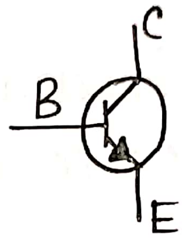
Bipolar Junction Transistor (BJT)
(as a circuit element)



Introduction to BJT

Reference Book: Electronic Devices
(6th edition)
Thomas L. Floyd
CHAPTER-4

* A bipolar junction transistor (BJT) is a type of transistor that uses both electrons and holes as charge carriers. Unipolar transistors, such as field effect transistors, use only one kind of charge carrier. A bipolar transistor allows a small current injected at one of its terminals to control a much larger current flowing between two other terminals, making the device capable of amplification or switching.

By
MD TOUKIR SHAH
EEE'18, CUET

Vacuum Tube

Alternatively reffered to as an electron tube or valve and first developed by John Ambrose Fleming in 1904. The vacuum tube is a glass tube that has its gas removed, creating a vacuum. Vacuum tubes contain electrodes for controlling electron flow and were used in early computers as a switch or an amplifier.

Problems of using vaccum tube as an amplifier or switch

Vacuum tubes were expensive, relatively large and consumes considerable amounts of power.
Principal problem was with the reliability of the tubes. They sufferred vacuum leaks which caused the devices to malfunction. and repeated heating of the cathode would eventually cause valve to blow.

What are Transistors?

* Versatile three lead semiconductor devices whose applications include electronic switching and modulation (amplification).

Transistors are miniature electronic switches.

Configuration of circuit determines whether the transistor will serve a switch and amplifier.

Building blocks of the microprocessor, which is the brain of the computer.

Have two operating positions- on and off.

Binary functionality of transistors enables the processing of information in a computer.

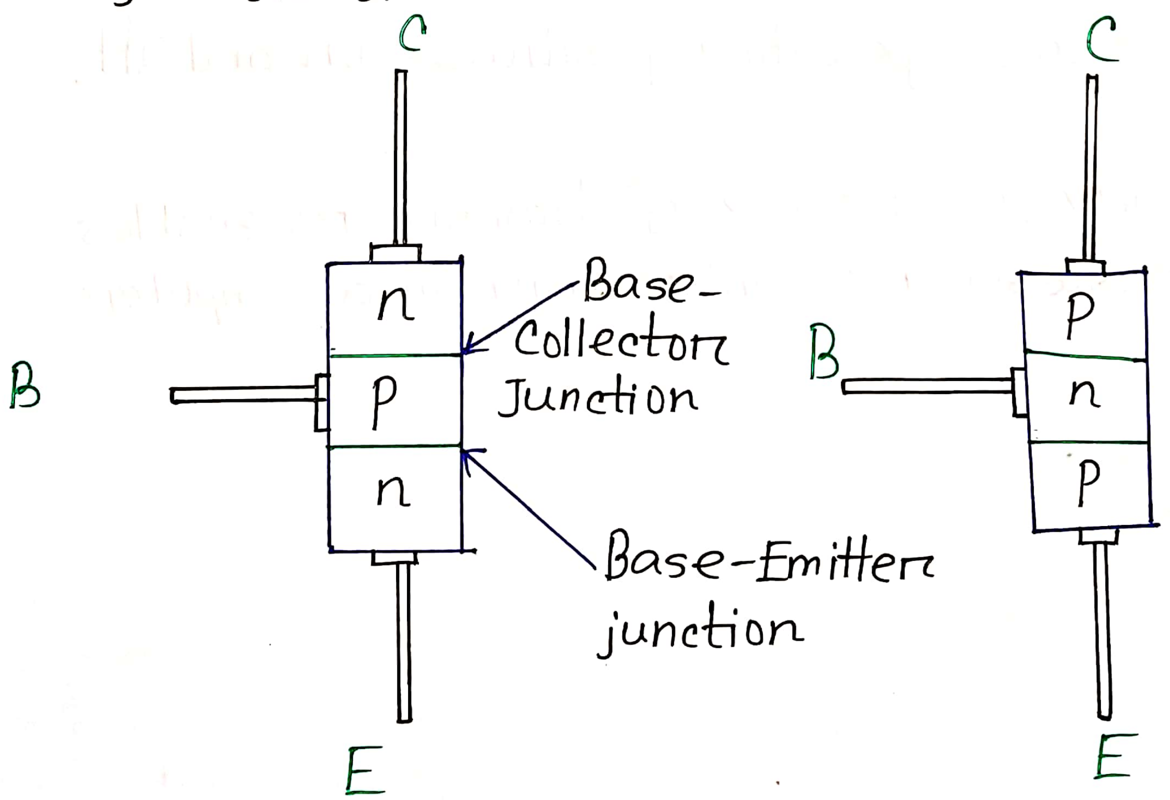
Transistor Structure

The BJT is a transistor with three regions and two pn junctions. The regions are named the emitter the base and the collector and each is connected to a lead.

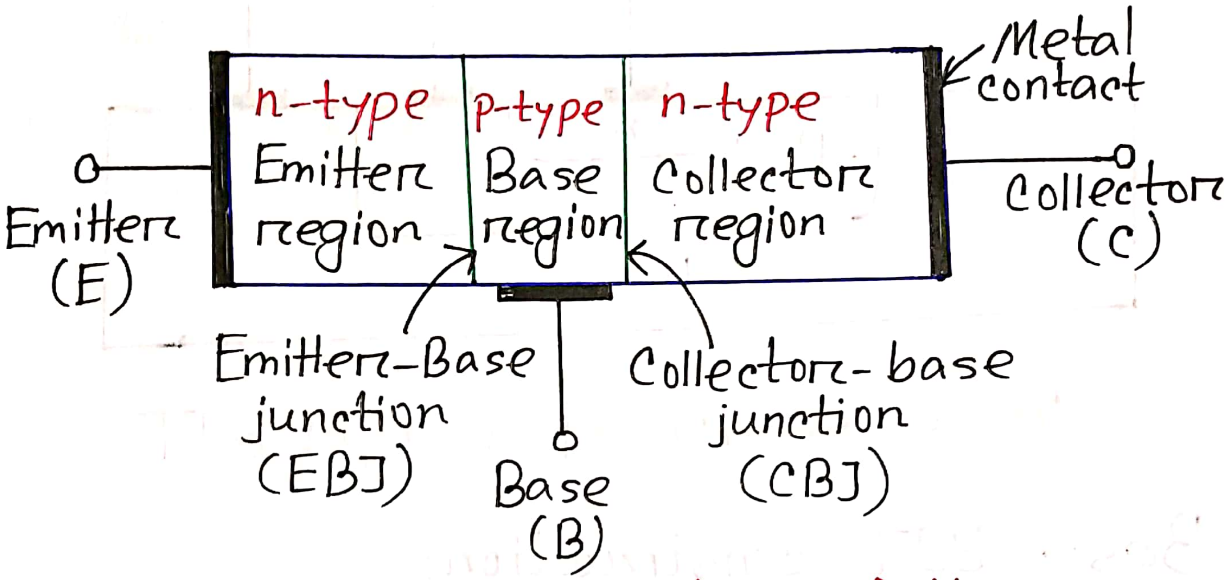
There are two types of BJTs –

(i) npn
(ii) pnp

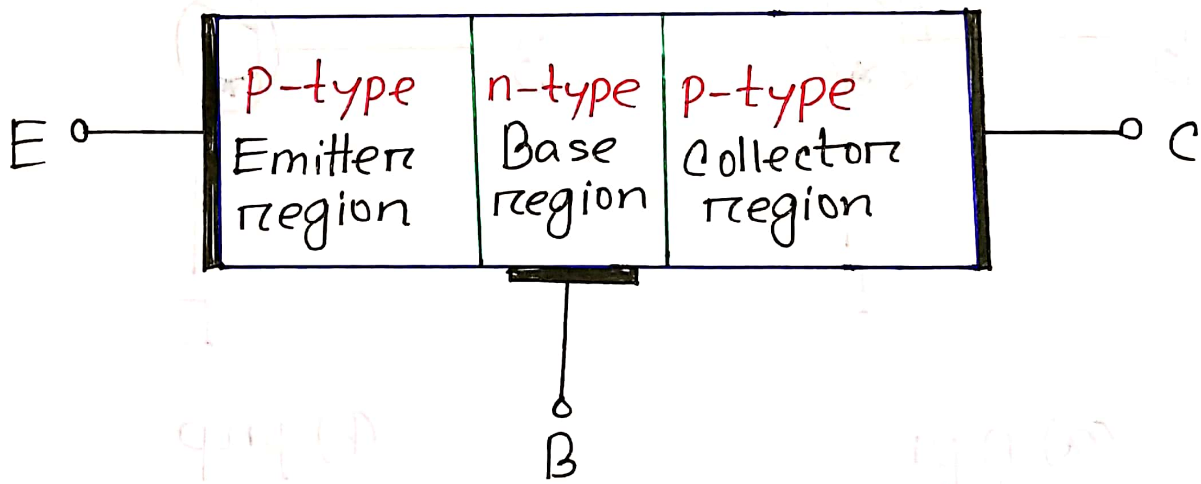
Separating the regions are two junctions.



☞ Physical Structure

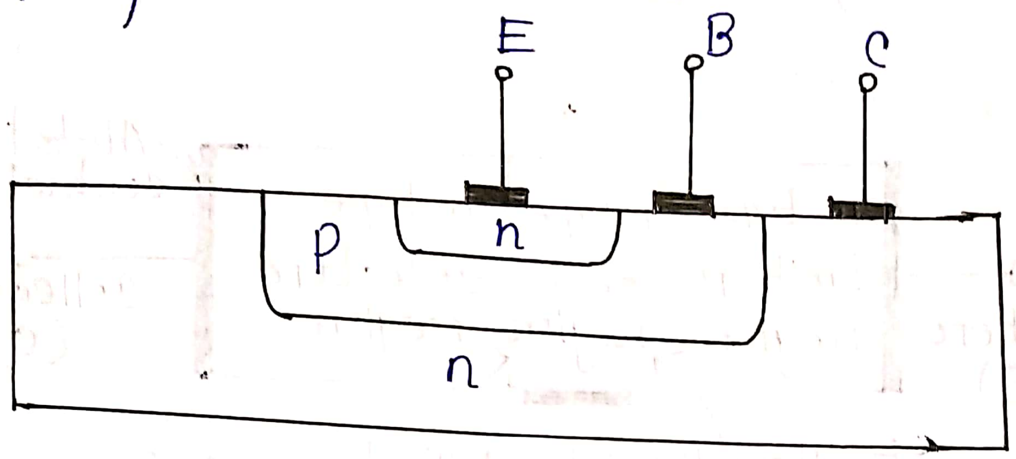


A simplified structure of the npn transistor.



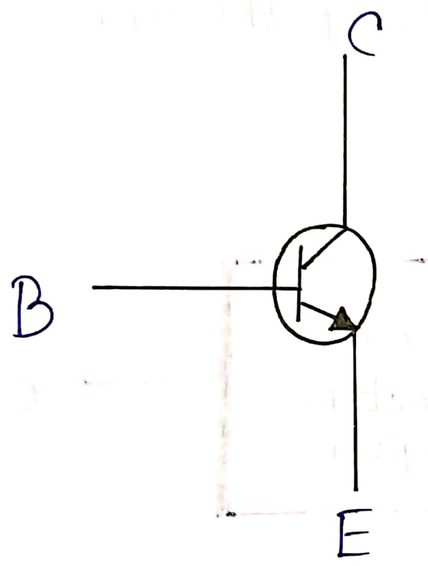
A simplified structure of the pnp transistor.

Physical Structure

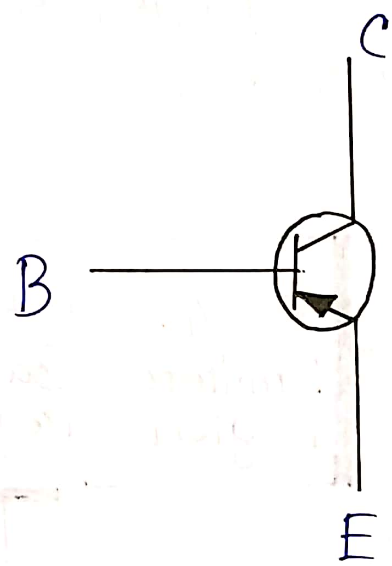


Cross-section of an npn BJT

Basic BJT construction:



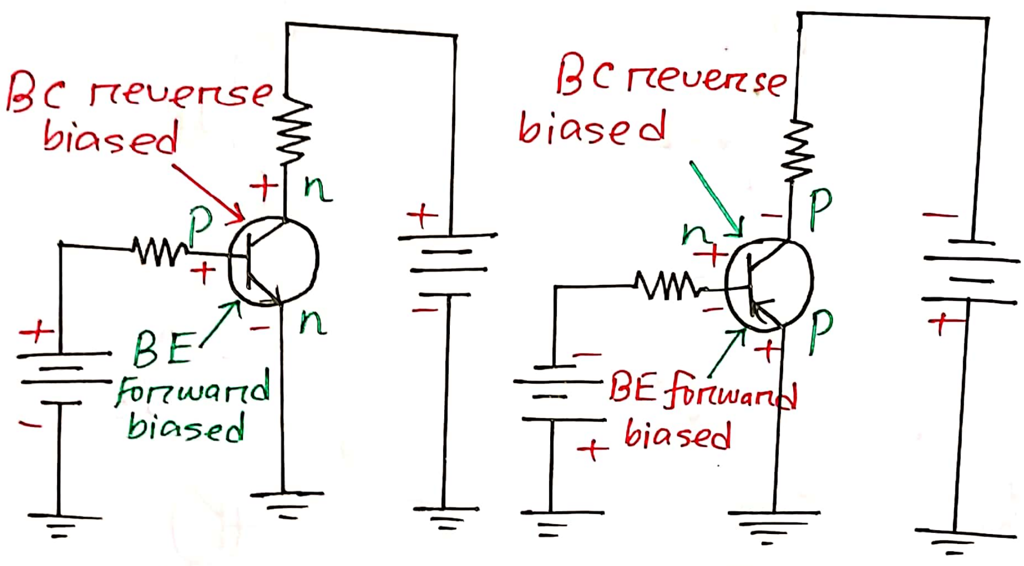
(a) npn



(b) pnp

Basic Transistor Operation

The following figures show the proper BIAS arrangement for both npn and pnp transistors for active operation as an amplifier. In both cases the base-emitter (BE) junction is forward.



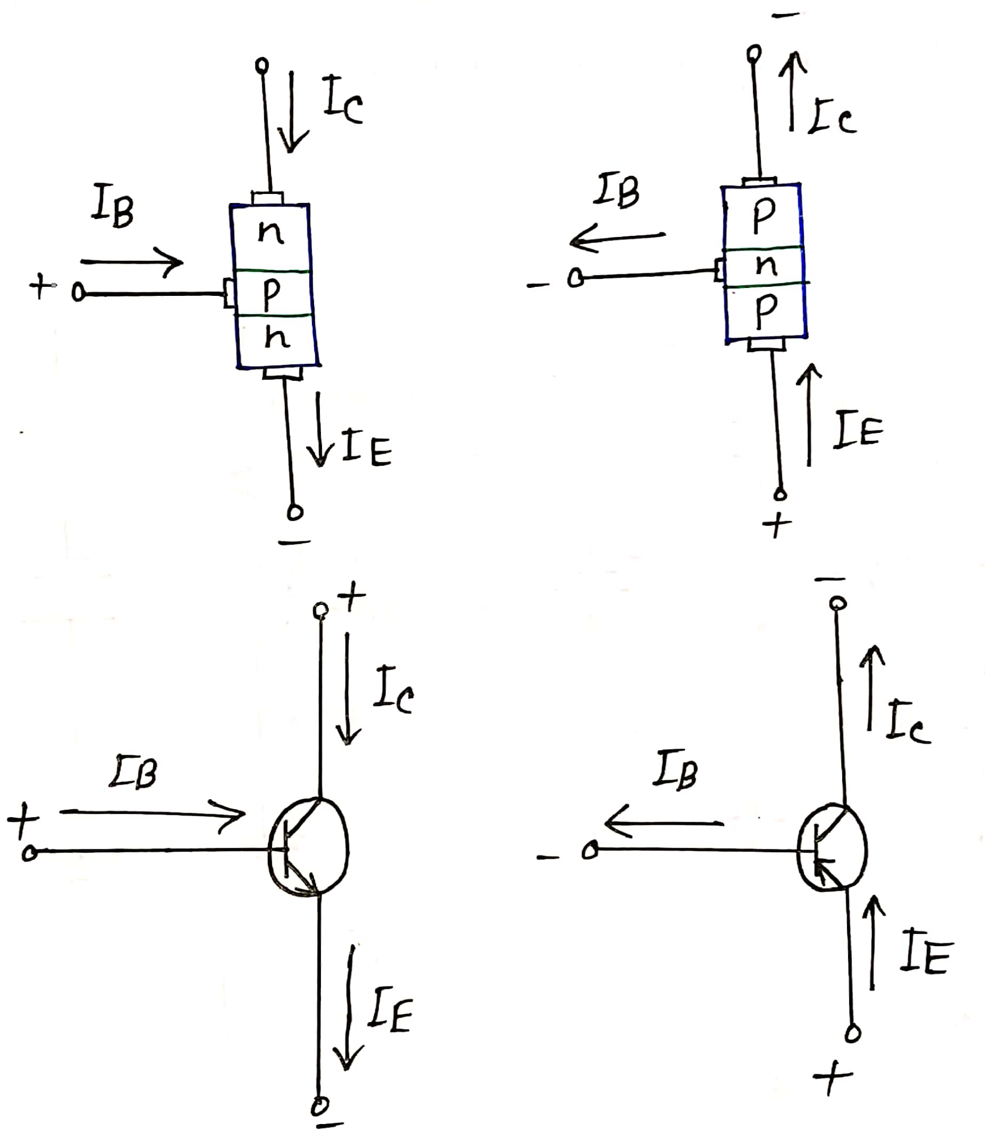
(a) npn

(b) pnp

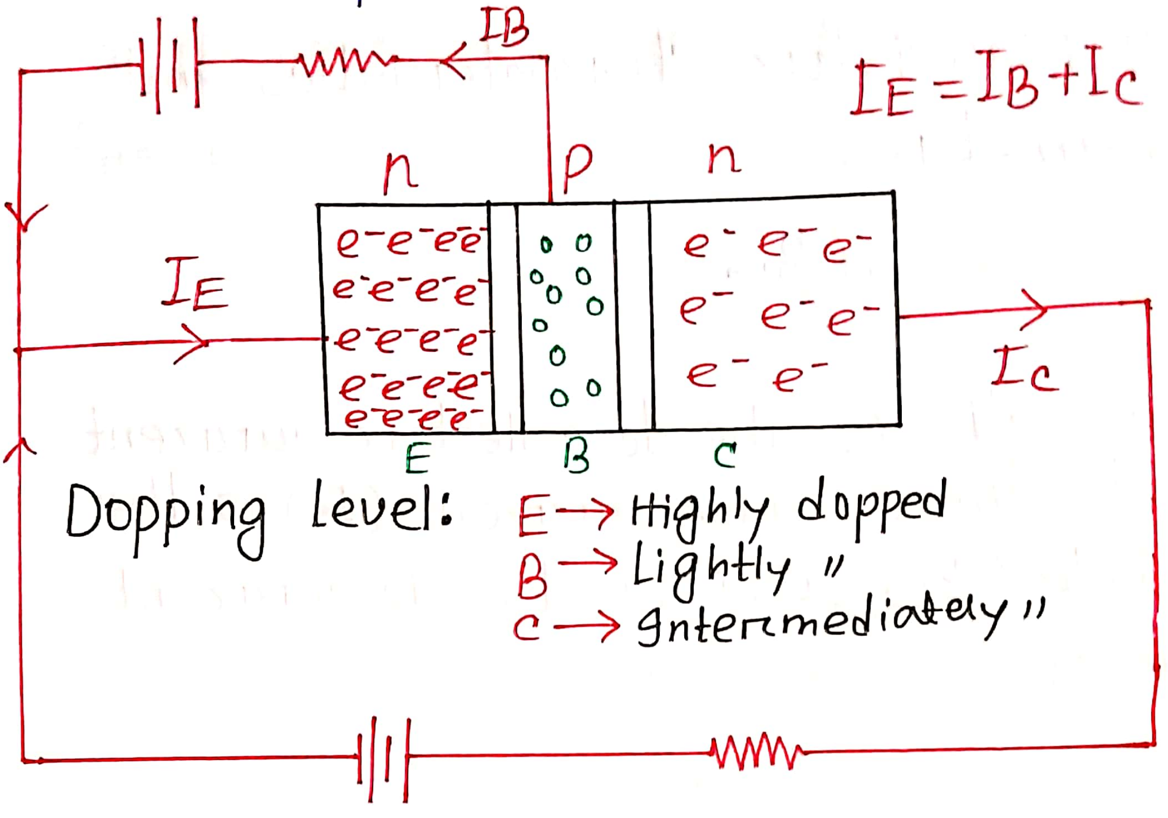
☞ Basic Transistor Operation

Transistor currents (Conventional current)

$$I_E = I_B + I_C$$



Operation



Dopping level: E → Highly dopped
B → Lightly "
C → Intermediately "

*** Forward bias narrows the B-E depletion region.

* Reverse bias widens the B-C depletion region.

* For the B-C junction to be reverse biased, the Collector is made more +ve than the Base.

Transistor Characteristics and Parameters

DC Beta (β_{DC})

The ratio of the dc collector current (I_C) to the dc base current (I_B) is the dc beta (β_{DC}), which is the dc current gain of a transistor.

$$\beta_{DC} = \frac{I_C}{I_B}$$

Typical values of β_{DC} range from less than 20 to 200 or higher. β_{DC} is usually designed as an equivalent hybrid (h) parameter, h_{FE}, on transistor data sheets.

$$\beta_{DC} = h_{FE}$$

The ratio of the dc collector current (I_C) to the dc emitter current (I_E) is the dc alfa (α_{DC})

$$\alpha_{DC} = \frac{I_C}{I_E}$$

Typically values of α_{DC} range from 0.95 to 0.99 or greater.

α_{DC} is always less than 1, because $I_E \approx I_C$.

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

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

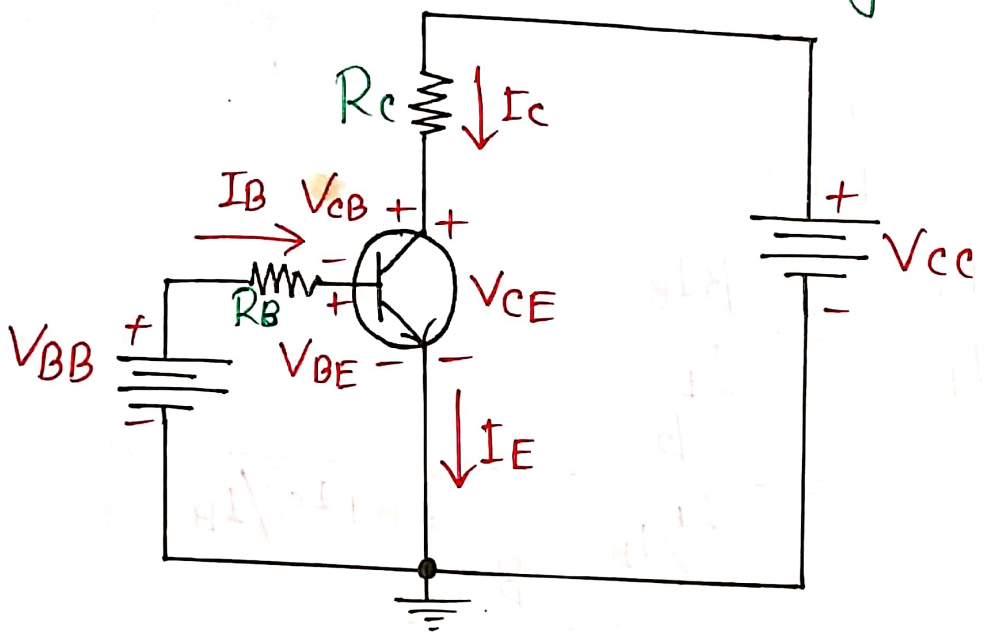
$$= \frac{\beta}{I_E/I_B} = \frac{\beta}{(I_B+I_C)/I_B}$$

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

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

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

Current and Voltage Analysis



I_B: dc base current

I_E: dc emitter current

I_C: dc collector current

V_{BE}: dc voltage at base with respect to emitter

V_{CB}: dc voltage at collector with respect to base

V_{CE}: dc voltage at collector with respect to emitter.

When the base-emitter junction is forward biased, it is like a forward-biased diode and has a nominal forward voltage drop of

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

Since the emitter is at ground (0V), by Kirchhoff's voltage law, the voltage across R_B is

$$V_{RB} = V_{BB} - V_{BE}$$

Also, by Ohm's law,

$$V_{RB} = I_B R_B$$

Substituting for V_{RB} yields

$$I_B R_B = V_{BB} - V_{BE}$$

$$\therefore I_B = \frac{V_{BB} - V_{BE}}{R_B}$$

The voltage at the collector with respect to the grounded emitter is

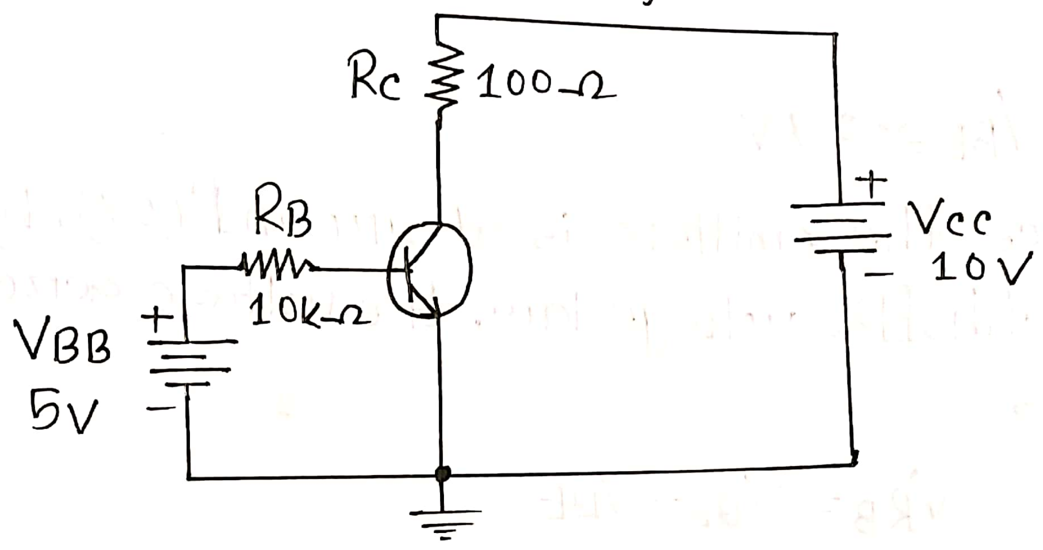
$$V_{CE} = V_{CC} - V_{RC}$$

Since the drop across R_C is $V_{RC} = I_C R_C$

$$\therefore V_{CE} = V_{CC} - I_C R_C \quad \Big| \; I_C = \beta_{DC} I_B$$

The voltage across the reverse-biased collector-base junction is $V_{CB} = V_{CE} - V_{BE}$

Problem: Determine I_B, I_C, I_E, V_{BE} and V_{CB} in the circuit of figure below. The transistor has a $\beta_{DC} = 150$.



Solution:

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

$$= \frac{(5 - 0.7)\,V}{10\,k\Omega} = 430\,\mu A$$

$$I_C = \beta_{DC} I_B$$

$$= (150)(430\,\mu A)$$

$$= 64.5\,mA$$

$$I_E = I_C + I_B$$

$$= 64.5\,mA + 430\,\mu A = 64.9\,mA$$

Solve for V_{CE} and V_{CB}:

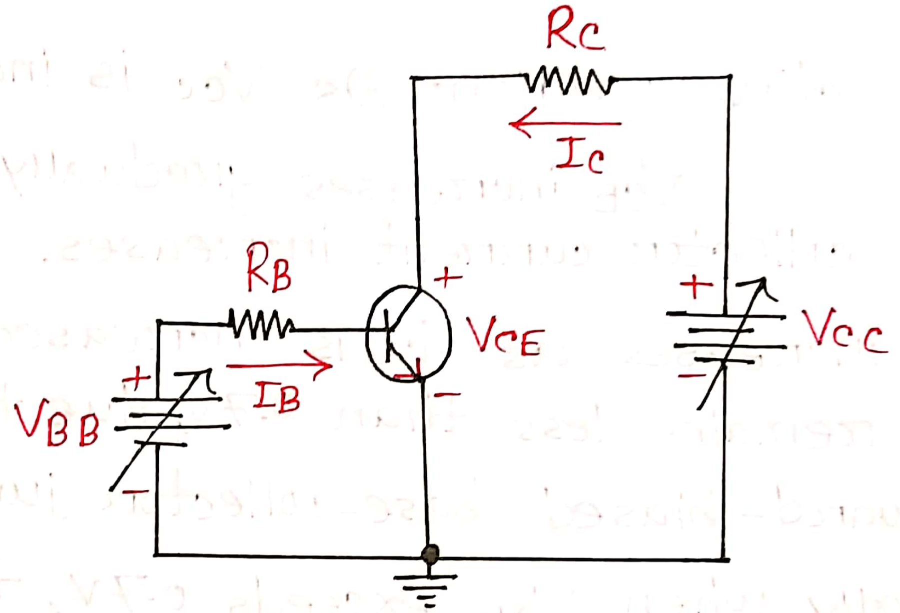
$$V_{CE} = V_{CC} - I_C R_C = 10 - (64.5\,mA)(100\,\Omega)$$

$$= 10V - 6.45V = 3.55V$$

$$V_{CB} = V_{CE} - V_{BE} = 3.55V - 0.7V = 2.85V.$$

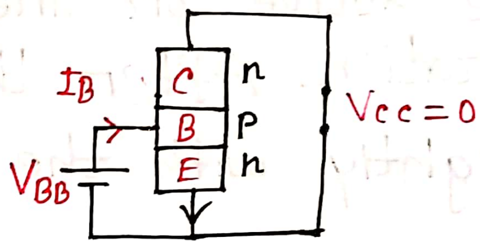
Collector Characteristic Curves

We can generate a set of collector characteristic curves that show how the collector current, I_C, varies with the collector-to-emitter voltage, V_{CE}, for specified values of base current, I_B.



Saturation Region: V_{BB} is set to a certain value for producing certain I_B and V_{CC} is zero.

BE junction and BC junction are forward-biased as



the base is at approximately 0.7 V while the emitter and collector are at 0 V.

The base current is through the base-emitter junction because of the low impedance path to ground and therefore I_C is zero. When both junctions are forward-biased, the transistor is in the saturation region of its operation.

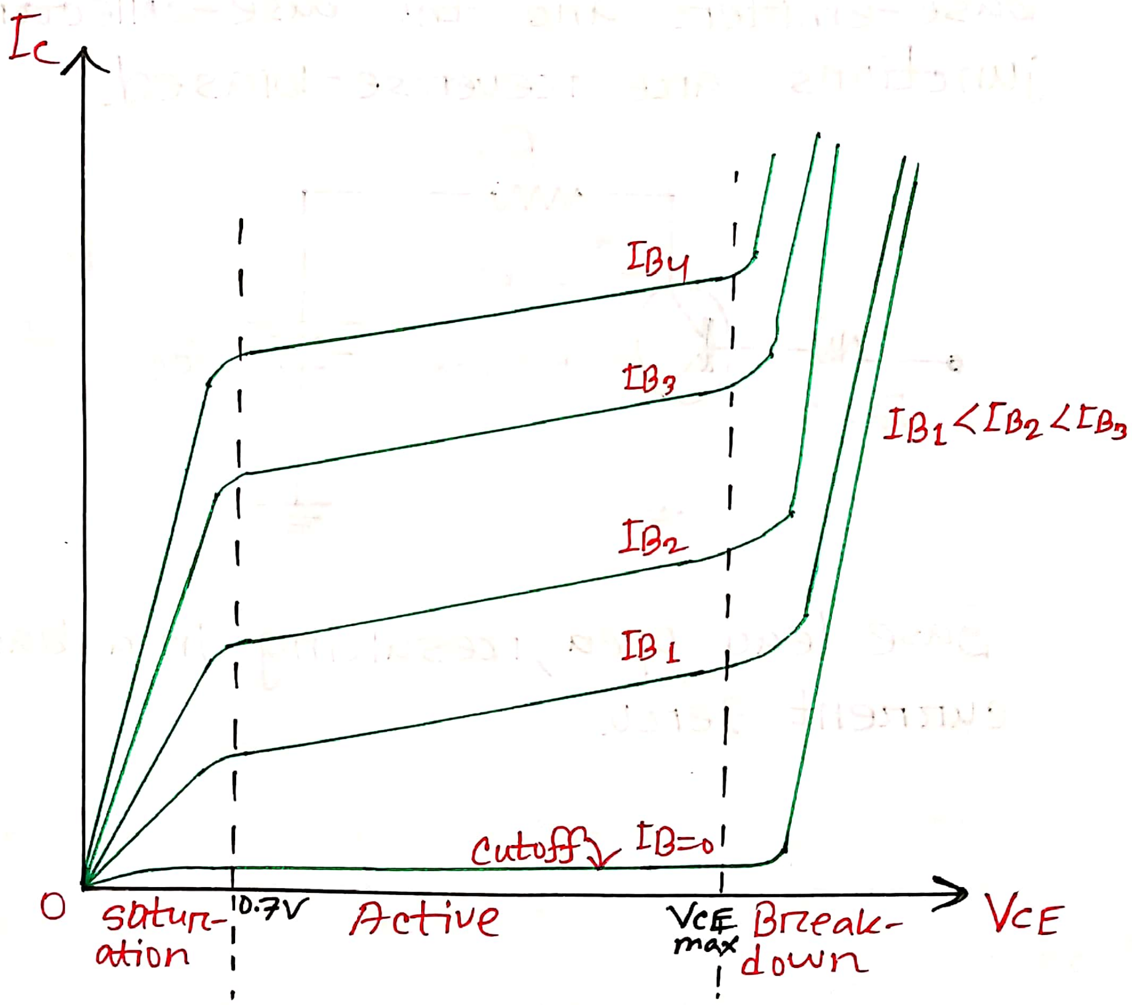
☞ Active region: As V_{CC} is increased, V_{CE} increases gradually as the collector current increases.

I_C increases as V_{CC} is increased as V_{CE} remains less than 0.7V, due to forward-biased base-collector junction.

Ideally when V_{CE} exceeds 0.7V, the base-collector junction becomes reverse-biased and the transistor goes into the active or linear region of its operation. After that I_C increases very slightly with the increases of V_{CC}.

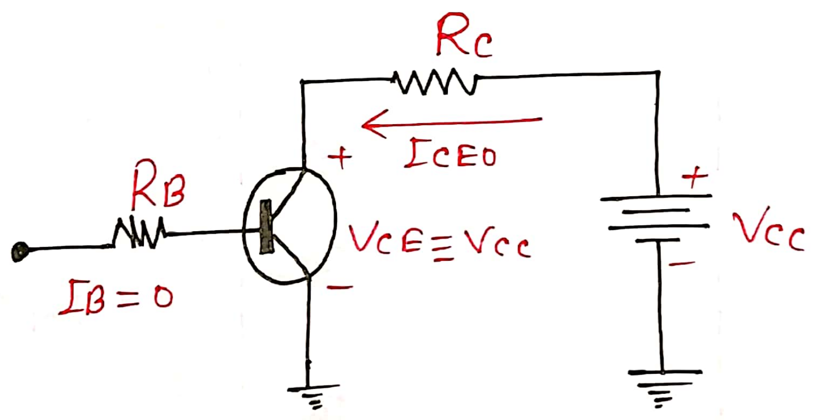
Breakdown region: When V_{CE} reaches a sufficiently high voltage, the reverse-biased base-collector junction goes into breakdown; and the collector current increases rapidly.

The transistor is in the cutoff region when $I_B = 0$ although there is a small collector leakage current.



Cutoff

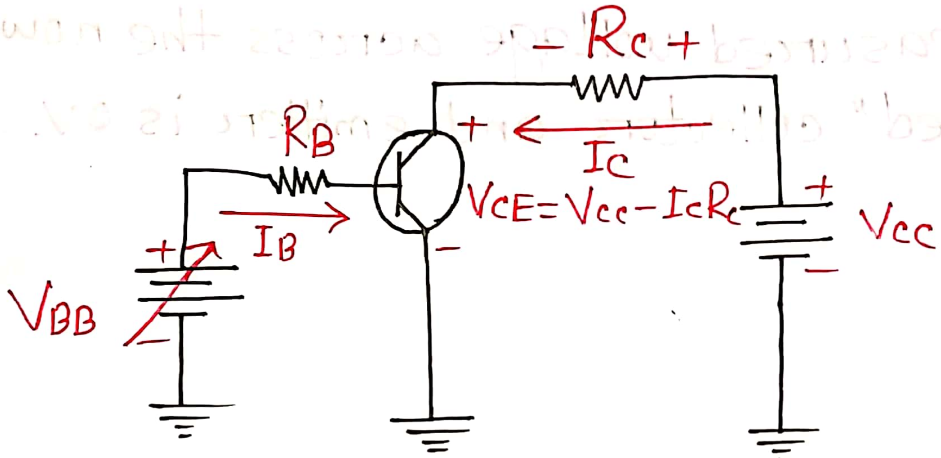
- When $I_B = 0$, the transistor is in the cutoff region of its operation. Under this condition, there is a very small amount of collector leakage current, I_{CEO}, due to thermally produced carriers. Because I_{CEO} is extremely small, it will usually be neglected in circuit analysis so that $V_{CE} = V_{CC}$. In cutoff, both the base-emitter and the base-collector junctions are reverse-biased.



Base lead open, resulting in a base current zero.

Saturation

When the base-emitter junction becomes forward-biased and the base current is increased, the collector current also increases ($I_C = \beta_{DC} I_B$) and V_{CE} decreases as a result of more drop across the collector resistance ($V_{CE} = V_{CC} - I_C R_C$).



At the point of saturation, the relation $I_C = \beta_{DC} I_B$ is no longer valid.
As I_B increases due to increasing V_{BB}, I_C also increases and V_{CE} decreases due to the increased voltage drop across the R_C. When the transistor reaches the saturation, I_C can increase no further regardless of further increase in I_B.
Base-emitter and base-collector junctions are forward-biased.

Saturation Region

Once the maximum is reached, the transistor is said to be in saturation. Saturation can be determined by application of Ohm's law.

$$I_{C(sat)} = \frac{V_{CC}}{R_C}$$

The measured voltage across the now "shorted" collector and emitter is 0V.

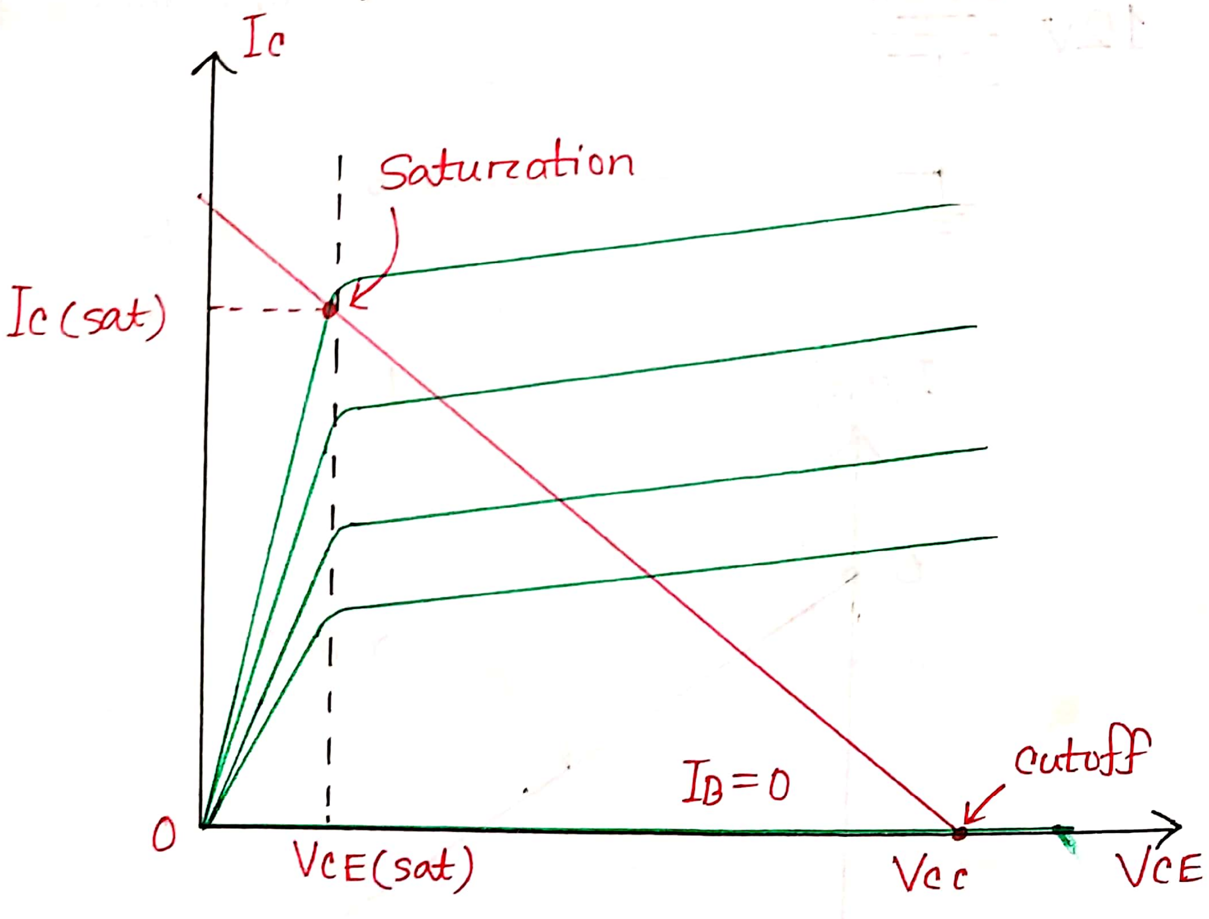
DC Load Line

Cutoff and saturation can be illustrated in relation to the collector characteristic curves by the use of a load line.

The bottom of the load line is at ideal cut-off where $I_C = 0$ and $V_{CE} = V_{CC}$.

The top of the load line is at saturation where $I_C = I_{C(sat)}$ and $V_{CE} = V_{CE(sat)}$.

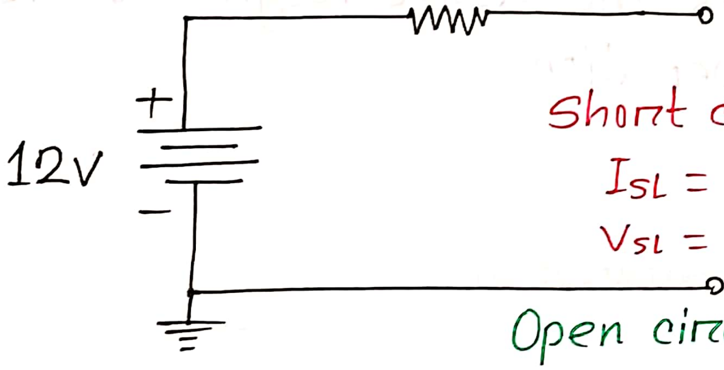
In between cutoff and saturation along the load line is the active region of the transistor's operation.



☞ More on DC load lines-1

A load line is an IV curve that represents the response of a circuit that is external to a specified load.

For example, the load line for the Thevenin circuit can be found by calculating the two end points: the current with a shorted load and the output voltage with no load.



Short circuit current:

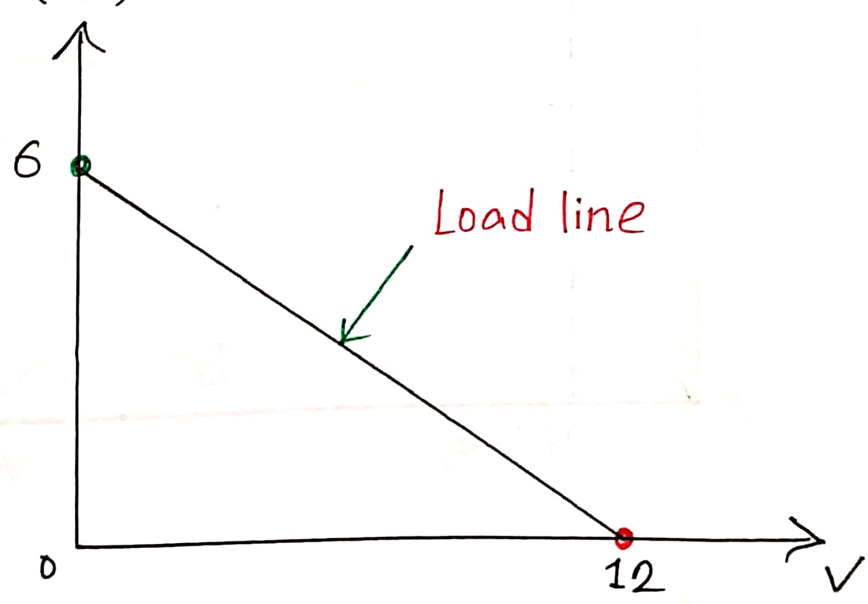
$I_{SL} = 6.0\,mA$

$V_{SL} = 0\,V$

Open circuit voltage:

$I_{NL} = 0\,A$

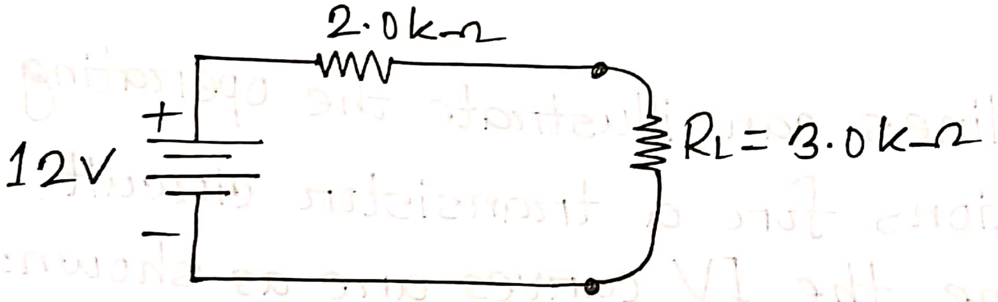
$V_{NL} = 12V$

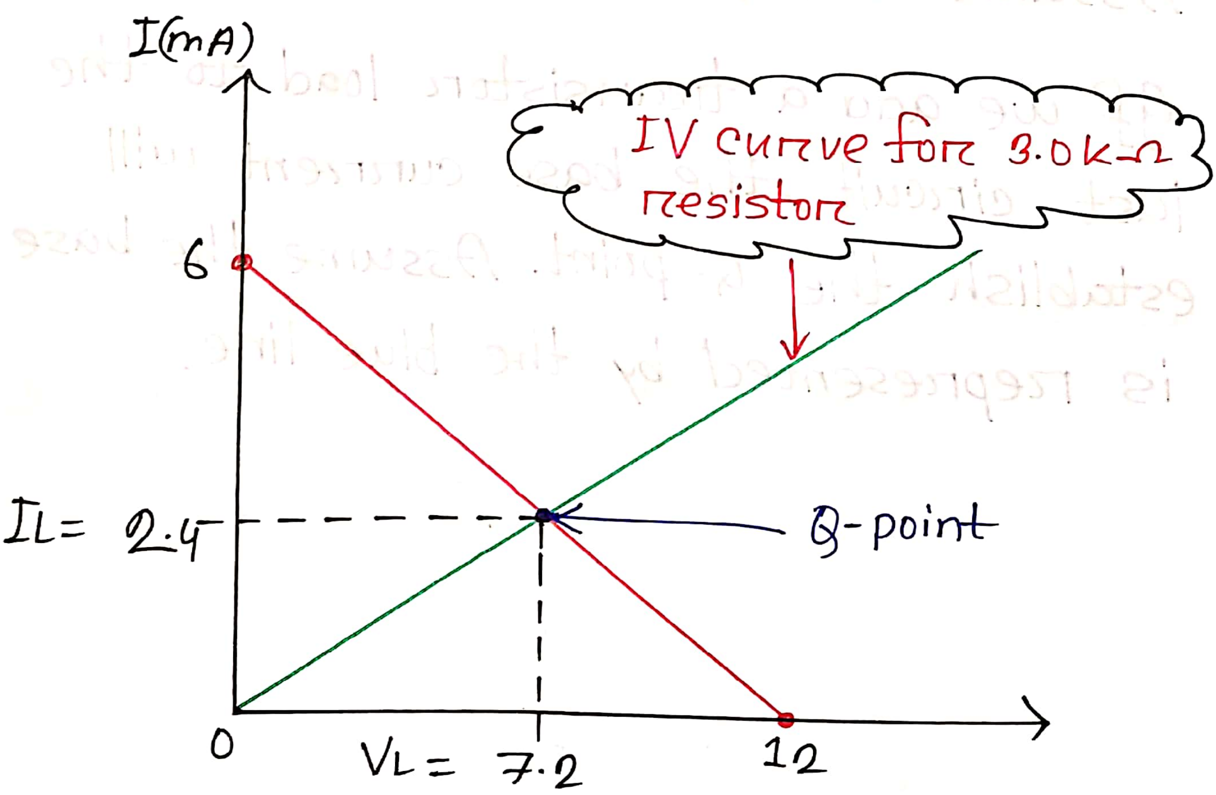


More on DC load lines-2

The IV response for any load will intersect the load line and enables you to read the load current and load voltage directly from the graph.

Example: Read the load current and load voltage from the graph if a 3.0kΩ resistor is the load.



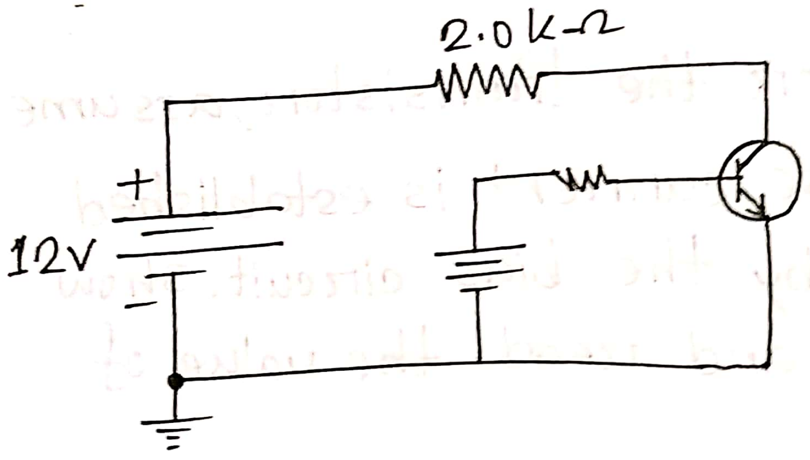


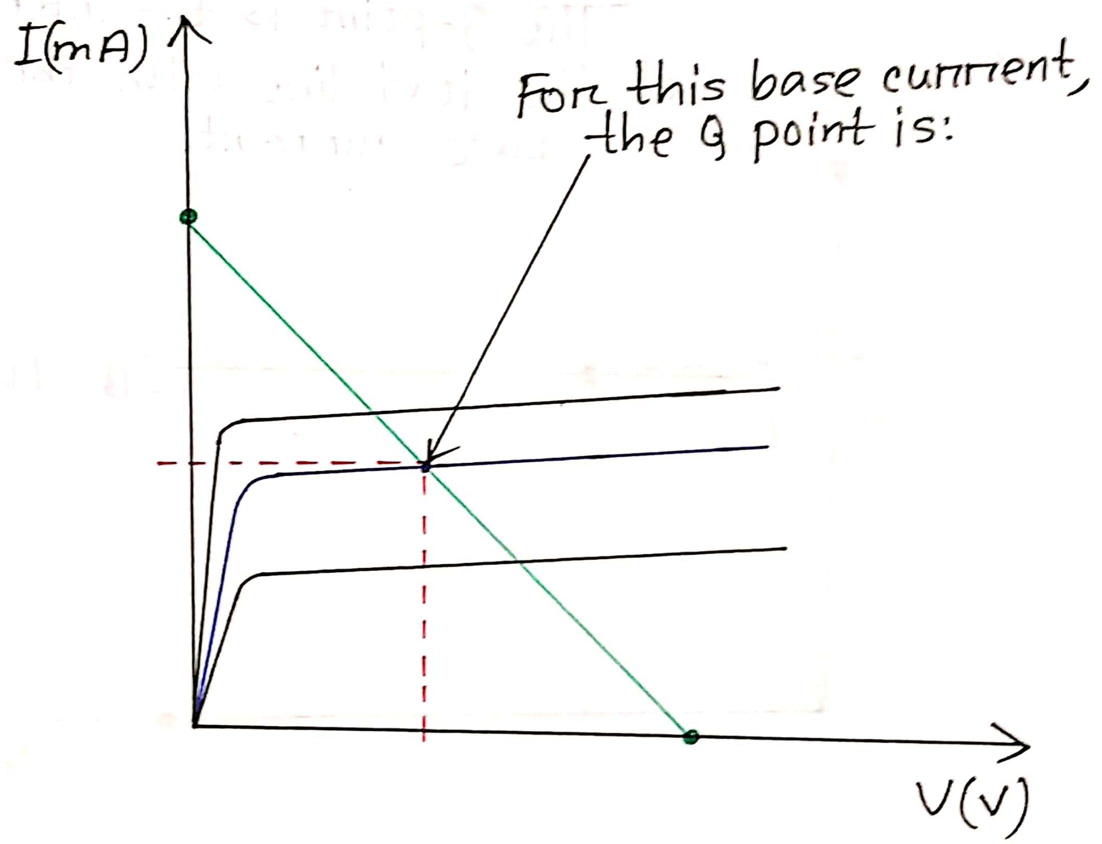
More on DC Load Lines-3

The load line concept can be extended to a transistor circuit. For example, if the transistor is connected as a load, the transistor characteristic curve and the base current establish the Q point.

Load lines can illustrate the operating conditions for a transistor circuit. Assume the IV curves are as shown:

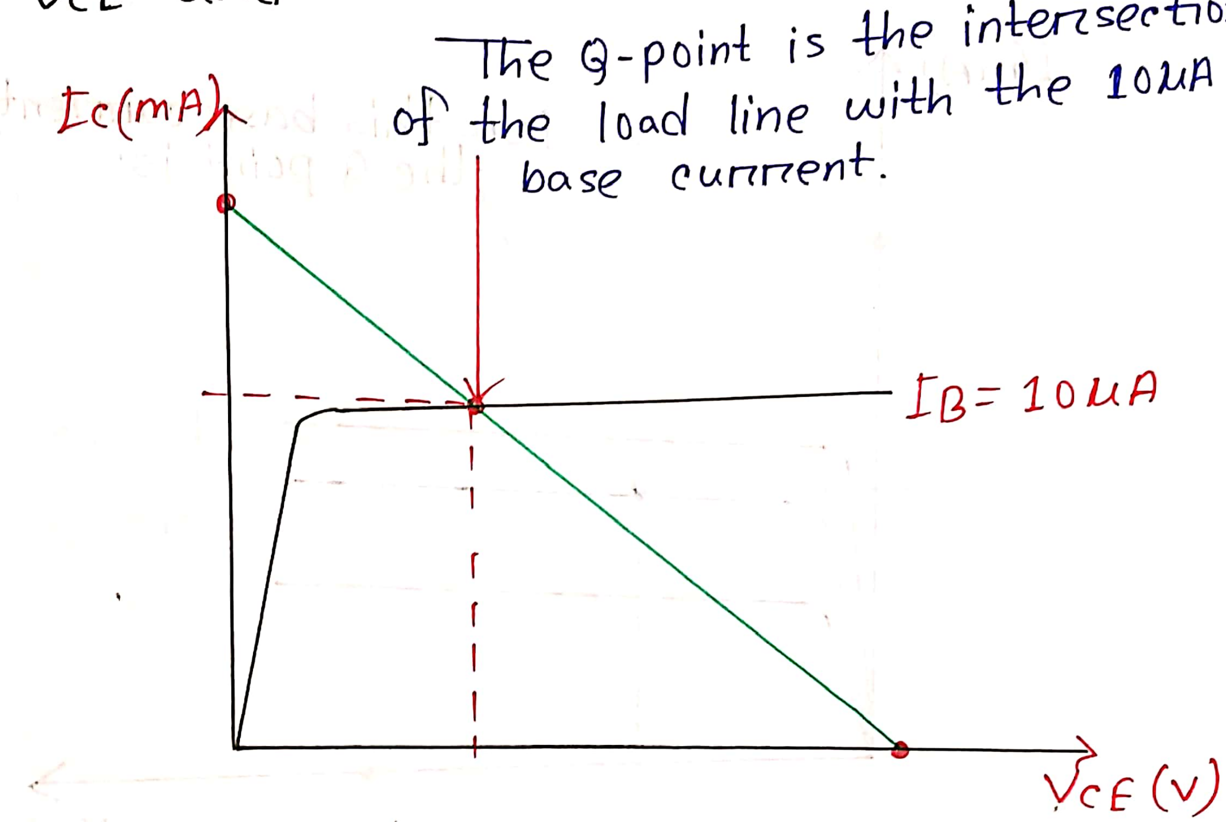
If we add a transistor load to the last circuit, the base current will establish the Q-point. Assume the base is represented by the blue line.





The load voltage (V_{CE}) and current (I_C) can be read from the graph.

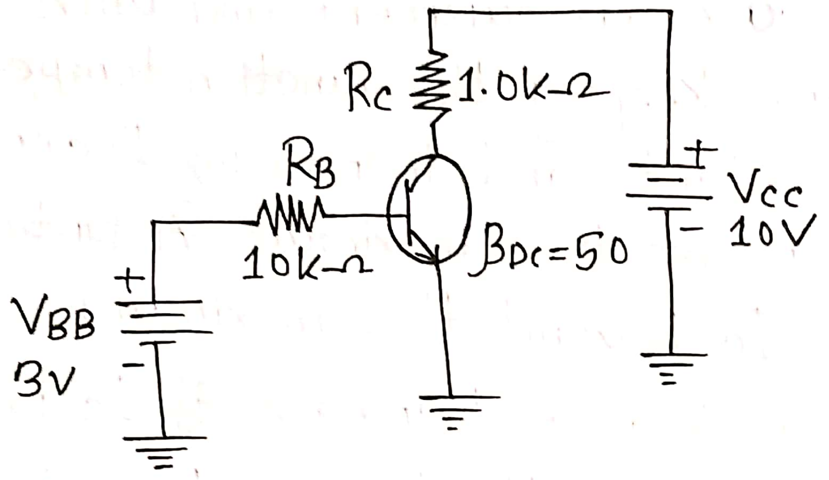
Example: For the transistor, assume the base current is established at 10 μA by the bias circuit. Show the Q-point and read the value of V_{CE} and I_C.



$V_{CE} = 7.0V$

$I_C = 2.4mA$

Determine whether or not the transistor in the following figure is in saturation. Assume $V_{CE(sat)} = 0.2\ V$.



Solution: $V_{CE(sat)} = 0.2\ V$

$$I_{C(sat)} = \frac{V_{CC} - V_{CE(sat)}}{R_C} = \frac{(10 - 0.2)\,V}{1\,k\Omega}$$

$$= 9.8\,mA$$

If I_B is large enough to produce $I_{C(sat)}$

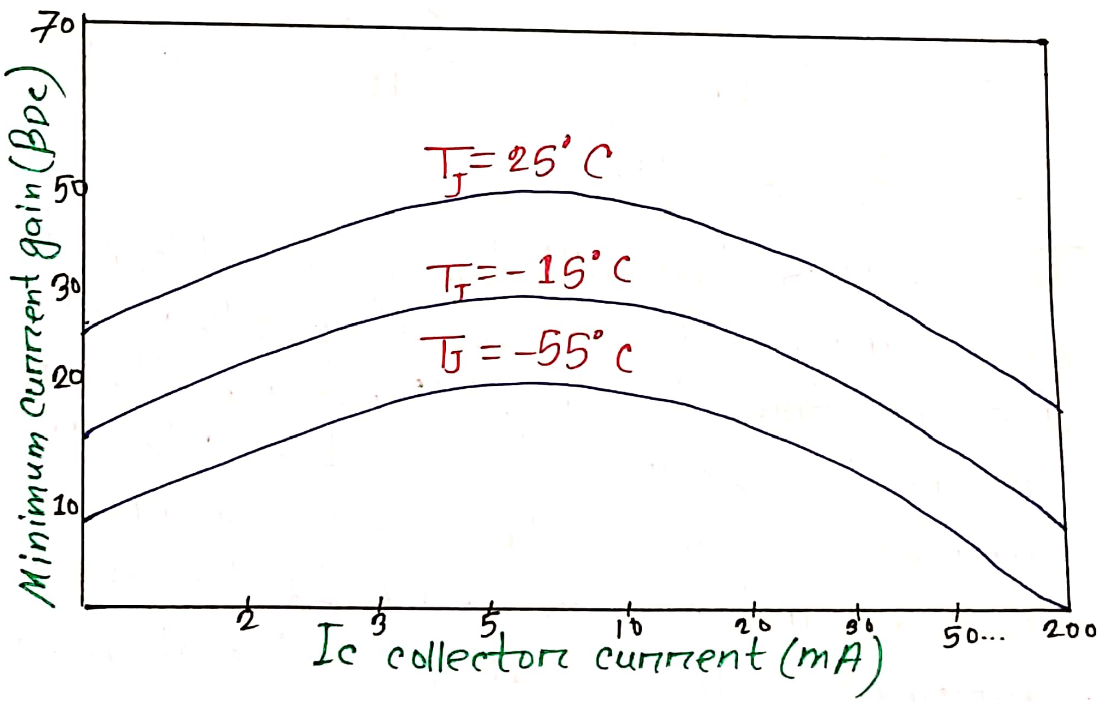
$$I_B = \frac{V_{BB} - V_{BE}}{R_B} = \frac{(3 - 0.7)\,V}{10\,k\Omega} = 0.23\,mA$$

$$I_C = \beta_{DC} I_B = 11.5\,mA$$

This shows that with the specified β_{DC}, this base current is capable of producing an I_C greater than $I_{C(sat)}$. Therefore, the transistor is saturated and the collector current value of 11.5mA is never reached. If we further increase I_B, the collector current remains at its saturation value.

More about β_{DC}

β_{DC} is not truly constant but varies with both collector current and with temperature. Keeping the junction temperature constant and increasing I_C causes β_{DC} to increase to a maximum. A further increase in I_C beyond this maximum point causes β_{DC} to decrease. If I_C is held constant and the temperature is varied, β_{DC} changes directly with the temperature. If the temperature goes up, β_{DC} goes up and vice versa.



Maximum Transistor Rating

A transistor, like any other electronic device, has limitations on its operation. These limitations are stated in the form of maximum rating and are normally specified on the manufacturing data sheet. Typically, maximum ratings are given for collector-to-base voltage, collector to emitter voltage, emitter to base voltage, collector current and power dissipation.

The product of V_{CE} and I_C must not exceed the maximum power dissipation. Both V_{CE} and I_C can not be maximum at the same time. If V_{CE} is maximum, I_C can be calculated as

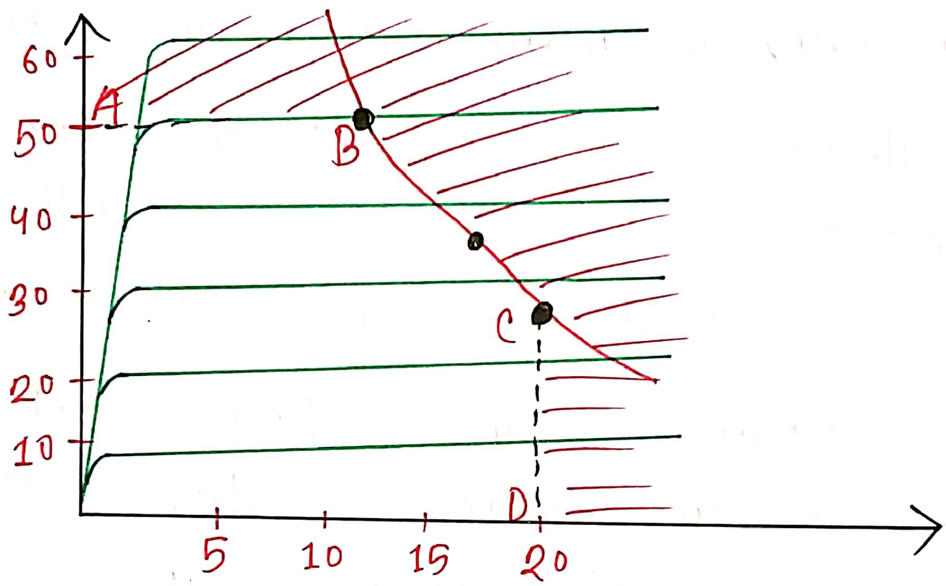
$$I_C = \frac{P_{D(max)}}{V_{CE}}$$

If I_C is maximum, V_{CE} can be calculated by rearranging -

$$V_{CE} = \frac{P_{D(max)}}{I_C}$$

Maximum power dissipation curve

For any given transistor, a maximum power dissipation curve can be plotted on the collector characteristic curves as shown below:



The values are tabulated as:

$P_{D(max)}$	V_{CE}	I_C
500 mW	5 V	100 mA
500 mW	10 V	50 mA
500 mW	15 V	33 mA
500 mW	20 V	25 mA

Assume $P_{D(max)}$ is 500 mW, $V_{CE(max)}$ is 20 V and $I_{C(max)}$ is 50 mA. The curve shows that this particular transistor can not be operated in the shaded portion of the graph. $I_{C(max)}$ is the limiting rating between points A and B, $P_{D(max)}$ is the limiting rating between points B and C, and $V_{CE(max)}$ is the limiting rating between points C and D.

Example: A certain transistor is to be operated with $V_{CE} = 6V$. If its maximum power rating is 250 mW, what is the most collector current that it can handle?

Solution: $$I_C = \frac{P_{D(max)}}{V_{CE}} = \frac{250mW}{6V}$$

$$= 41.7mA$$

This is not necessarily the maximum I_C. The transistor can handle more collector current if V_{CE} is reduced, as $P_{D(max)}$ is not exceed.