitter current constant and vary the V_{CB} value for different points, now record the I_C values at each point.
- ✓ Repeat the same process at different I_E values.
- ✓ Finally we need to draw the plot between V_{CB} and I_C at constant $I_{E.}$
- ✓ The below figure show the output characteristics of common base configuration. The equation to calculate the output resistance value is given below.
  - ✓ $R_{out} = V_{CB} / I_C$ (when I_E is constant)





- ✓ The current gain is generally equal or less than to unity for this type of configuration.
- ✓ The input and output signals are in-phase in this configuration.
- ✓ The amplifier circuit configuration of this type is called as non-inverting amplifier circuit.
- ✓ This transistor configuration has high output impedance and low input impedance.
- ✓ The voltage gain for this configuration of circuit is given below.
- ✓ $A_V = V_{out}/V_{in} = (I_C*R_L) / (I_E*R_{in})$
- ✓ Current gain in common base configuration is given as
- ✓ α = Output current/Input current
- ✓ $\alpha = I_C/I_E$

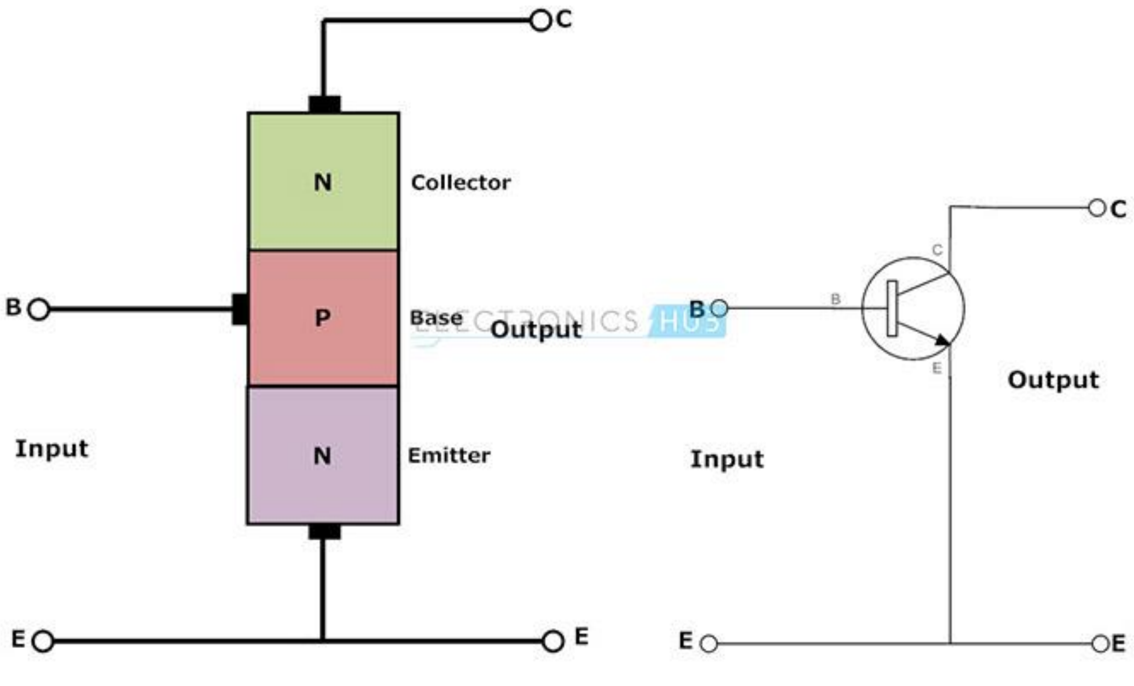
Common Emitter Configuration

- ✓ In this configuration we use emitter as common terminal for both input and output.

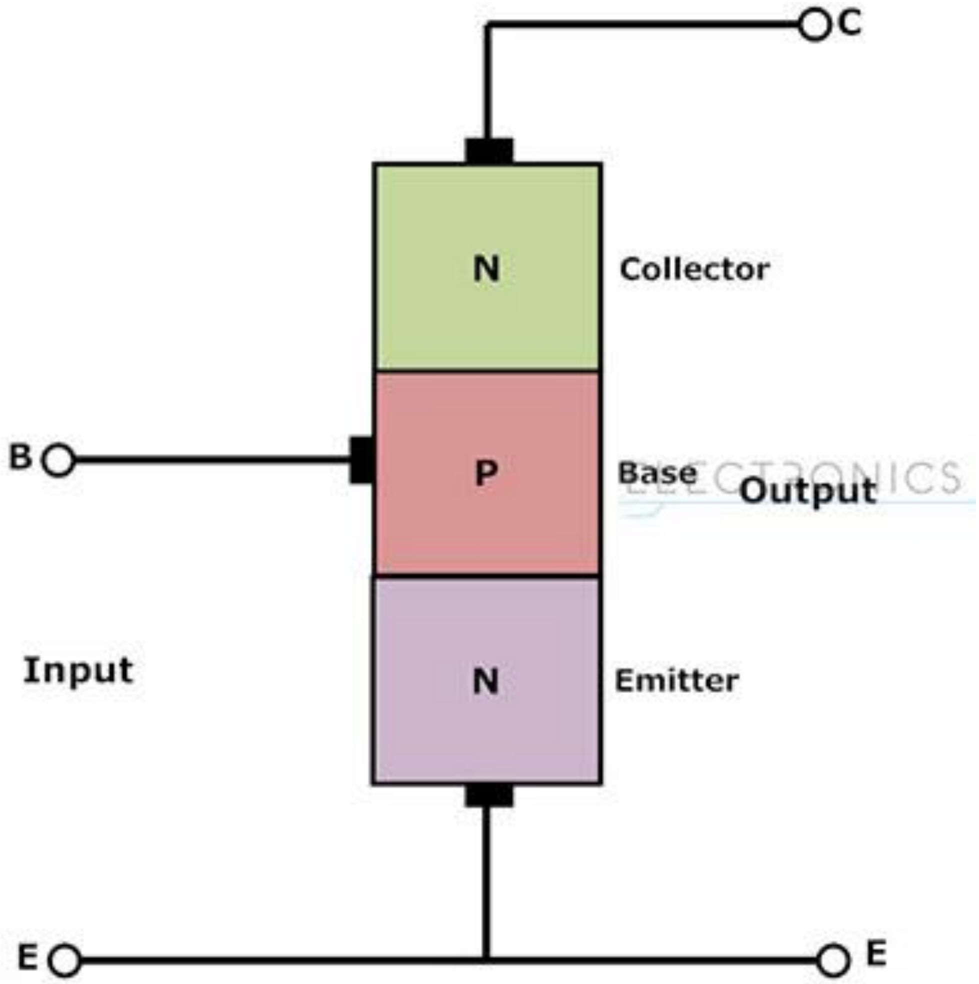
- ✓ Here the input is applied between base-emitter region and the output is taken between collector and emitter terminals.

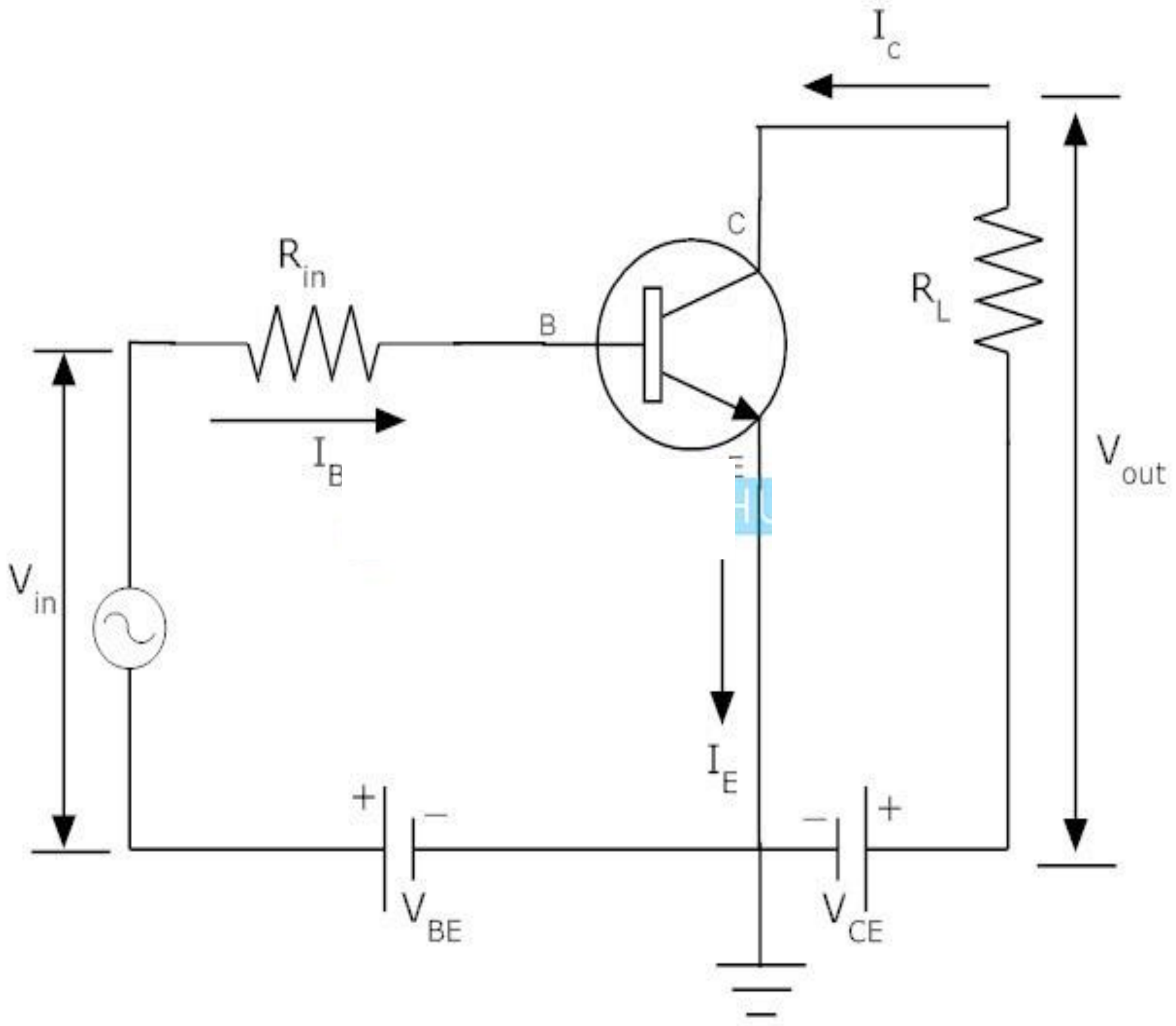
- ✓ In this configuration the input parameters are V_{BE} and I_B and the output parameters are V_{CE} and I_C.

- ✓ We know that the ratio between collector current and emitter current gives current gain alpha in Common Base configuration similarly the ratio between collector current and base current gives the current gain beta in common emitter configuration.
- ✓ Current gain (α) = I_C/I_E
- ✓ Current gain (β) = I_C/I_B
- ✓ Collector current $I_C = \alpha I_E = \beta I_B$



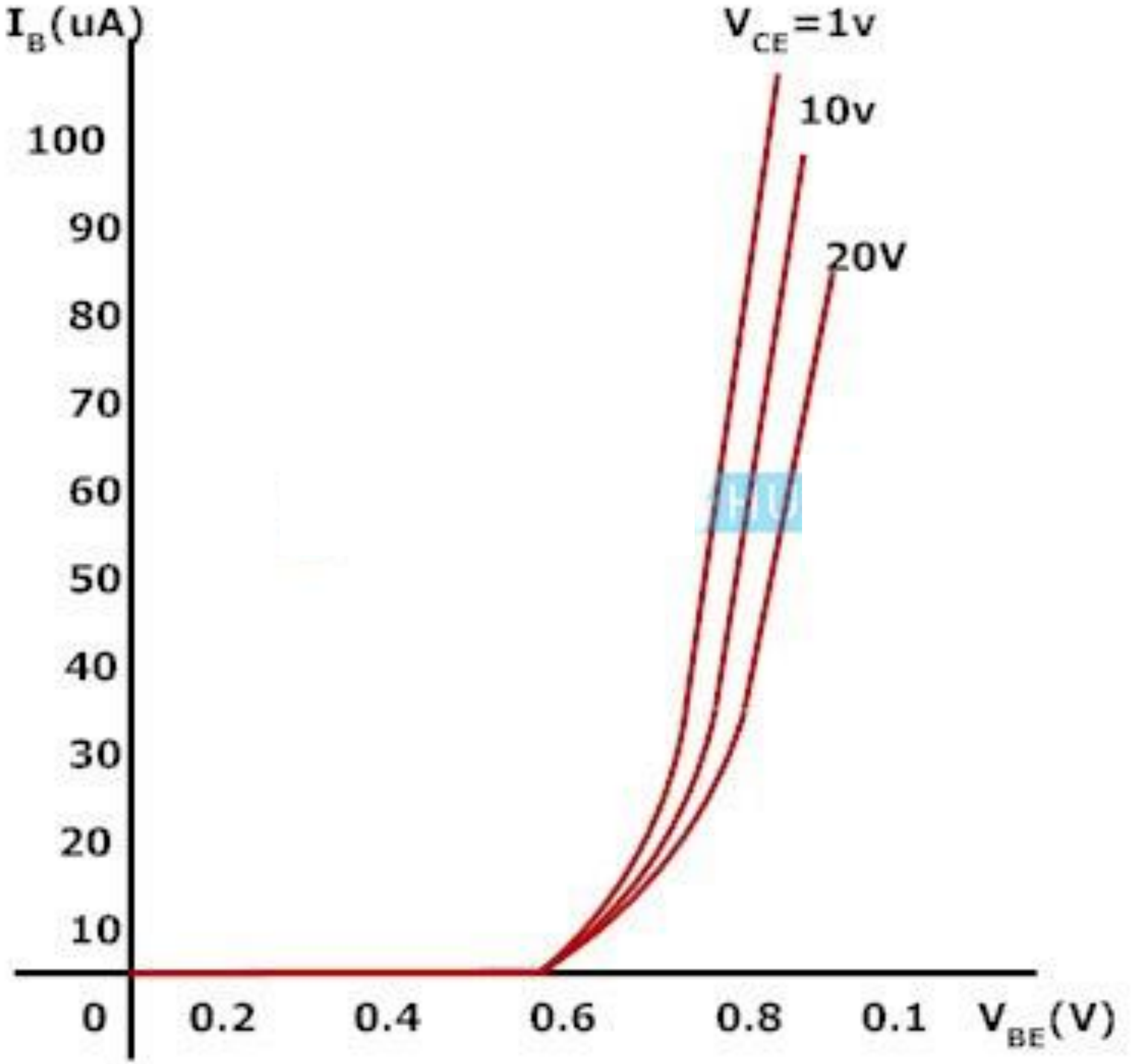
Common Emitter Configuration





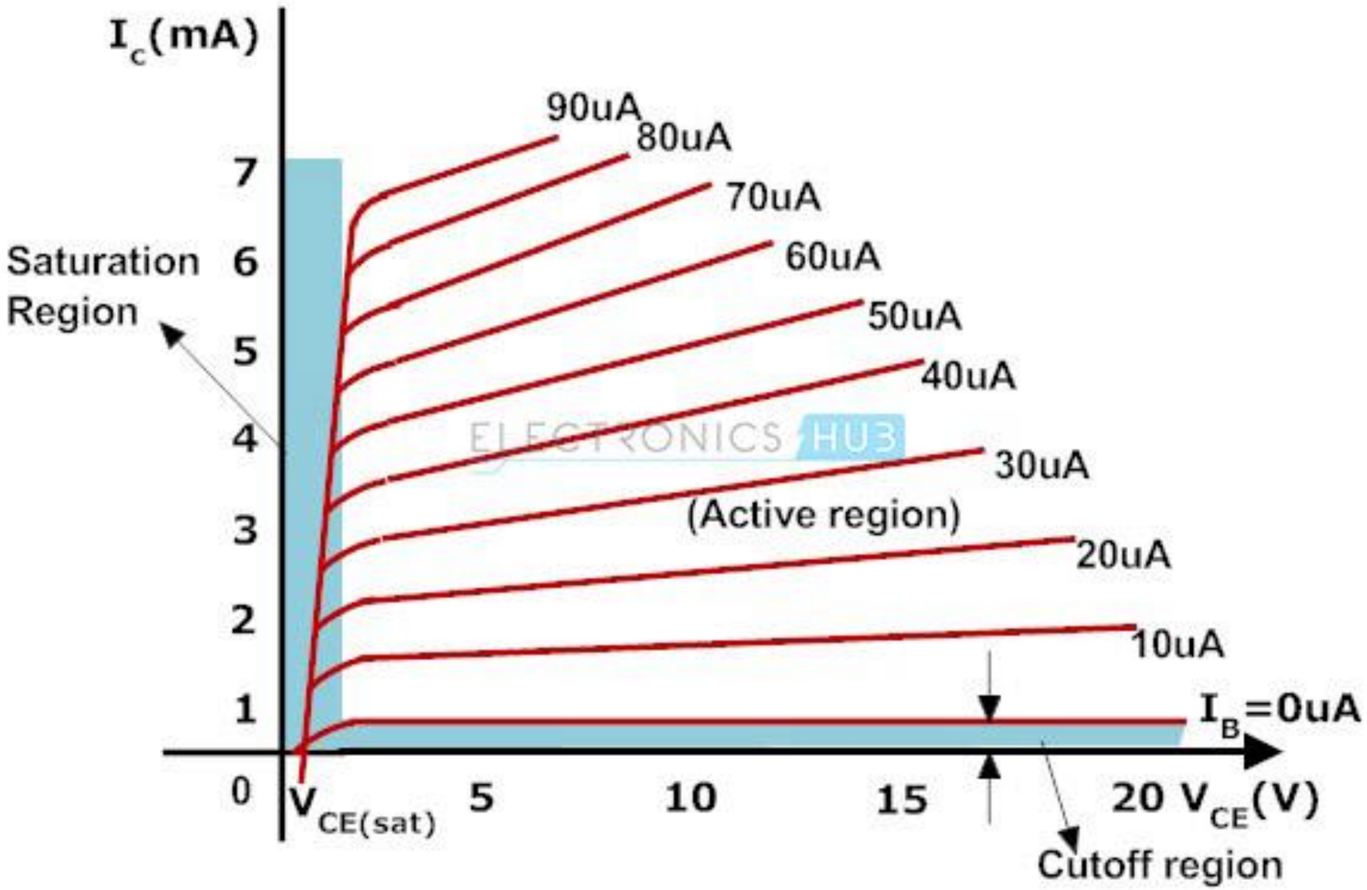
Input Characteristics

- ✓ The input characteristics of common emitter configuration are obtained between input current I_B and input voltage V_{BE} with constant output voltage V_{CE}.
- ✓ Keep the output voltage V_{CE} constant and vary the input voltage V_{BE} for different points,
- ✓ then record the values of input current at each point.
- ✓ Now using these values we need to draw a graph between the values of I_B and V_{BE} at constant V_{CE}.
- ✓ The equation to calculate the input resistance R_{in} is given as:
- ✓ $R_{in} = V_{BE}/I_B$ (when V_{CE} is constant)



Output Characteristics

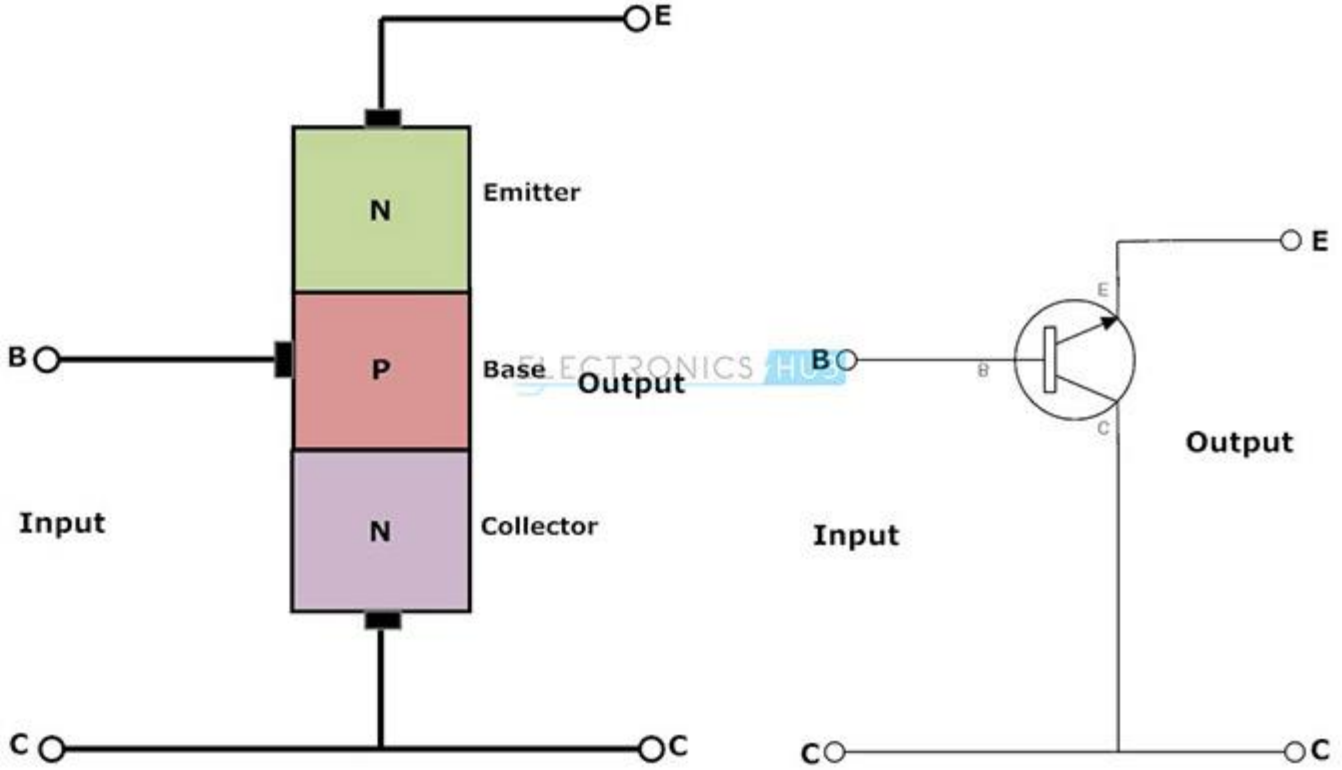
- ✓ The output characteristics of common emitter configuration are obtained between the output current I_C and output voltage V_{CE} with constant input current I_B.
- ✓ Keep the base current I_B constant and vary the value of output voltage V_{CE} for different points, now note down the value of collector I_C for each point.
- ✓ Plot the graph between the parameters I_C and V_{CE} in order to get the output characteristics of common emitter configuration.
- ✓ The equation to calculate the output resistance from this graph is given below.
- ✓ R = V /I (when I is at



It also has the medium current and voltage gains.

But the output signal has a phase shift of 180 i.e. the input and output are inverse to each other.

Common Collector Configuration

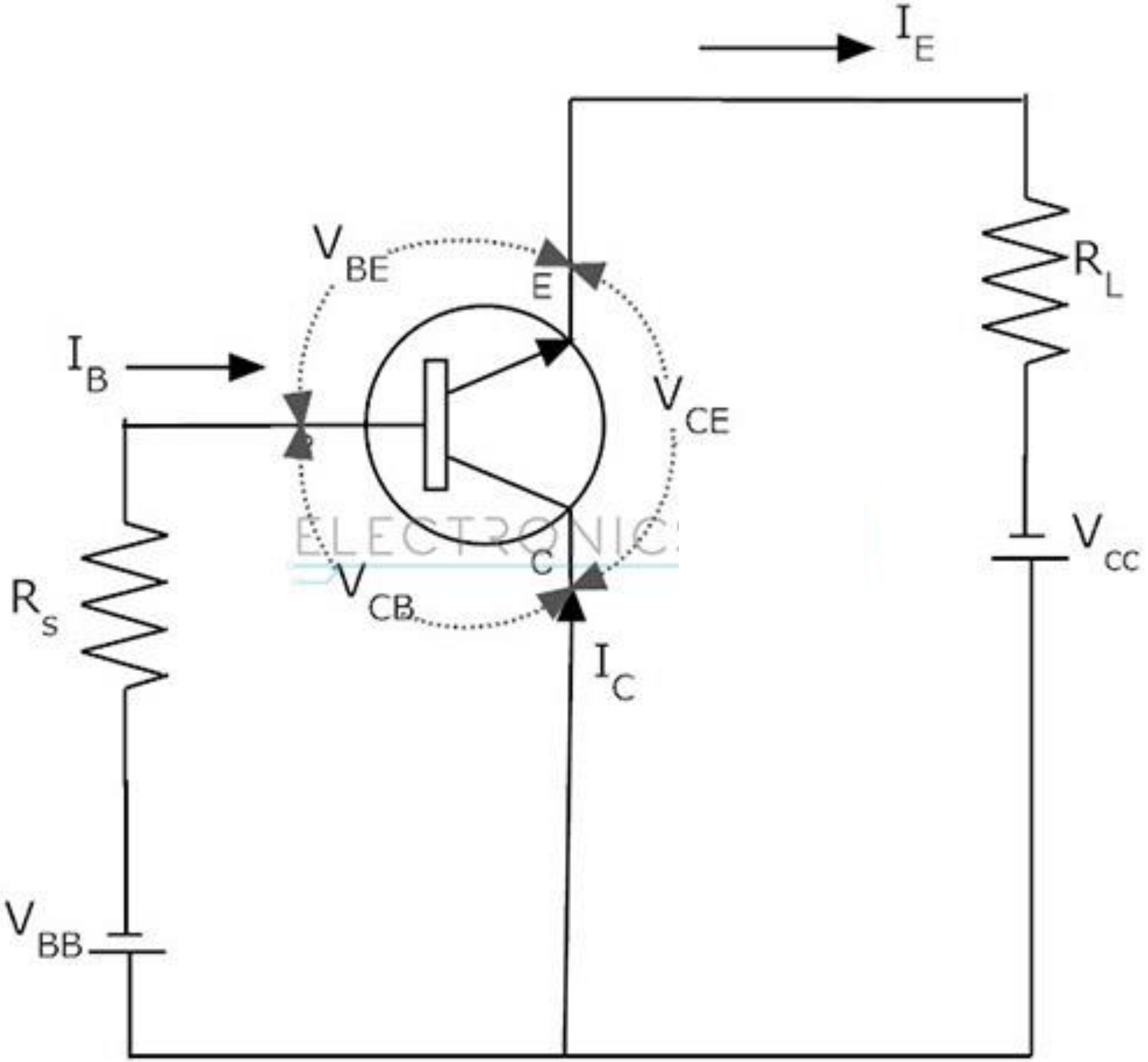


- ✓ In this configuration we use collector terminal as common for both input and output signals.
- ✓ This configuration is also known as emitter follower configuration because the emitter voltage follows the base voltage. This configuration is mostly used as a buffer.
- ✓ These configurations are widely used in impedance matching applications because of their high input impedance. Here the input parameters are V_{BC} and I_B and the output parameters are V_{EC} and I_E.
- ✓ The common collector configuration has high input impedance and low output impedance.
- ✓ The input and output signals are in phase.

- In this configuration the input signal is applied between the base-collector region and the output is taken from the emitter-collector region.

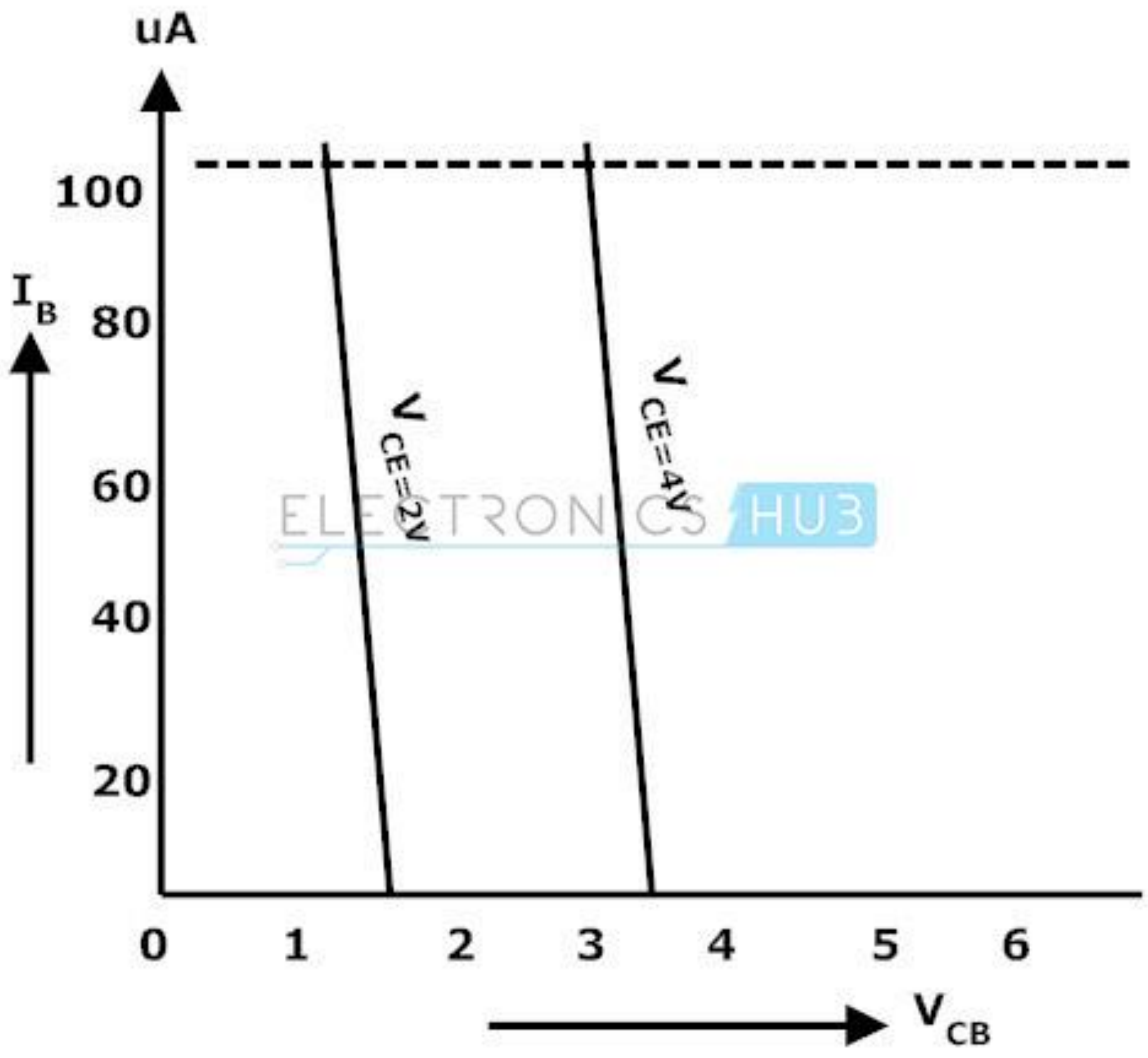
- Here the input parameters are V_{BC} and I_B ar
- the output parameters are V_{EC} and $_{IE}$.

- Current gain,
- A_i = output current/Input current
- $$A_i = I_E/I_B$$
- $$A_i = (I_C + I_B)/I_B$$
- $$A_i = (I_C/I_B) + 1$$
- $$A_i = \beta + 1$$
- The voltage gain for this circuit is
- less than unity
- but it has large current gain because
- the load resistor in this circuit receives both the
- collector and base currents.

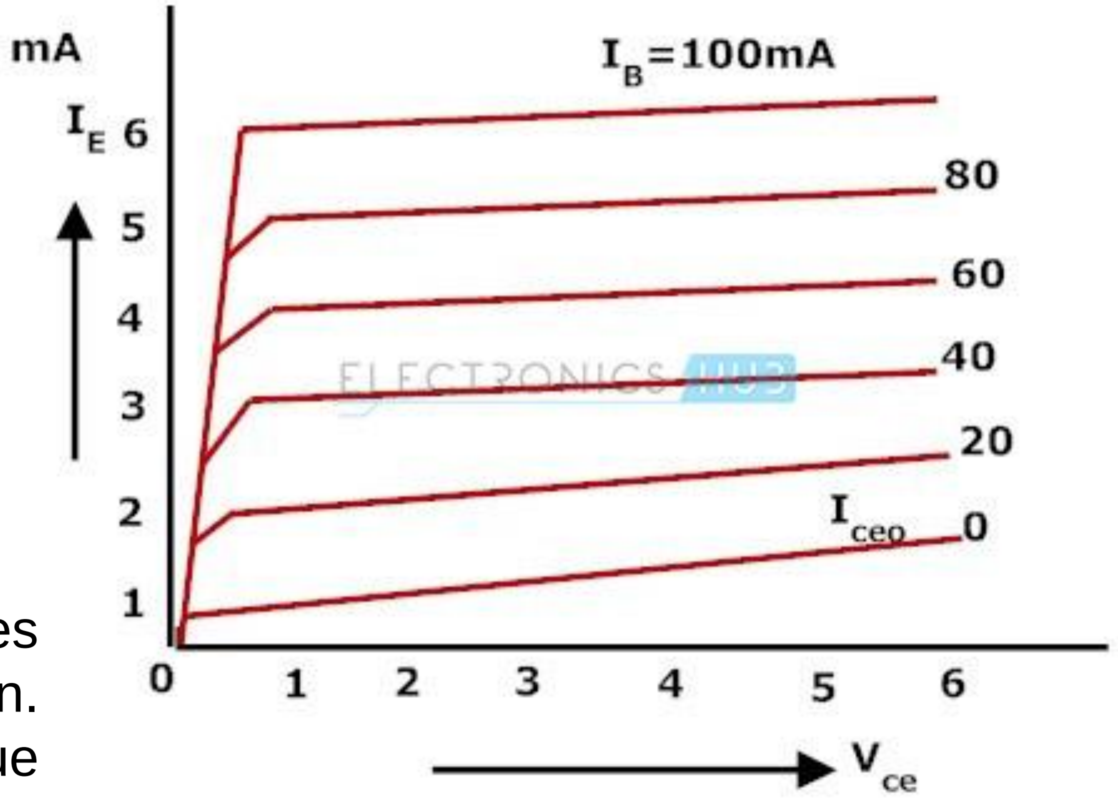


- ✓ The input characteristics of a common collector configuration are quite different from the common base and common emitter configurations because the input voltage V_{BC} is largely determined by V_{EC} level.

- ✓ The input characteristics of a common-collector configuration are obtained between inputs current I_B and the input voltage V_{CB} at constant output voltage V_{EC}. Keep the output voltage V_{EC} constant at different levels and vary the input voltage V_{BC} for different points and record the I_B values for each point. Now using these values we need to draw a graph between the parameters of V_{BC} and I_B at constant V_{EC}.



- ✓ The operation of the common collector circuit is same as that of common emitter circuit. The output characteristics of a common collector circuit are obtained between the output voltage V_{EC} and output current I_E at constant input current I_B. In the operation of common collector circuit if the base current is zero then the emitter current also becomes zero. As a result no current flows through the transistor



- ✓ If the base current increases then the transistor operates in active region and finally reaches to saturation region. To plot the graph first we keep the I_B at constant value and we will vary the V_{EC} value for various points, now we need to record the value of I_E for each point. Repeat the same process for different I_B values. Now using these values we need to plot the graph between the parameters of I_E and V_{CE} at constant values of I_B. The below figure show the output characteristics of common collector.

Transistor Configuration Summary Table			
Transistor Configuration	**Common Base**	**Common Collector (Emitter Follower)**	**Common Emitter**
Voltage Gain	High	Low	Medium
Current Gain	Low	High	Medium
Power Gain	Low	Medium	High
Input / Output Phase Relationship	0°	0°	180°
Input Resistance	Low	High	Medium
Output Resistance	High	Low	Medium

Expression for Collector Current in Common Base Configuration Including Small Reverse Saturation Current

Total collector current. The total collector current consists of the following two parts :

(i) The current produced by normal transistor action *i.e.*, component controlled by emitter current. This is due to the majority carrier and its value is αI_E

(ii) The leakage current I_{leakage}. This current is due to the motion of minority carriers across base-collector junction on account of it being reverse-biased. This is much smaller than αI_E . The leakage current is abbreviated as I_{CBO} *i.e.*, collector-base current with emitter open. This is shown in fig. (9)

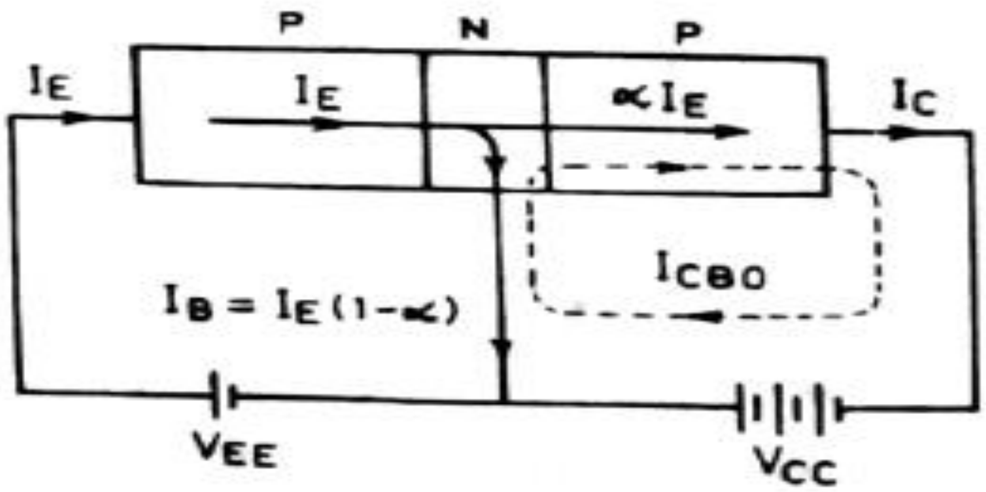


Fig. (9) Showing leakage current.

∴ Total collector current

$$I_C = \underbrace{\alpha I_E}_{\text{Majority}} + \underbrace{I_{CBO}}_{\text{Minority}} \qquad \ldots(4)$$

Expression for Collector Current in Common Base Configuration Including Small Reverse Saturation Current

The total collector current consists of :

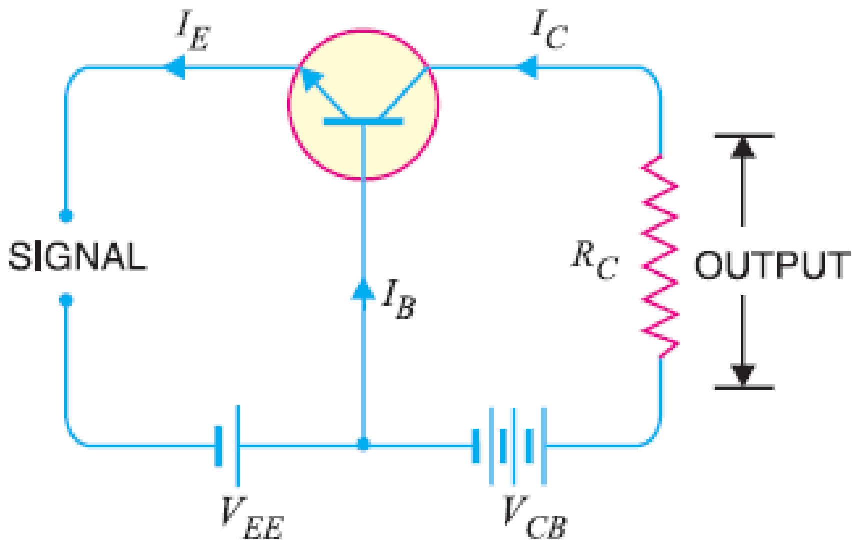
part of emitter current which reaches the collector terminal i.e. αI_E

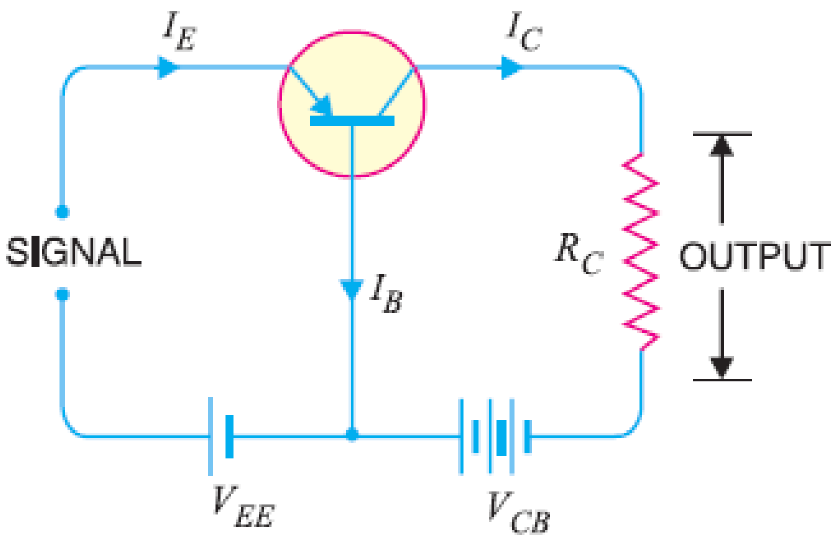
Leakage current $I_{leakage}$, due to the movement of minority carriers across the base-collector junction as it is reverse biased. This is much smaller than αI_E.

$$\text{Total collector current,} \quad I_C = \alpha I_E + I_{leakage}$$

When the emitter is open, i.e. $I_E = 0$, a small leakage current sill flows in the collector circuit.

This $I_{leakage}$ is abbreviated as I_{CBO} , i.e. collector-base current with emitter open.





Expression for Collector Current

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

When the emitter is open, i.e. $I_E = 0$, a small leakage current sill flows in the collector circuit.

This $I_{leakage}$ is abbreviated as I_{CBO} , i.e. collector-base current with emitter open.

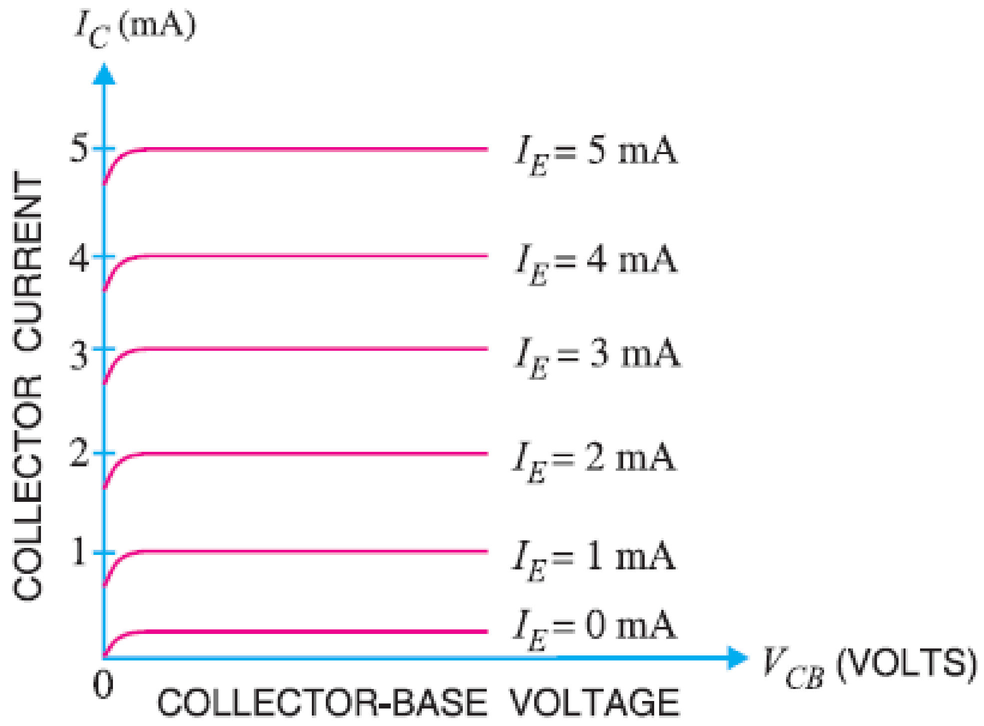
$$\therefore \quad I_C = \alpha I_E + I_{CBO}$$

$$\text{Now} \quad I_E = I_C + I_B$$

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

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

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



Hence, It is clear from these relations that the collector current of a transistor can be controlled by either the emitter or base current.

Expression for Collector Current in Common Emitter Configuration

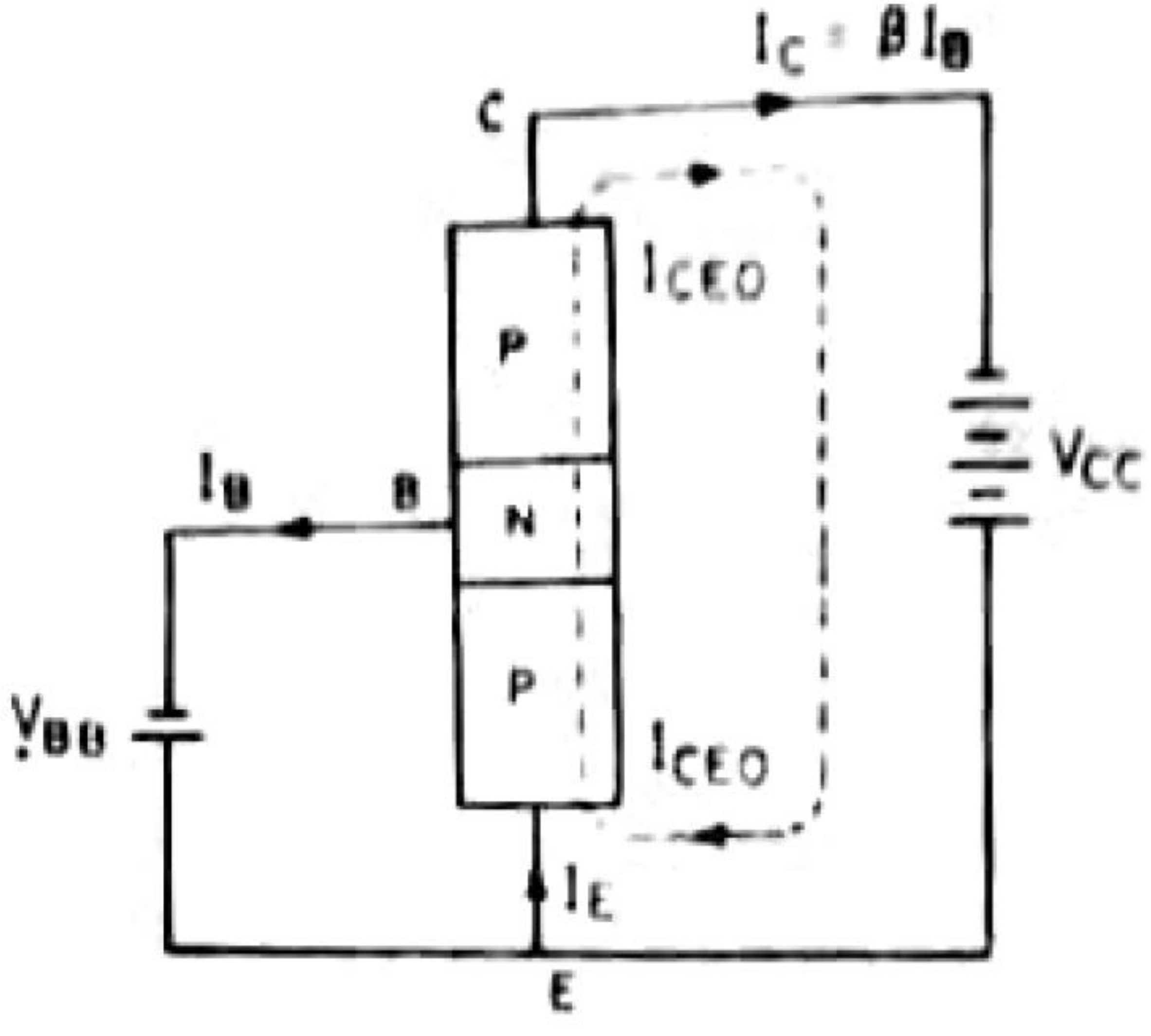
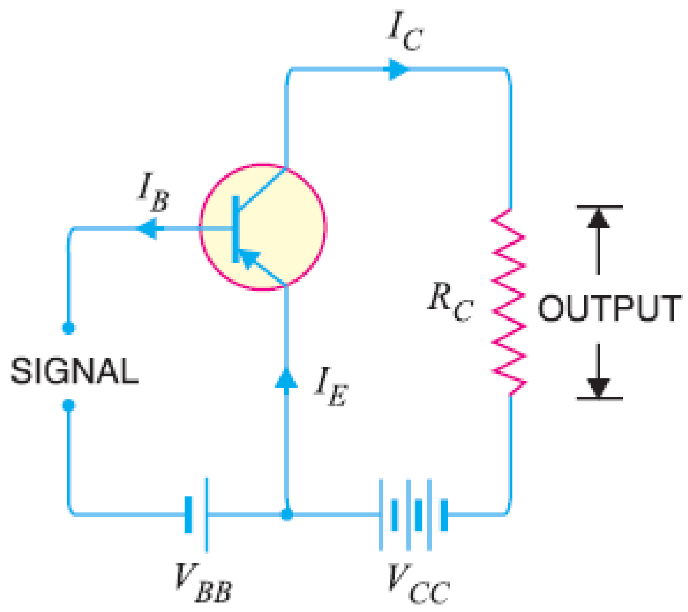
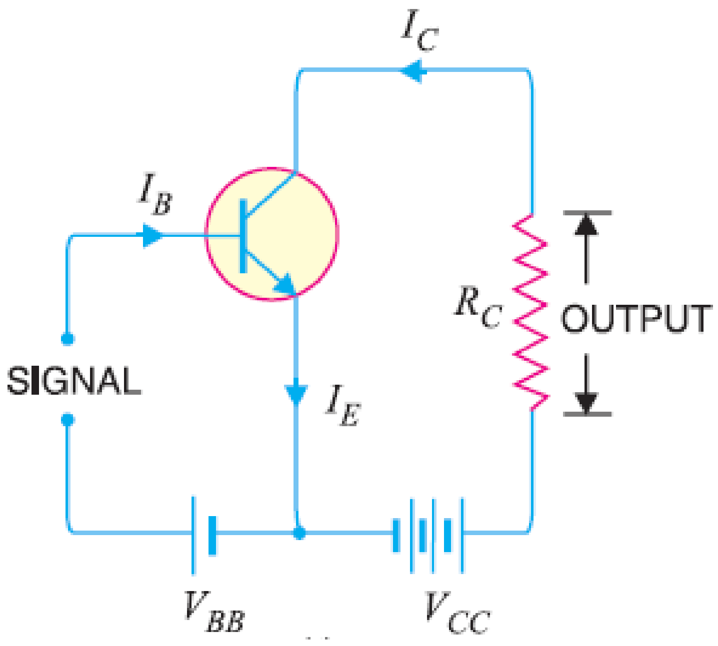


Fig. (11) Showing leakage current





Expression for Collector Current in Common Emitter Configuration

$$\text{We know } I_E = I_B + I_C \quad \ldots(i)$$

and
$$I_C = \alpha I_E + I_{CBO} \quad \ldots(ii)$$

From exp. (*ii*), we get,
$$I_C = \alpha I_E + I_{CBO} = \alpha(I_B + I_C) + I_{CBO}$$

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

or
$$I_C = \frac{\alpha}{1-\alpha} I_B + \frac{1}{1-\alpha} I_{CBO} \quad \ldots(iii)$$

From exp. (*iii*), it is apparent that if $I_B = 0$ (*i.e.* base circuit is open), the collector current will be the current to the emitter. This is abbreviated as I_{CEO}, meaning collector-emitter current with base open.

$$\therefore \quad I_{CEO} = \frac{1}{1-\alpha} I_{CBO}$$

Substituting the value of $\frac{1}{1-\alpha} I_{CBO} = I_{CEO}$ in exp. (*iii*), we get,

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

or
$$I_C = \beta I_B + I_{CEO} \qquad \left(\because \beta = \frac{\alpha}{1-\alpha}\right)$$

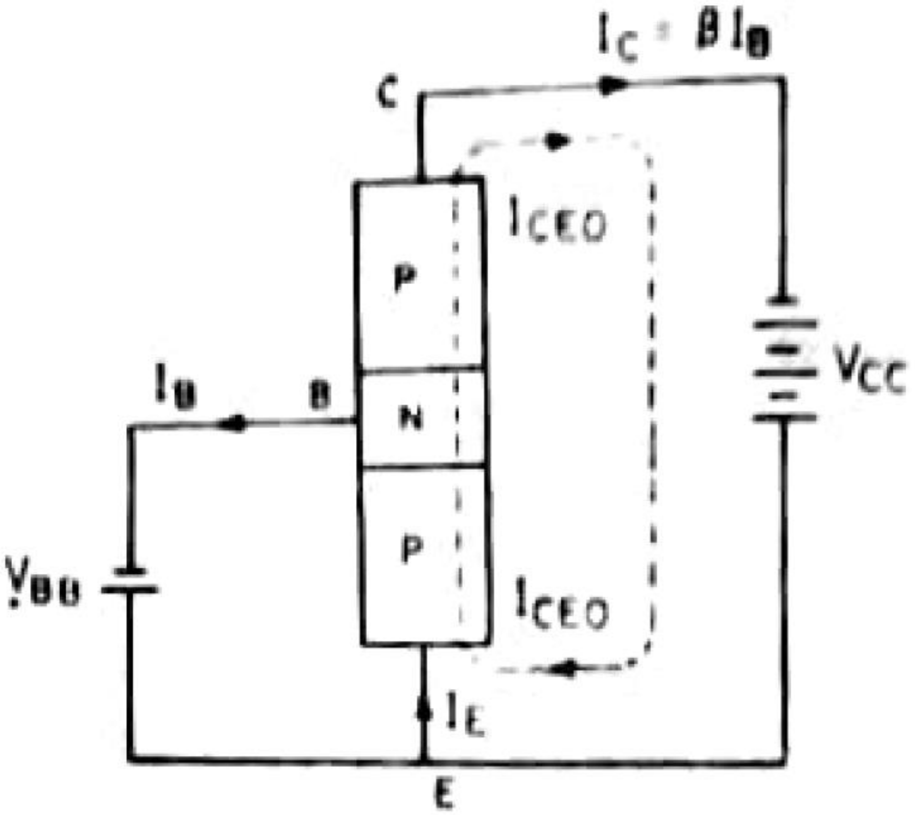


Fig. (11) Showing leakage current

Expression for Total Collector Current in CC Configuration

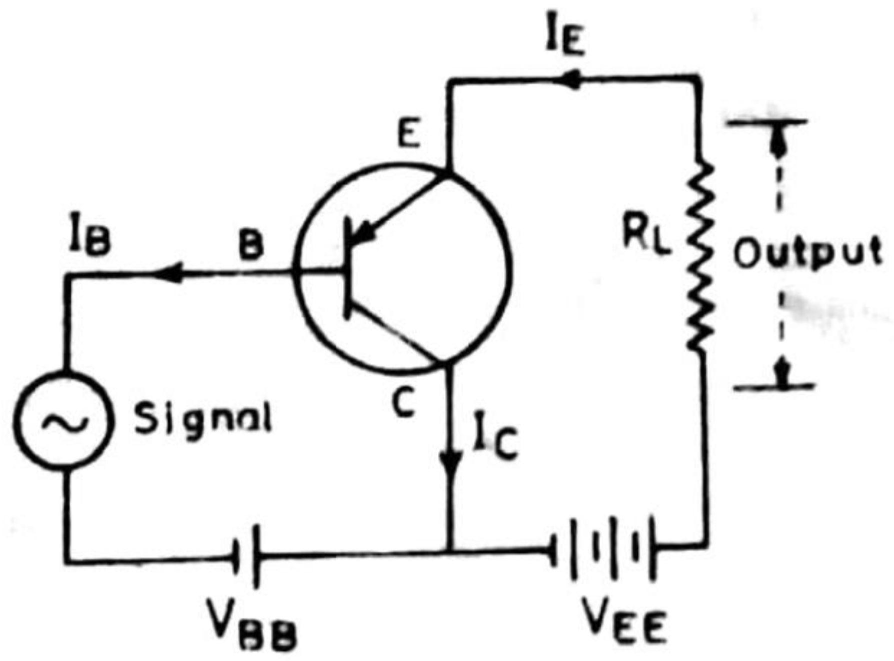


Fig. (12) Common collector PNP transistor amplifier

Current amplification factor (γ). When no signal is applied, then the ratio of emitter current to the base current is called as dc gamma (γ_{dc}) of the transistor.

$$(\gamma_{dc}) = \gamma = \frac{I_E}{I_B} \qquad \text{...(1)}$$

Expression for Total Collector Current in CC Configuration

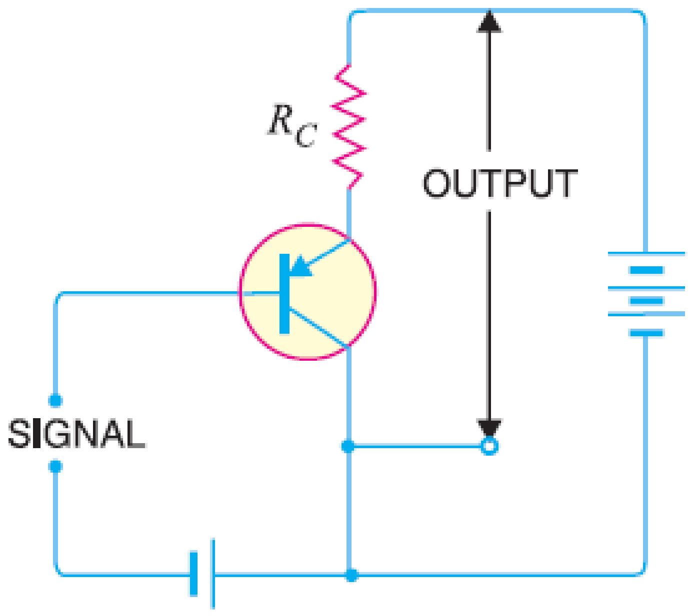
We know $$I_C = \alpha I_E + I_{CBO}$$

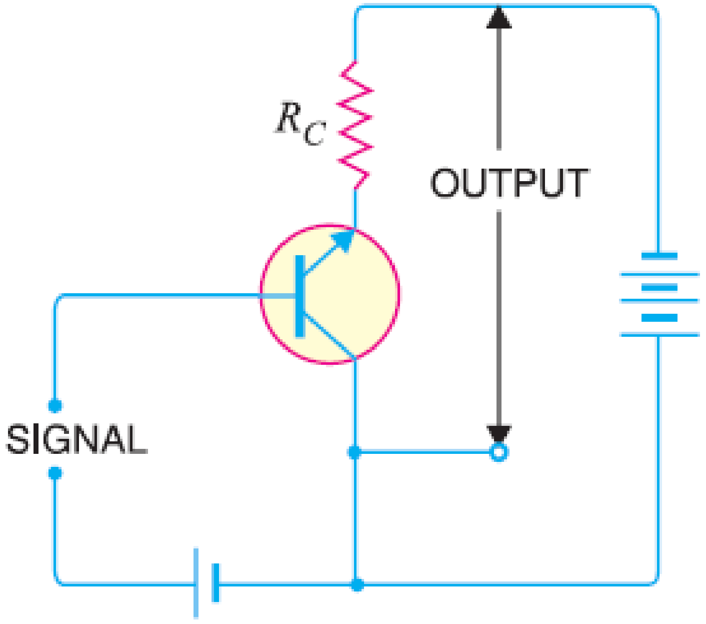
Also $$I_E = I_B + I_C = I_B + (\alpha I_E + I_{CBO})$$

$$\therefore \quad I_E (1 - \alpha) = I_B + I_{CBO}$$

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

or $$I_C \; ; \; I_E = (\beta + 1) I_B + (\beta + 1) I_{CBO}$$





Unit III: **TRANSISTORS**

- Construction and characteristics of bipolar junction transistors (BJT’s)-
- Comm. Base, Comm. emitter, Comm. Collector configuration,
- Transistor biasing and bias stabilization: -
  - the operating point,
  - stability factor,
- analysis of
  - fixed base bias,
  - collector to base bias,
  - Emitter resistance bias circuit and
  - self bias circuit.

TRANSISTOR BIASING

&

THERMAL STABILIZATION

Transistor Biasing

The basic function of transistor is amplification. The process of raising the strength of weak signal without any change in its general shape is referred as faithful amplification. For faithful amplification it is essential that:-

1. Emitter-Base junction is forward biased
2. Collector- Base junction is reversed biased
3. Proper zero signal collector current

The proper flow of zero signal collector current and the maintenance of proper collector emitter voltage during the passage of signal is called transistor biasing.

WHY BIASING?

If the transistor is not biased properly, it would work inefficiently and produce distortion in output signal.

HOW A TRANSISTOR CAN BE BIASED?

A transistor is biased either with the help of battery or associating a circuit with the transistor. The later method is more efficient and is frequently used. The circuit used for transistor biasing is called the biasing circuit.

BIAS STABILITY

❖ Through proper biasing, a desired quiescent operating point of the transistor amplifier in the active region (linear region) of the characteristics is obtained. It is desired that once selected the operating point should remain stable. The maintenance of operating point stable is called Stabilisation.

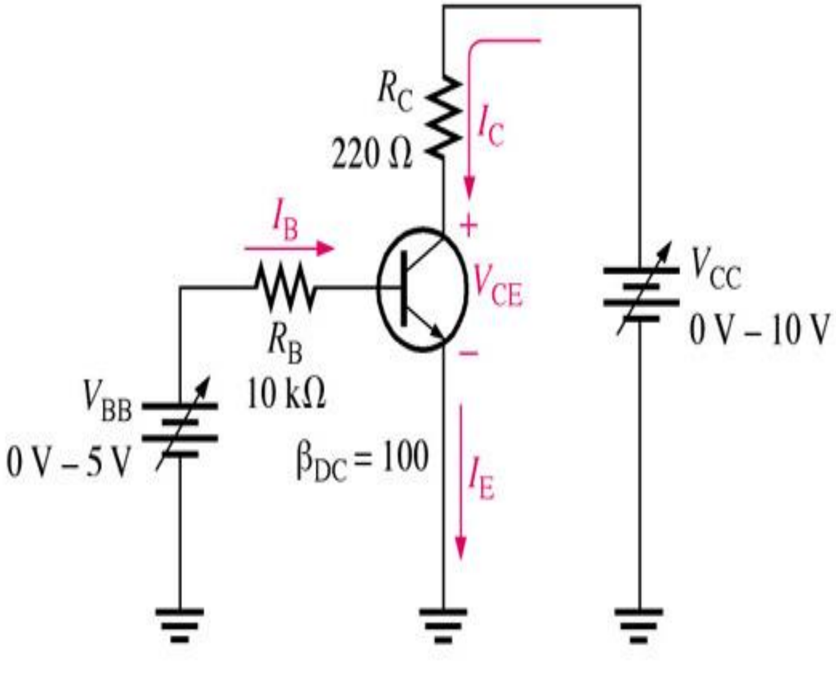
❖ The selection of a proper quiescent point generally depends on the following factors:

(a) The amplitude of the signal to be handled by the amplifier and distortion level in signal
(b) The load to which the amplifier is to work for a corresponding supply voltage

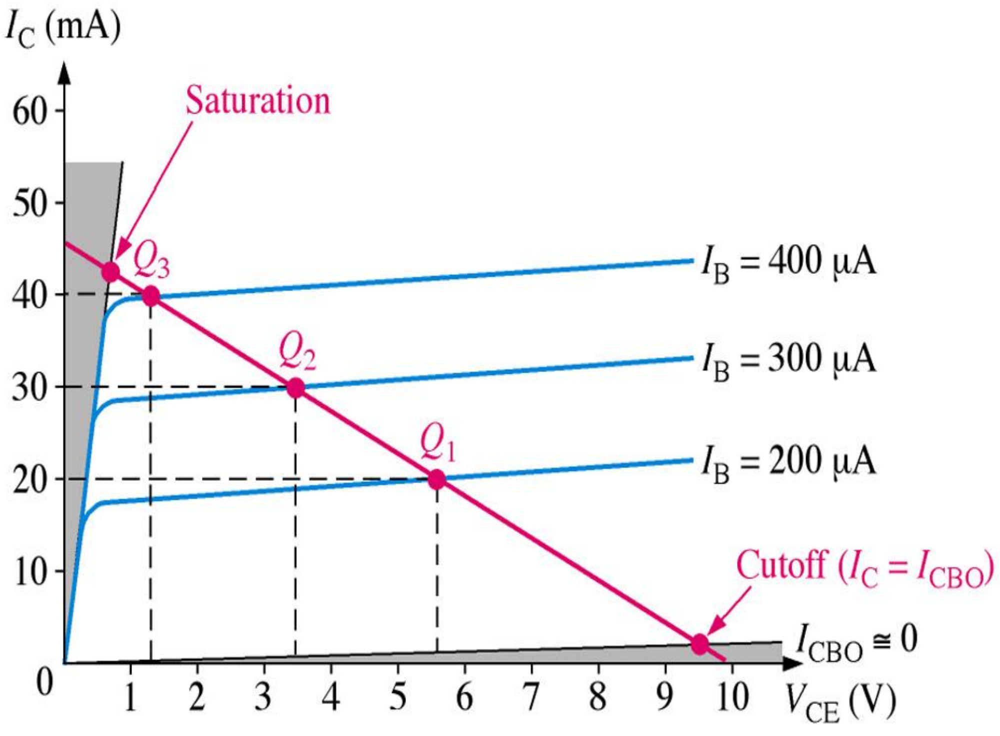
❖ The operating point of a transistor amplifier shifts mainly with changes in temperature, since the transistor parameters — β, I_{CO} *and* V_{BE} *(where the symbols carry their usual meaning)—are functions of* temperature.

The DC Operating Point

For a transistor circuit to amplify it must be properly biased with dc voltages. The dc operating point between saturation and cutoff is called the **Q-point.** The goal is to set the Q-point such that that it does not go into saturation or cutoff when an a ac signal is applied.



(a) DC biased circuit



Requirements of biasing network

- Ensuring proper zero signal collector current.
- Ensuring V_{CE} not falling below 0.5V for Ge transistor and 1V for Silicon transistor at any instant.
- Ensuring Stabilization of operating point. (zero signal I_C and V_{CE})

10-3 STABILITY FACTOR

The stability factor S is defined as the rate of change of collector current I_C with respect to the reverse saturation current I_{CO}, keeping β and V_{BE} constant, *i.e.*,

$$S = \frac{\partial I_C}{\partial I_{CO}} \approx \frac{\Delta I_C}{\Delta I_{CO}} \qquad ...(1)$$

This expression shows that smaller is the value of S, higher is the stability. So the stability factor S should be kept as small as possible. The lowest value of S that can be obtained is unity since I_C must include I_{CO}. Closer is the value of S to unity, lesser will be the variation of operating point with temperature.

In the definition of S, β and V_{BE} are assumed to be constant while they vary with temperature. Hence we define the following two other stability constants :

(i) ***Stability factor*** S_β. This is defined as the rate of change of I_C with β keeping I_{CO} and V_{BE} constant, *i.e.*,

$$S_\beta = \frac{\partial I_C}{\partial \beta} \approx \frac{\Delta I_C}{\Delta \beta} \qquad ...(2)$$

(ii) ***Stability factor*** S_V. This is defined as the rate of change of I_C with V_{BE}, keeping I_{CO} and β constant, *i.e.*,

$$S_V = \frac{\partial I_C}{\partial V_{BE}} = \frac{\Delta I_C}{\Delta V_{BE}} \qquad ...(3)$$

Expression for stability factor S. When a transistor is biased in the active region of its characteristics, the collector current I_C is related to the base current I_B by the following expression.

$$I_C = \beta I_B + (1 + \beta)\, I_{CO} \qquad \ldots(4)$$

Differentiating eq. (4) with respect to I_C considering β to be constant, we get

$$1 = \beta \frac{dI_B}{dI_C} + (1 + \beta) \frac{\partial I_{CO}}{\partial I_C}$$

or
$$1 = \beta \frac{dI_B}{dI_C} + (1 + \beta) \cdot \frac{1}{S} \qquad \left(\because S = \frac{\partial I_C}{\partial I_{CO}} \right)$$

or
$$1 - \beta \frac{dI_B}{dI_C} = (1 + \beta) \cdot \frac{1}{S}$$

$\therefore$
$$S = \frac{(1 + \beta)}{1 - \beta \dfrac{dI_B}{dI_C}} \qquad \ldots(5)$$

The value of dI_B/dI_C depends upon the type of biasing arrangement. The stability factor S gives a measure of the change in I_C with respect to I_{CO} whether the change is the result of temperature variation or due to the transistor being replaced by another of the same type.

Expression for stability factor S_β. Differentiating eq. (4) with respect to I_C and assuming I_{CO} to be constant, we get

Expression for stability factor S_β. Differentiating eq. (4) with respect to I_C and assuming I_{CO} to be constant, we get

$$1 = \beta \frac{dI_B}{dI_C} + I_B \frac{\partial \beta}{\partial I_C} + I_{CO} \frac{\partial \beta}{\partial I_C}$$

or

$$\frac{\partial \beta}{\partial I_C} [I_{CO} + I_B] = 1 - \beta \frac{dI_B}{dI_C}$$

or

$$\frac{I_{CO} + I_B}{S_\beta} = 1 - \beta \frac{dI_B}{dI_C} \qquad \left(\because S_\beta = \frac{\partial I_C}{\partial \beta} \right)$$

$\therefore$

$$S_\beta = \frac{I_{CO} + I_B}{1 - \beta \dfrac{dI_B}{dI_C}} \qquad \ldots(6)$$

With the help of this equation we can find out variation in I_C as a result of variation in β.

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- analysis of biasing circuits
  - ✓ fixed base bias,
  - ✓ collector to base bias,
  - ✓ Emitter resistance bias circuit and
  - ✓ self bias circuit.

The Thermal Stability of Operating Point (S_{Ico})

❖**Stability Factor *S*:-** The stability factor *S, as the change of collector current with respect to the reverse saturation* current, keeping β *and VBE constant. This can be written as:*

The Thermal Stability Factor : S_{Ico}

$$S_{Ico} = \left. \frac{\partial I_c}{\partial I_{co}} \right|_{V_{be},\, \beta}$$

This equation signifies that I_c Changes S_{Ico} times as fast as I_{co}

Differentiating the equation of Collector Current $I_C = (1+\beta)I_{co} + \beta I_b$ & rearranging the terms we can write

$$S_{Ico} = \frac{1+\beta}{1-\beta\,(\partial I_b/\partial I_C)}$$

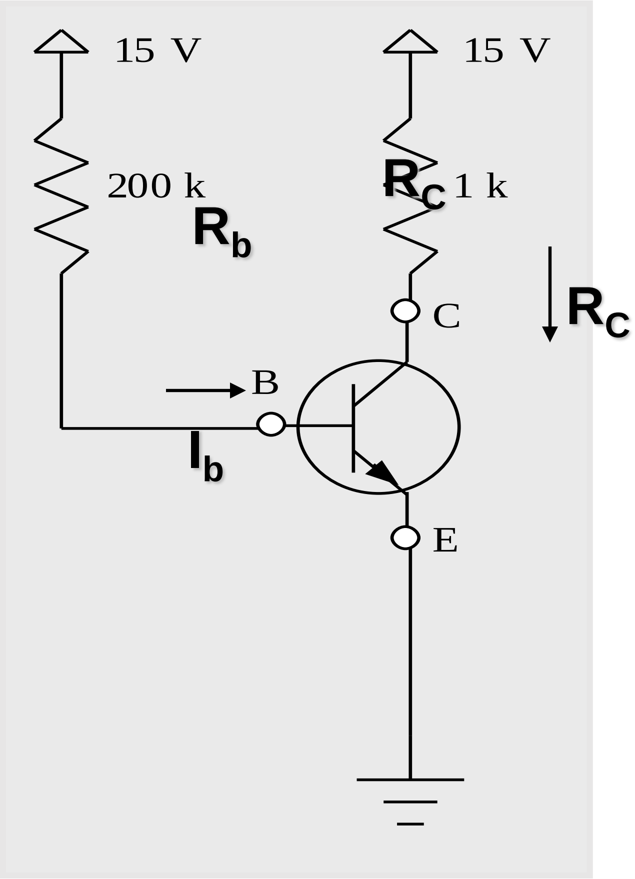
It may be noted that Lower is the value of S_{Ico} better is the stability

Various Biasing Circuits

- **Fixed Bias Circuit**
- **Fixed Bias with Emitter Resistor**
- **Collector to Base Bias Circuit**
- **Potential Divider Bias Circuit**

The basic principle involved in all the above methods is to obtain the required base current (*i.e.*, collector current) from V_{CC} in zero signal conditions. The value of collector load is selected in such a way that the voltage between collector and emitter should not fall below 0·5 volt for germanium transistor and 0·7 volt for silicon transistor.

The Fixed Bias Circuit



The Thermal Stability Factor : S_{Ico}

$$S_{Ico} = \left.\frac{\partial I_c}{\partial I_{co}}\right|_{V_{be},\ \beta}$$

General Equation of S_{Ico} Comes out to be

$$S_{Ico} = \frac{1+\beta}{1-\beta\,(\partial I_b/\partial I_C)}$$

Applying KVL through Base Circuit we can write, $I_b R_b + V_{be} = V_{cc}$

Diff w. r. t. I_C, we get $(\partial I_b / \partial I_c) = 0$

$S_{Ico} = (1+\beta)$ is very large

Indicating high un-stability

Merits:

- It is simple to shift the operating point anywhere in the active region by merely changing the base resistor (R_B).
- A very small number of components are required.

Demerits:

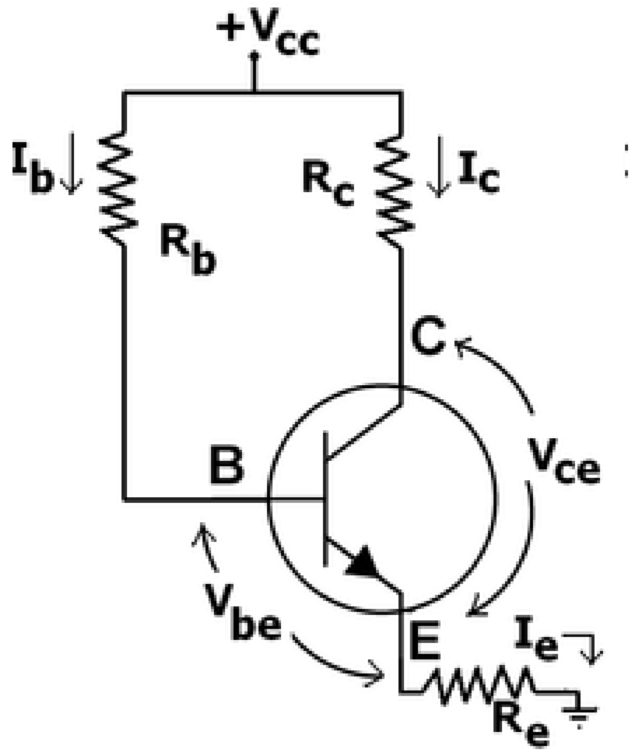
- The collector current does not remain constant with variation in temperature or power supply voltage. Therefore the operating point is unstable.
- When the transistor is replaced with another one, considerable change in the value of β can be expected. Due to this change the operating point will shift.
- For small-signal transistors (e.g., not power transistors) with relatively high values of β (i.e., between 100 and 200), this configuration will be prone to thermal runaway. In particular, the stability factor, which is a measure of the change in collector current with changes in reverse saturation current, is approximately β+1.
- To ensure absolute stability of the amplifier, a stability factor of less than 25 is preferred, and so small-signal transistors have large stability factors.

Usage:

- Due to the above inherent drawbacks, fixed bias is rarely used in linear circuits (i.e., those circuits which use the transistor as a current source). Instead, it is often used in circuits where transistor is used as a switch. However, one application of fixed bias is to achieve crude automatic gain control in the transistor by feeding the base resistor from a DC signal derived from the AC output of a later stage.

Fixed bias with emitter resistor

The fixed bias circuit is modified by attaching an external resistor to the emitter. This resistor introduces negative feedback that stabilizes the Q-point.



Merits:

- The circuit has the tendency to stabilize operating point against changes in temperature and β-value.

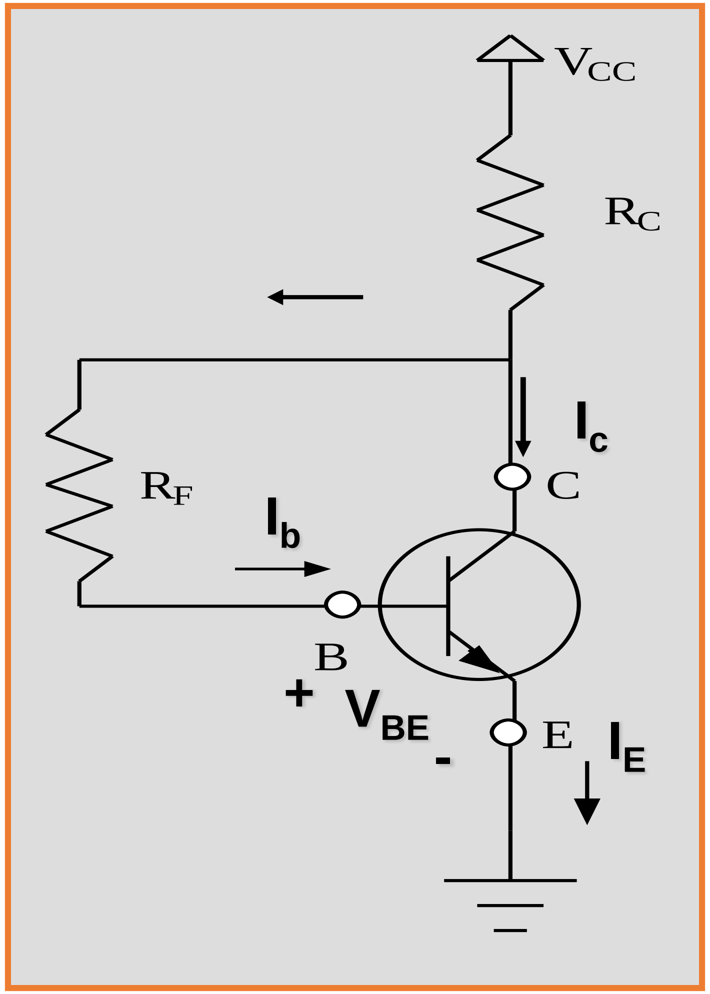
Demerits:

- As β-value is fixed for a given transistor, this relation can be satisfied either by keeping R_E very large, or making R_B very low.
  - If R_E is of large value, high V_{CC} is necessary. This increases cost as well as precautions necessary while handling.
  - If R_B is low, a separate low voltage supply should be used in the base circuit. Using two supplies of different voltages is impractical.
- In addition to the above, R_E causes ac feedback which reduces the voltage gain of the amplifier.

Usage:

The feedback also increases the input impedance of the amplifier when seen from the base, which can be advantageous. Due to the above disadvantages, this type of biasing circuit is used only with careful consideration of the trade-offs involved.

The Collector to Base Bias Circuit



This configuration employs negative feedback to prevent thermal runaway and stabilize the operating point. In this form of biasing, the base resistor R_F is connected to the collector instead of connecting it to the DC source V_{CC}. So any thermal runaway will induce a voltage drop across the R_C resistor that will throttle the transistor's base current.

Applying KVL through base circuit

we can write $(I_b + I_C) R_C + I_b R_f + V_{be} = V_{cc}$

Diff. w. r. t. I_C we get

$(\partial I_b / \partial I_c) = - R_C / (R_f + R_C)$

Therefore, $$S_{Ico} = \frac{(1+\beta)}{1 + [\beta R_C / (R_C + R_f)]}$$

Which is less than $(1+\beta)$, signifying better thermal stability

Merits:

- Circuit stabilizes the operating point against variations in temperature and β (i.e. replacement of transistor)

Demerits:

- As β -value is fixed (and generally unknown) for a given transistor, this relation can be satisfied either by keeping R_c fairly large or making R_f very low.

  - If R_c is large, a high V_{cc} is necessary, which increases cost as well as precautions necessary while handling.
  - If R_f is low, the reverse bias of the collector–base region is small, which limits the range of collector voltage swing that leaves the transistor in active mode.

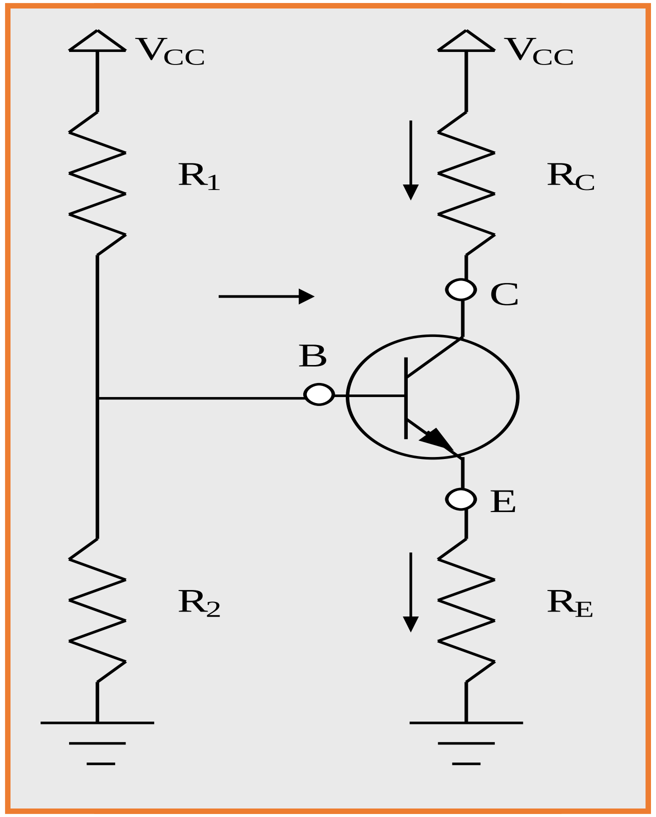
- The resistor R_f causes an AC feedback, reducing the voltage gain of the amplifier. This undesirable effect is a trade-off for greater Q-point stability.

Usage: The feedback also decreases the input impedance of the amplifier as seen from the base, which can be advantageous. Due to the gain reduction from feedback, this biasing form is used only when the trade-off for stability is warranted.

The Potential Divider Bias Circuit

- ✓ This is the most commonly used arrangement for biasing as it provide good bias stability.
- ✓ In this arrangement the emitter resistance ‘R_E’ provides stabilization. The resistance ‘R_E’ cause a voltage drop in a direction so as to reverse bias the emitter junction.
- ✓ Since the emitter-base junction is to be forward biased, the base voltage is obtained from R_1-R_2 network.
- ✓ The net forward bias across the emitter base junction is equal to V_B- dc voltage drop across ‘R_E’.
- ✓ The base voltage is set by Vcc and R_1 and R_2. The dc bias circuit is independent of transistor current gain.
- ✓ In case of amplifier, to avoid the loss of ac signal, a capacitor of large capacitance is connected across R_E.
- ✓ The capacitor offers a very small reactance to ac signal and so it passes through the condensor.

The Potential Divider Bias Circuit

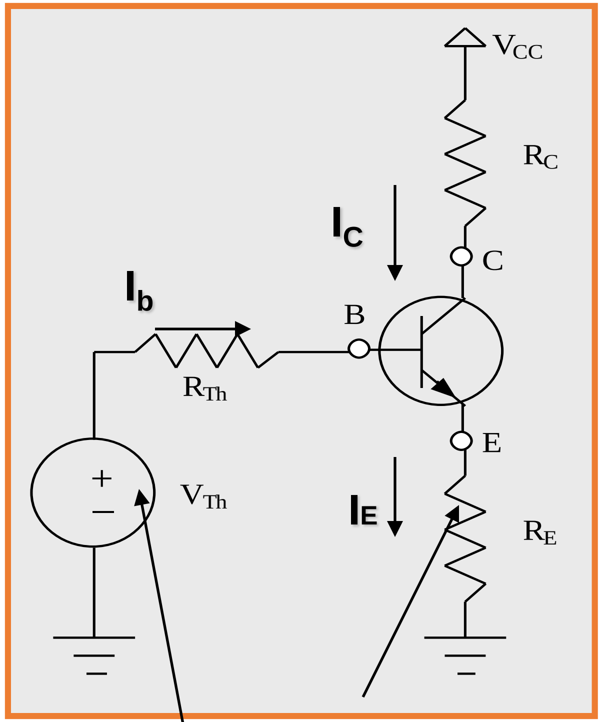


To find the stability of this circuit we have to convert this circuit into its Thevenin's Equivalent circuit

$$R_{th} = \frac{R_1 * R_2}{R_1 + R_2} \quad \& \quad V_{th} = \frac{Vcc\ R_2}{R_1 + R_2}$$

The Potential Divider Bias Circuit

Thevenin Equivalent Ckt



Self-bias Resistor

Thevenin Equivalent Voltage

Applying KVL through input base circuit

we can write $I_b R_{Th} + I_E R_E + V_{be} = V_{Th}$

Therefore, $I_b R_{Th} + (I_C + I_b) R_E + V_{BE} = V_{Th}$

Diff. w. r. t. I_C & rearranging we get

$$(\partial I_b / \partial I_c) = - R_E / (R_{Th} + R_E)$$

Therefore,

$$S_{Ico} = \frac{1+\beta}{1+\left[\beta \frac{R_E}{R_E + R_{Th}}\right]}$$

This shows that S_{Ico} is inversely proportional to R_E and It is less than (1+β), signifying better thermal stability

Merits:

- Operating point is almost independent of β variation.
- Operating point stabilized against shift in temperature.

Demerits:

- As β-value is fixed for a given transistor, this relation can be satisfied either by keeping R_E fairly large, or making R1||R2 very low.
  - If R_E is of large value, high V_{CC} is necessary. This increases cost as well as precautions necessary while handling.
  - If R1 || R2 is low, either R1 is low, or R2 is low, or both are low. A low R1 raises V_B closer to V_C, reducing the available swing in collector voltage, and limiting how large R_C can be made without driving the transistor out of active mode. A low R2 lowers Vbe, reducing the allowed collector current. Lowering both resistor values draws more current from the power supply and lowers the input resistance of the amplifier as seen from the base.
  - AC as well as DC feedback is caused by RE, which reduces the AC voltage gain of the amplifier. A method to avoid AC feedback while retaining DC feedback is discussed below.

Usage:

The circuit's stability and merits as above make it widely used for linear circuits.

Summary

- The Q-point is the best point for operation of a transistor for a given collector current.
- The purpose of biasing is to establish a stable operating point (Q-point).
- The linear region of a transistor is the region of operation within saturation and cutoff.
- Out of all the biasing circuits, potential divider bias circuit provides highest stability to operating point.

THANK YOU