Bipolar transistors

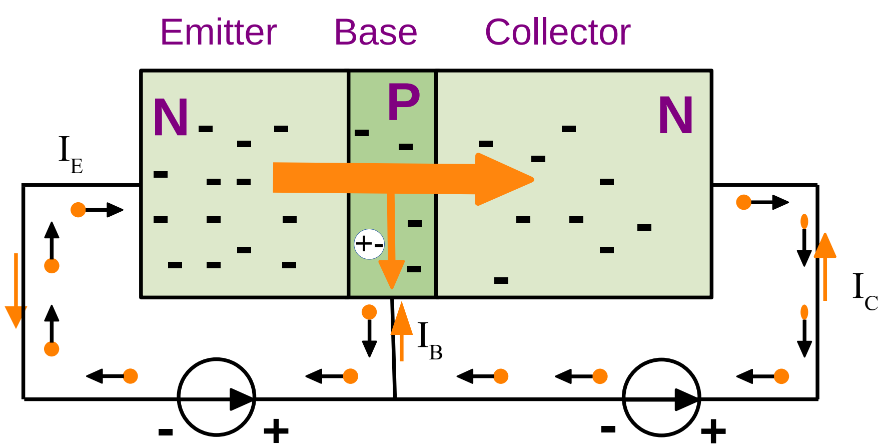
1. Transistor working

The emitter-base junction of a transistor is forward biased whereas collector-base junction is reverse biased. If for a moment, we ignore the presence of emitter-base junction, then *practically (see note 1)* no current would flow in the collector circuit because of the reverse bias. However, if the emitter-base junction is also present, then forward bias on it causes the emitter current to flow. It is seen that this emitter current almost entirely flows in the collector circuit. Therefore, the current in the collector circuit depends upon the emitter current. If the emitter current is zero, then collector current is nearly zero. However, if the emitter current is 1mA, then collector current is also about 1mA. This is precisely what happens in a transistor. We shall now discuss this transistor action for NPN and PNP transistors.

Note 1 : In actual practice, a very little current, a few µA, would flow in the collector circuit. This is called collector cut off current and is due to minority carriers.

1.1. NPN Transistor working

The Below Fig shows the NPN transistor with forward bias to emitter-base junction and reverse bias to collector-base junction. The forward bias causes the electrons in the N-type emitter to flow towards the base. This constitutes the emitter current I_E. As these electrons flow through the *P*-type base, they tend to combine with holes. As the base is lightly doped and very thin, therefore, only a few electrons (less than 5%) combine with holes to constitute base (note 2) current I_B. The remainder ((Note 3) more than 95%) cross over into the collector region to constitute collector current I_C. In this way, almost the entire emitter current flows in the collector circuit. It is clear that emitter current is the sum of collector and base currents *i.e.:* $I_E = I_B + I_C$



basic connection of NPN transistor

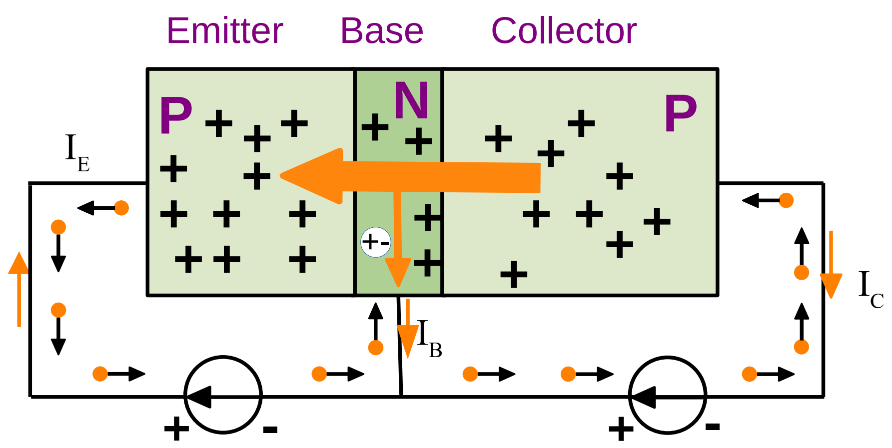
Note 2: The electrons which combine with holes become valence electrons. Then as valence electrons, they flow down through holes and into the external base lead. This constitutes base current I_B.

Note 3: The reasons that most of the electrons from emitter continue their journey through the base to collector to form collector current are :

- *The base is lightly doped and very thin. Therefore, there are a few holes which find enough time to combine with electrons.*
- *The reverse bias on collector is quite high and exerts attractive forces on these electrons.*

1.2. *PNP Transistor working*

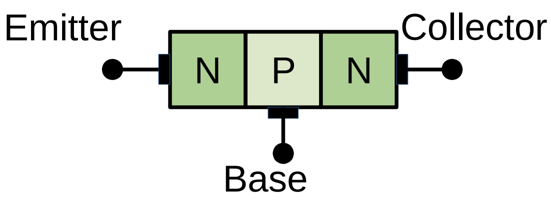
The below Fig shows the basic connection of a PNP transistor. The forward bias causes the holes in the P-type emitter to flow towards the base. This constitutes the emitter current I_E. As these holes cross into N-type base, they tend to combine with the electrons. As the base is lightly doped and very thin, therefore, only a few holes (less than 5%) combine with the electrons. The remainder (more than 95%) cross into the collector region to constitute collector current I_C. In this way, almost the entire emitter current flows in the collector circuit. It may be noted that current conduction within PNP transistor is by holes. However, in the external connecting wires, the current is still by electrons.



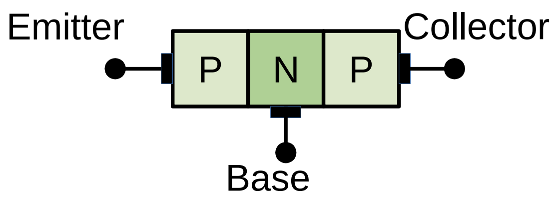
Basic connection of PNP transistor

1.3. Definitions

The bipolar transistor is a 3-electrode component with 2 PN junctions. It is a semiconductor crystal in which we can distinguish 3 segments doped either N or P, according to one of the above two configurations (Principle structures).



NPN Transistor

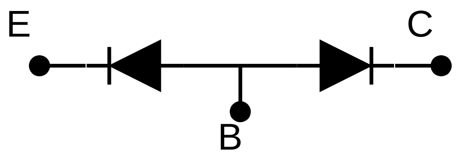


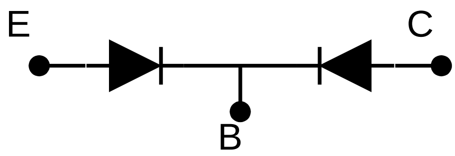
PNP Transistor

The three segments are named Base, Emitter and Collector and are equipped with metal electrodes.

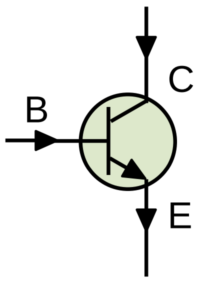
- B = Base, very thin and very little doped
- E = Emitter, highly doped
- C = Collector, large volume and less doped than the Emitter.

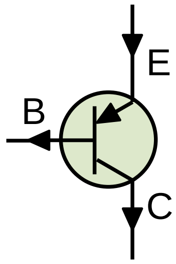
The following figures give a 2 diodes analogy of transistors:





1.4. Symbolic representation:

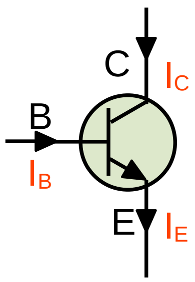




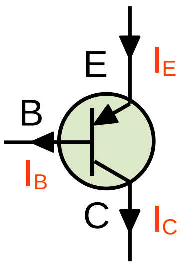
Note: The arrow on the Emitter indicates the passing direction of the base Emitter junction.

2. Static characteristics:

2.1. Direction of currents convention:



NPN



PNP

Note: For the rest, we will study only the NPN transistor. It is the most used one

The transistor can be characterized by 2 transfer coefficients:

- α = Transfer coefficient of the emitter current
- β = Transfer coefficient of the base current.

The base-emitter junction is polarized forward (normal regime). The electrons of the emitter will therefore easily cross this junction, and will end up in the base, which is very little doped => Little recombination electrons/holes.

In addition, the base is thin. The electrons coming from the Emitter are therefore mainly found at the base collector junction which is polarized in reverse. The electrons will then easily cross this junction. The collector current will therefore be almost entirely constituted by the electrons coming from the Emitter.

$$\Rightarrow \qquad I_C = \alpha . I_E \qquad \text{with } \alpha \in [\, 0{,}95;\, 0{,}995]$$

However, we also have

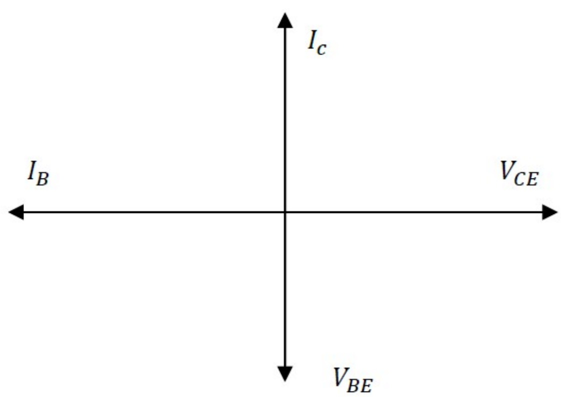
$$I_B + I_C = I_E$$

$$\alpha . I_B + \alpha . I_C = \alpha . I_E$$

$$I_C (1-\alpha) = \alpha . I_B$$

$$I_C = \frac{\alpha}{(1-\alpha)} . I_B \qquad so \qquad I_C = \beta . I_B \qquad (\beta \in [15\,;\,500])$$

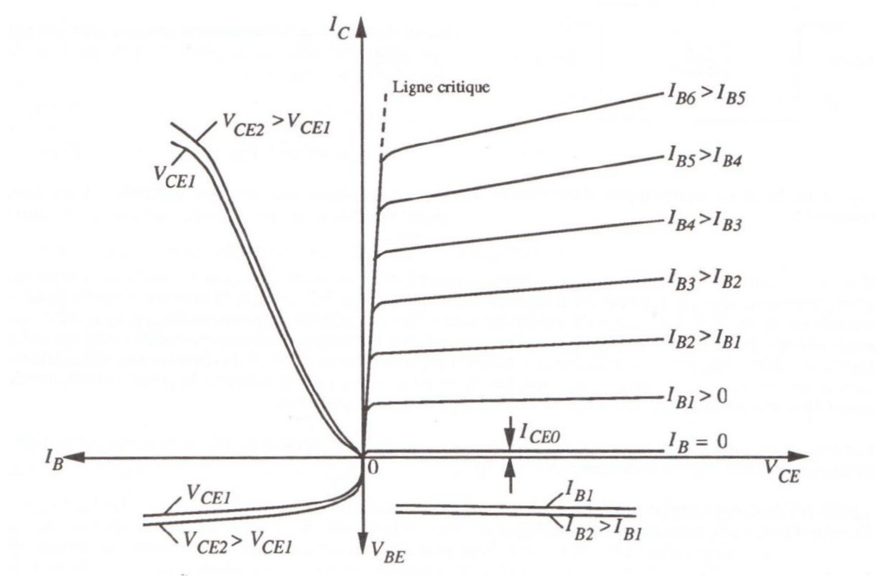
It is customary to represent the characteristics of a transistor with the following axes:



1. Curves $V_{BE} = f(I_B)\, at\, V_{CE} = cst$ The set of these curves is called <u>the input network</u>. The curves correspond to the characteristic of a forward PN junction.
2. Curves $I_C = f(I_B)\, at\, V_{CE} = cst$: This family is called <u>characteristic curves of current transfer</u>. They are often approximated by a straight line and make it possible to determine β. ($I_C = \beta . I_B$).

3. Curves $I_C = f(I_B)$ at $I_B = cst$: This family of curves is called output characteristic.
4. Curves $V_{BE} = f(V_{CE})$ at $I_B = cst$: This family of curves is called voltage transfer characteristic.

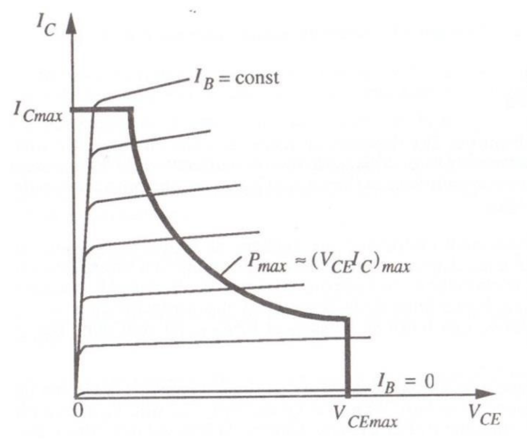
The complete characteristics network is the following:



2.2. The absolute limit values

The absolute limit values are given in the manufacturers catalogs. They delimit on the output characteristics of the transistor a domain outside which the use of the transistor is dangerous:

- I_{Cmax} = Maximum collector current value.
- V_{CEmax} = Value of the maximum voltage V_{CE}
- P_{max} = Maximum value of the power supported by the transistor.



The power delivered by the transistor is maximum when it operates in normal mode.

In saturated regime, it is relatively low because of the small value of V_{ce}. In blocked mode, it is small because of the low value of I_E

The power dissipated by the transistor is determined by $P = V_{CE} I_C$

The manufacturer gives P_{max} then $I_{Cmax} = \frac{P_{max}}{V_{CE}}$

We can also have on the manufacturer documentation: I_{Bmax}, V_{CBmax} and V_{BEmax}

3. Transistors Polarization:

3.1. Preliminary

The transistor is a current amplifier, we will therefore use it to amplify signals from various sources.

It will be necessary to implement a whole assembly around the transistor for several reasons:

- The transistor, while being classified in the active components, does not provide energy: it will therefore come from somewhere! This is the role of the power supply that will be used to bring the polarization voltages and energy that the assembly will be likely to provide at the output.
- The transistor only allows the current to pass in one direction: it will therefore be necessary to polarize it to be able to pass alternating current, that is to say superimpose on the alternating current a direct current large enough so that the total current (direct + alternating) always circulates in the same direction.
- In addition, the alternating component of the current must be sufficiently small in front of the continuous component for the linearization made under the small signal hypothesis to be justified.
- The transistor is a current generator. As it is more convenient to manipulate voltages, it will be necessary to convert these currents into voltages: we will do it simply by putting resistors in judiciously chosen places of the assembly.

As far as possible, the polarization must make the assembly insensitive to thermal drifts of the transistor and it must be independent of its characteristics (including gain), this so that the assembly is universal, and does not work only with the transistor available to make the model. This also makes it possible to change the transistor on the assembly without asking questions in case of failure.

The equations of the transistor and its characteristics are not linear. But, as with the diode, they can be considered as such for small signals. The amplitudes of small signals can be all the larger the larger the linear cross-sections of the characteristics used.

Even before the small signal is applied, the operating point of the transistor must be placed in the linear area of its characteristics. This is the role of the polarization circuit. The polarization is carried out with a power source.

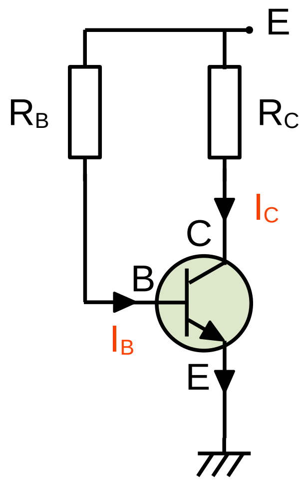
To calculate the polarization point, it is necessary to determine:

- The external characteristics (meshes and nodes laws) and
- The internal characteristics (specific to the transistor).

This results in a system with 5 unknowns ($I_{B0}, I_{C0}, I_{E0}, V_{BE0}, V_{CE0}$). The zero index means that these are the values at the point of operation. Additional conditions related to the specifications make it possible to find the value of the resistors and the generator.

3.2. Base resistor polarization

This method of biasing is common in switching circuits. The figure shows a base-biased transistor.



Base resistor polarization

The base resistor R_B ensure a fixed current I_{B0}, which results in a fixed collector current $I_{C0}=\beta I_{B0}$

The collector **resistor** R_C, in addition to ensuring a correct polarization of the base-collector junction, converts the collector current (and its variations) into voltage.

The analysis of this circuit for the linear region shows that it is directly dependent on β.

Base Resistor calculation:

- External conditions: We take two meshes:

  $V_{BE}+R_B I_B=E$ *(1)* $V_{CE}+R_C I_C=E$ *(2)*

- Internal conditions:

  $I_C=\beta I_B$ *(3)* $I_C+I_B=I_E$ *(4)*

in (1), we replace I_B with its value in (3) and then with numerical values

$V_{CE}+R_C I_C=E$ *(1)* => $R_C=\frac{(E-V_{CE0})}{I_{C0}}$

$V_{BE}+R_B \frac{I_C}{\beta}=E$ *(2)* => $R_B=\beta\frac{(E-V_{BE})}{I_{C0}}$

__**Example given specifications**__:

$E=10V,$ The transistor has : $\beta=100$ and $V_{BE}=0.6V.$

and we want $I_{C0}=10\,mA$ and $V_{CE0}=5\,V.$

$$R_C = \frac{(10-5)}{10.10^{-3}} = 500\,\Omega \qquad R_B = 100\frac{(10-0.6)}{10.10^{-3}} = 94\,k\Omega$$

Notes:

1. In the above example we started from what we want (the current I_{C0} and the voltage V_{CE0}), and go up the chain to calculate R_C and R_B.
   - The quiescent collector current I_{C0} is chosen according to the application, and in general will vary between 10 µA and 10 mA.
   - The collector voltage V_{CE0} is generally taken equal to E/2, so that the collector voltage can vary both upwards and downwards when an alternating signal is applied.
2. In some designs we could have R_B and R_C given and have to calculate the polarization point Q (V_{CE0}, I_{C0}).

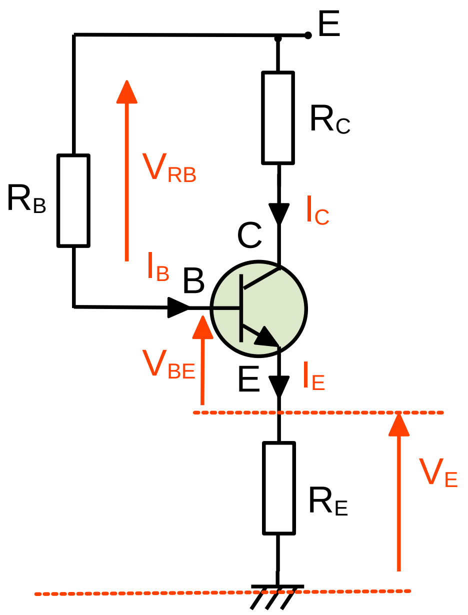
Q-Point Stability of Base Bias

Notice that Above Equation shows that Icis dependent on β. The disadvantage of this is that a variation in β causes I_C and, as a result, V_{CE} to change, thus changing the Q-point of the transistor. This makes the base bias circuit extremely beta-dependent and unpredictable.

Recall that β varies with temperature and collector current. In addition, there is a large spread of β values from one transistor to another of the same type due to manufacturing variations.

For these reasons, base bias is rarely used in linear circuits but is discussed here so you will be familiar with it.

3.3. Emitter feedback polarization



Emitter feedback Bias

If an emitter resistor is added to the base-bias circuit, the result is emitter-feedback bias, as shown in Figure. The idea is to help make base bias more predictable with negative feedback, which negates any attempted change in collector current with an opposing change in base voltage. If the collector current tries to increase, the emitter voltage increases, causing an increase in base voltage because $V_B = V_E + V_{BE}$.

This increase in base voltage reduces the voltage across RB, thus reducing the base current and keeping the collector current from increasing. A similar action occurs if the collector current tries to decrease. While this is better for linear circuits than base bias, it is still dependent on β and is not as predictable as voltage-divider bias.

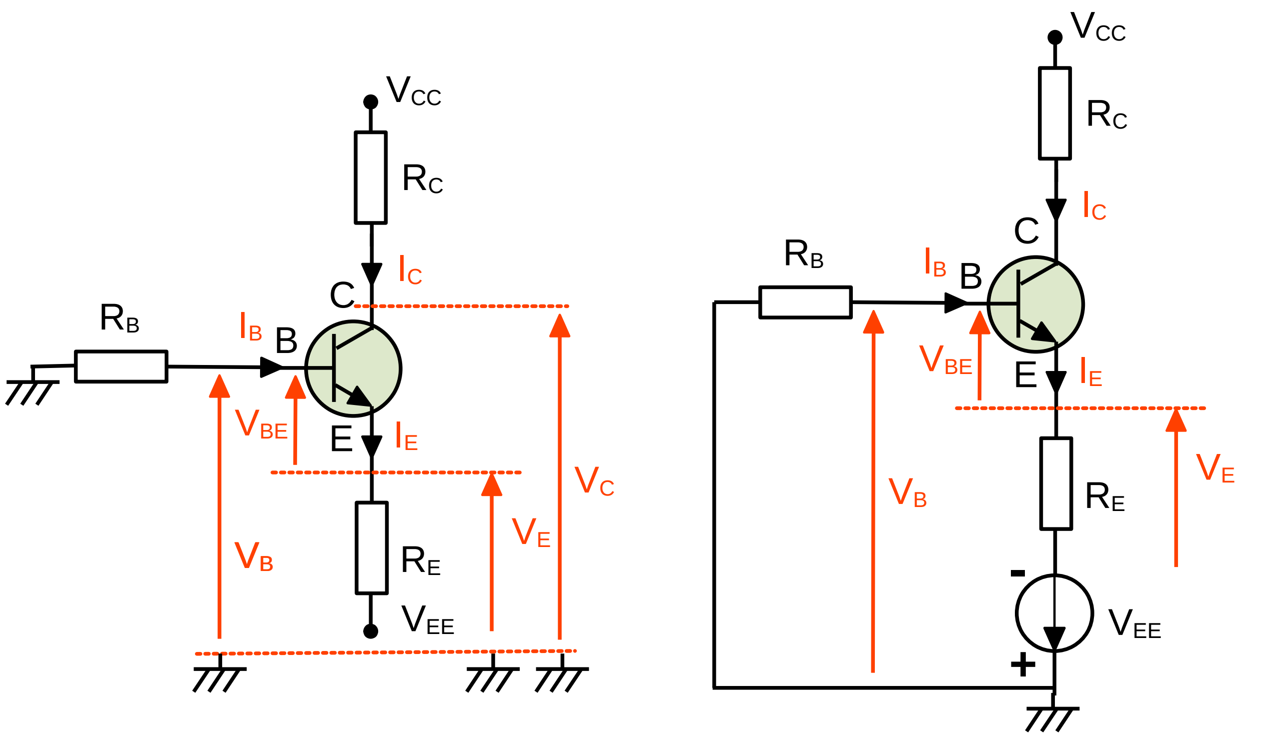
To calculate I_C, you can write Kirchhoff's voltage law (KVL) around the base circuit.

$$I_B . R_B + V_{BE} + I_E . R_E = E,$$

Substituting $\frac{I_C}{\beta}$ for I_B and considering $I_E \approx I_C$, we can see that $I_C = \frac{(E - V_{BE})}{\left(R_E + \frac{R_B}{\beta}\right)}$ is still dependent on β.

3.4. Emitter polarization

Emitter bias provides excellent bias stability in spite of changes in β or temperature. It uses both a positive and a negative supply voltage. To obtain a reasonable estimate of the key dc values in an emitter-biased circuit, analysis is quite easy. In an NPN circuit, such as shown in Figure, the small base current causes the base voltage to be slightly below ground.



a. b.

Kirchhoff's voltage law can be applied as follows to develop a more detailed formula for I_C. Kirchhoff's voltage law applied around the base-emitter circuit in Figure (a), which has been redrawn in part (b) for analysis, gives the following equation: $V_{EE}+V_B+V_{BE}+V_E=0$

Substituting using Ohm's law: $V_{EE}+I_B.R_B+V_{BE}+I_E.R_E=0$

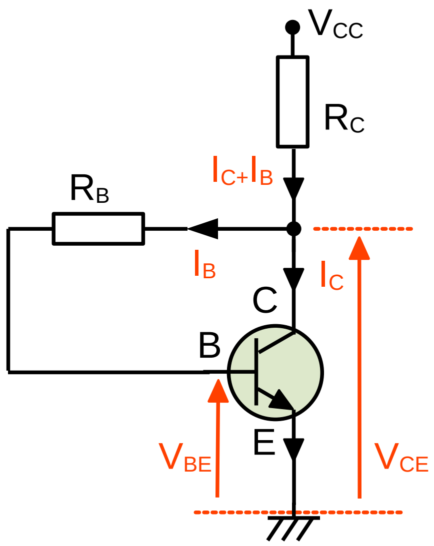
Substituting $\frac{I_C}{\beta}$ for I_B and considering $I_E \approx I_C$, then: $\frac{I_C}{\beta}.R_B+I_C.R_E+V_{BE}=-V_{EE}$

We can see that $I_C=\frac{(-V_{EE}-V_{BE})}{(R_E+\frac{R_B}{\beta})}$ is still dependent on β.

Voltages with respect to ground are indicated by a single subscript.

The emitter voltage with respect to ground is: $V_E=V_{EE}+I_E.R_E$, the base voltage to respect to ground is: $V_B=V_E+V_{BE}$ and the collector voltage in respect to ground is: $V_C=V_{CC}-I_C.R_C$

3.5. Collector feedback polarization



Collector Feedback Bias

In this figure, the base resistor R_B is connected to the collector rather than to V_{CC}, as it was in the base bias arrangement discussed earlier. The collector voltage provides the bias for the base-emitter junction. The negative feedback creates an "offsetting" effect that tends to keep the Q-point stable. If I_C tries to increase, it drops more voltage across R_C, thereby causing V_C to decrease. When V_C decreases, there is a decrease in voltage across R_B, which decreases I_B. The decrease in I_B produces less I_C which, in turn, drops less voltage across R_C and thus offsets the decrease in V_C.

By Ohm's law, the base current can be expressed as $I_B=\frac{(V_{CE}-V_{BE})}{R_B}$ (1)

Let's assume that $I_C \gg I_B$ (which is often the case). The collector-emitter voltage is then:

$$V_{CE} \approx V_{CC} - I_C . R_C$$

Also $I_B = \frac{I_C}{\beta}$, substituting for V_{CE} in the equation (1)

$\frac{I_C}{\beta} = \frac{(V_{CC} - I_C . R_C - V_{BE})}{R_B}$ that we can arrange as $\frac{I_C}{\beta} . R_B + I_C . R_C = V_{CC} - V_{BE}$

and $I_C = \frac{(V_{CC} - V_{BE})}{(R_C + \frac{R_B}{\beta})}$

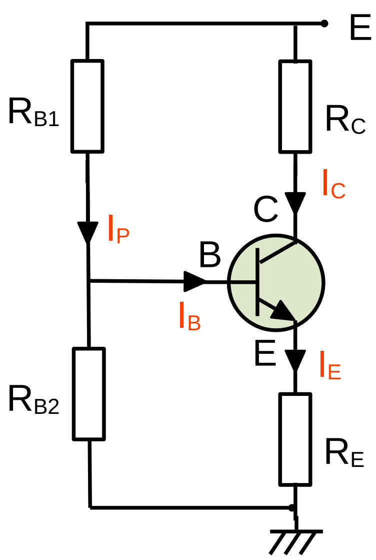
Q-Point Stability Over Temperature

Above Equation shows that the collector current is dependent to some extent on β and V_{BE} . This dependency, of course, can be minimized by making $R_C \gg \frac{R_B}{\beta}$ and $V_{CC} \gg V_{BE}$. An important feature of collector-feedback bias is that it essentially eliminates the β and V_{BE} dependency even if the stated conditions are met.

As you have learned, β varies directly with temperature, and V_{BE} varies inversely with temperature.

As the temperature goes up in a collector-feedback circuit, β goes up and V_{BE} goes down. The increase in β acts to increase I_C . The decrease in V_{BE} acts to increase I_B which, in turn also acts to increase I_C . As I_C tries to increase, the voltage drop across R_C also tries to increase. This tends to reduce the collector voltage and therefore the voltage across R_B , thus reducing I_B and offsetting the attempted increase in I_C and the attempted decrease in V_{CE} . The result is that the collector-feedback circuit maintains a relatively stable Q-point. The reverse action occurs when the temperature decreases.

3.6. Base bridge polarization.



Base Bridge Polarization

This scheme is a bit more complex than the previous ones. We will first analyze the differences, and then we will follow step by step the method of calculating polarization.

The base is polarized using a bridge of resistors R_{B1} and R_{B2}. The role of these resistors will be to set the base potential. As the voltage V_{BE} is close to 0.7 V, this requires to put a resistor between the emitter and the ground.

The resistors of the base bridge will be chosen in such a way that the current circulating in this bridge is much higher than the current entering the base (at least 10 times larger), so that small variations in the base current do not modify the potential of the base, which will therefore remain fixed.

The emitter voltage will be equal to the base voltage minus about 0.7 V and will also be fixed, at a given base current. In this case, the voltage across R_E is determined. The emitter current (so that of the collector, and that of the base, via the β) will then be fixed by the value of the resistance R_E and the voltage of the base bridge.

The collector current being defined, we choose the collector resistor to have V_{CE} in the middle of the usable voltage range.

What is the advantage of this assembly?

Suppose that the current I_{CE} increases under the effect of temperature. The voltage at the terminals of R_E will then increase. As the base potential is fixed by the bridge (R_{B1}, R_{B2}), the voltage V_{BE} will decrease. This decrease will lead to a decrease in the base current and therefore the collector current.

This effect is therefore opposed to the increase in collector current due to the increase in leakage current I_{CE}. The assembly self-stabilizes.

The other advantage is that the collector current is fixed by the base bridge and the emitter resistor. These elements are known to within 5% in general, so, from one assembly to another, we will have little dispersion, and above all, the collector current will be independent of the gain β of the transistor. It has been said for this purpose that the base bridge is calculated so that the base voltage is independent of the base current: this potential will not depend on the transistor, and the base current will automatically adjust according to the gain of the transistor without disturbing the base bridge.

The calculations will be done in the following order:

- **The quiescent collector current** I_C is fixed. Note that the emitter current will be almost the same because $I_C = I_E - I_B \approx I_E$
- **The emitter potential** V_E is set (at most at $\frac{E}{3}$, and in practice, a lower value: 1 to 2 V is a value ensuring a fairly good thermal compensation without too much reducing the output dynamic)

- The **resistance** R_E is then calculated by the formula:

$$R_E = \frac{V_E}{I_C}$$

- We **set** the **collector voltage emitter** V_{CE0}: in general, it will be taken equal to half of the available voltage which is no longer equal to E, but to E - V_E. We **deduce the resistance** R_C

$$\boxed{R_C = \frac{(E - V_E - V_{CE})}{I_C}}$$

- We **fix the current of the base bridge** (we will take an average value for the β transistor, this value is not critical here):

$$I_P = 10\, I_B = 10 \frac{I_C}{\beta}$$

- We **calculate** R_{B2} (as a general rule, we will take V_{BE} equal to 0.7 V):

$$\boxed{R_{B2} = \frac{(V_E + V_{BE})}{I_P}}$$

We **deduce** R_{B1}:

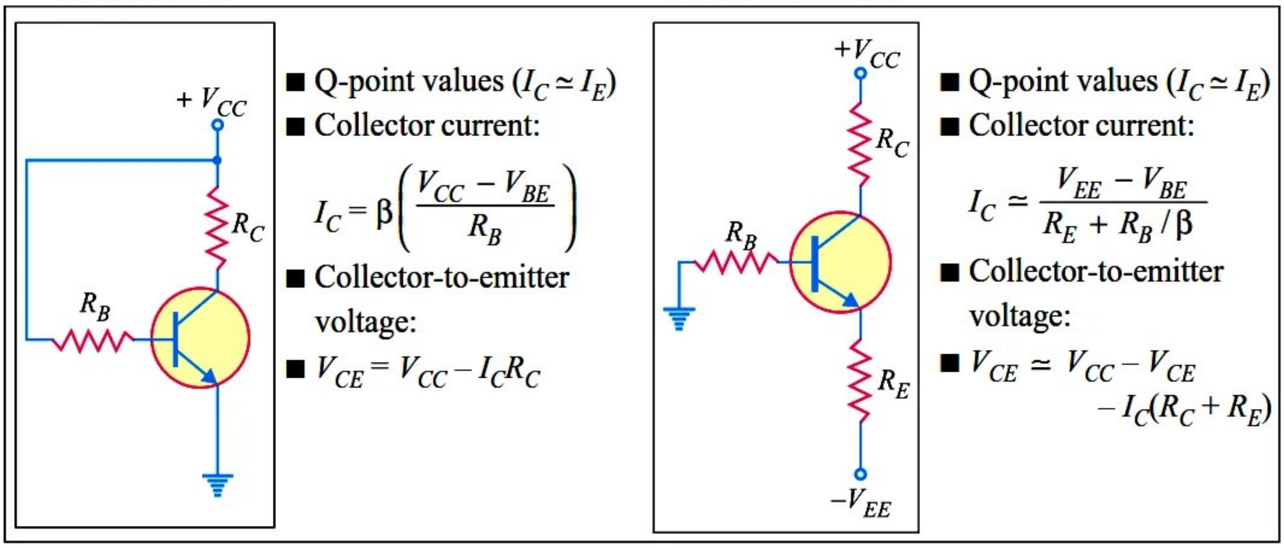
$$\boxed{R_{B1} = \frac{E}{I_P} - R_{B2}}$$

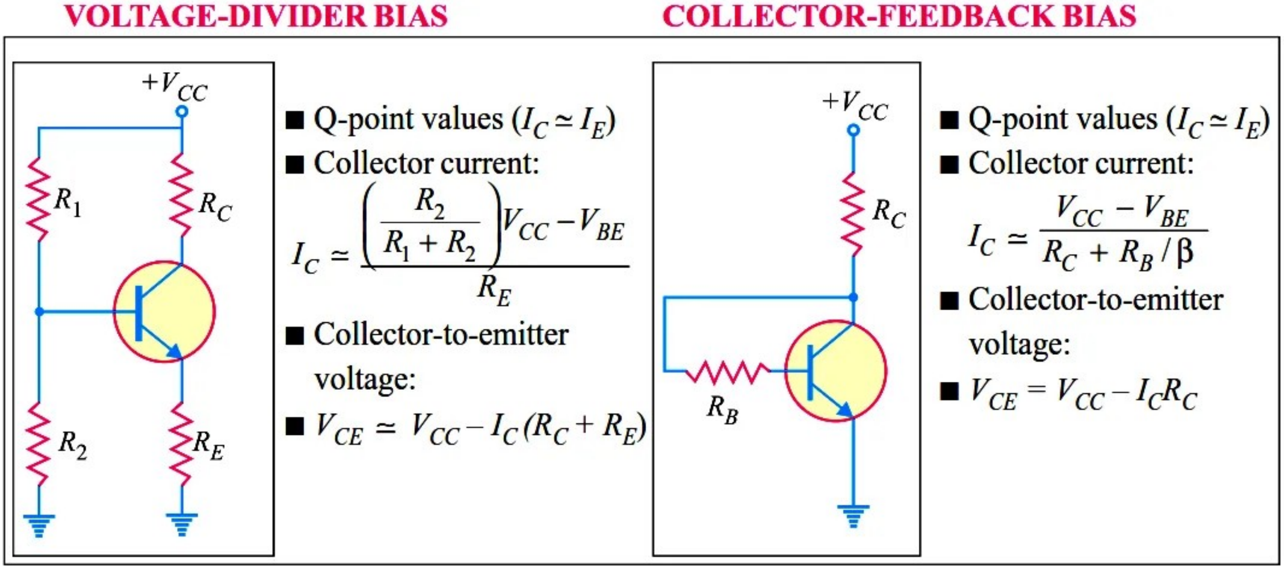
3.7. Summary of Transistor Bias Circuits

In figures below, NPN transistors are shown. Supply voltage polarities are reversed for PNP transistors.

BASE BIAS

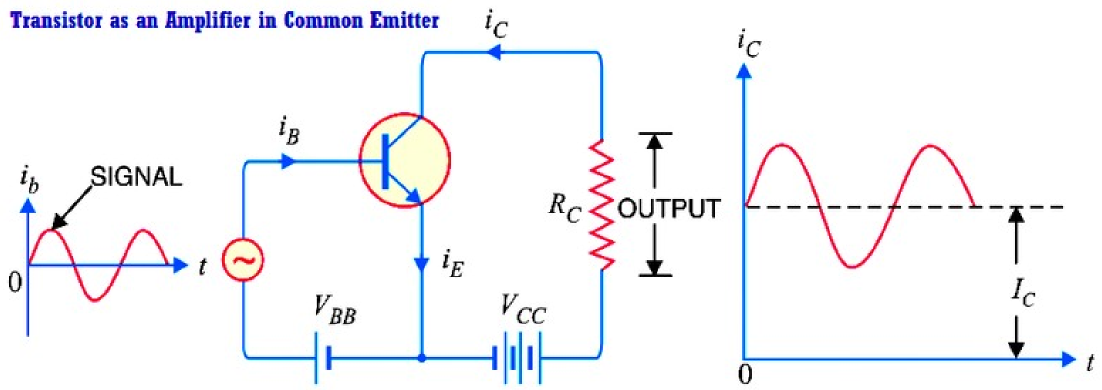
EMITTER BIAS





4. Transistor as an Amplifier in Common Emitter

The below Fig. shows the common emitter NPN amplifier circuit. Note that a battery V_{BB} is connected in the input circuit in addition to the signal voltage. This DC voltage is known as *bias voltage* and its magnitude is such that it always keeps the emitter-base junction forward biased regardless of the polarity of the signal source.



4.1. Operation.

During the positive half-cycle of the signal, the forward bias across the emitter-base junction is increased. Therefore, more electrons flow from the emitter to the collector *via* the base. This causes an increase in collector current. The increased collector current produces a greater voltage drop across the collector load resistance R_C. However, during the negative half-cycle of the signal, the forward bias across emitter-base junction is decreased. Therefore, collector current decreases. This results in the decreased output voltage (in the opposite direction). Hence, an amplified output is obtained across the load.

4.2. Analysis of collector currents

When no signal is applied, the input circuit is forward biased by the battery V_{BB}. Therefore, a DC collector current I_C flows in the collector circuit. This is called *zero signal collector current*. When the signal voltage is applied, the forward bias on the emitter-base junction increases or decreases depending upon whether the signal is positive or negative. During the positive half-cycle of the signal, the forward bias on emitter-base junction is increased, causing total collector current i_C to increase. Reverse will happen for the negative half-cycle of the signal.

Above Fig. (right) shows the graph of total collector current i_C versus time. From the graph, it is clear that total collector current consists of two components, namely ;

- The DC collector current I_C (zero signal collector current) due to bias battery V_{BB} . This is the current that flows in the collector in the absence of signal.
- The AC collector current i due to signal. Total collector current, $i_C = i + I_C$

The useful output is the voltage drop across collector load R_C due to the AC. component *i*. The purpose of zero signal collector current is to ensure that the emitter-base junction is forward biased at all times.

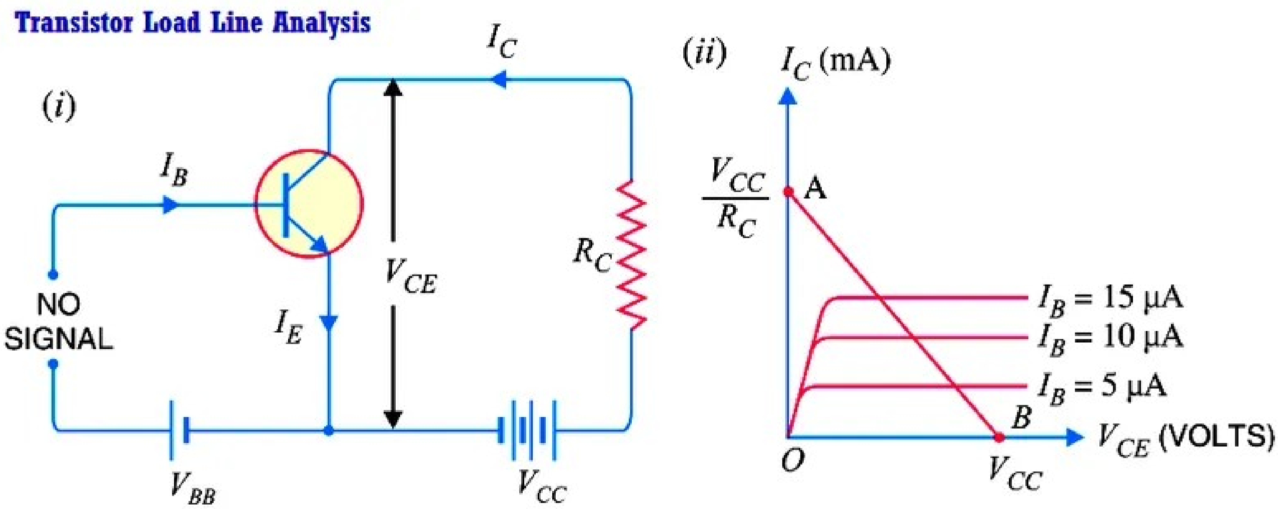
5. Transistor Load Line Analysis

In the transistor circuit analysis, it is generally required to determine the collector current for various collector-emitter voltages. One of the methods can be used to plot the output characteristics and determine the collector current at any desired collector-emitter voltage. However, a more convenient method, known as ***load line*** *method* can be used to solve such problems. As explained later in this section, this method is quite easy and is frequently used in the analysis of transistor applications.

5.1. DC load line.

Consider a common emitter NPN transistor circuit shown in Fig. (*i*) where no signal is applied. Therefore, DC conditions prevail in the circuit. The output characteristics of this circuit are shown in Fig. (*ii*).

The value of collector-emitter voltage V_{CE} at any time is given by $V_{CE} = V_{CC} - I_C . R_C$



As V_{CC} and R_C are fixed values, therefore, it is a first degree equation and can be represented by a straight line on the output characteristics.

This is known as ***DC load line*** and determines the locus of (V_{CE}, I_C) points for any given value of R_C. To add load line, we need two end points of the straight line. These two points can be located as under :

- When the collector current $I_C=0$, then collector-emitter voltage is maximum and is equal to V_{CC} *i.e*

  $\boxed{V_{CEmax}=V_{CC}-I_C.R_C=V_{CC}}$ (as $I_C=0$)

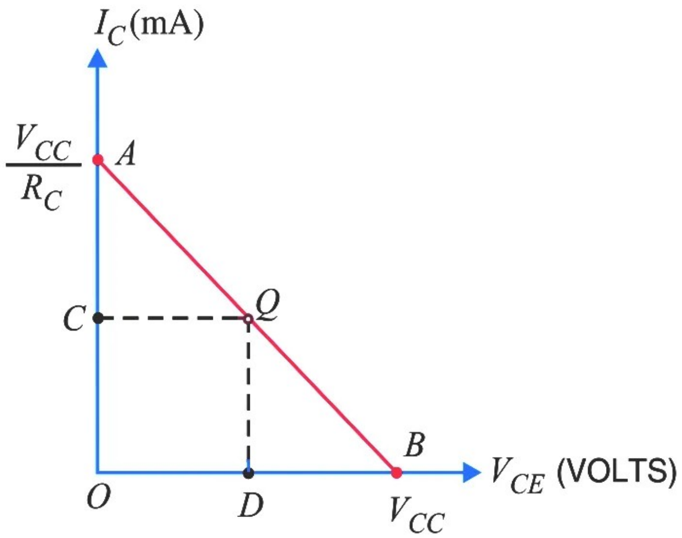
  This gives the first point *B* ($OB=V_{CC}$) on the collector-emitter voltage axis as shown in Fig. (*ii*).

- When collector-emitter voltage $V_{CE}=0$, the collector current is maximum and is equal to $\frac{V_{CC}}{R_C}$ *i.e.*

  $V_{CE}=V_{CC}-I_C.R_C$ or $0=V_{CC}-I_C.R_C$ $\boxed{I_{Cmax}=\frac{V_{CC}}{R_C}}$

  This gives the second point *A* ($OA=\frac{V_{CC}}{R_C}$) on the collector current axis as shown in Fig. (*ii*).

  By joining these two points, DC load line *AB* is constructed.



5.2. Importance.

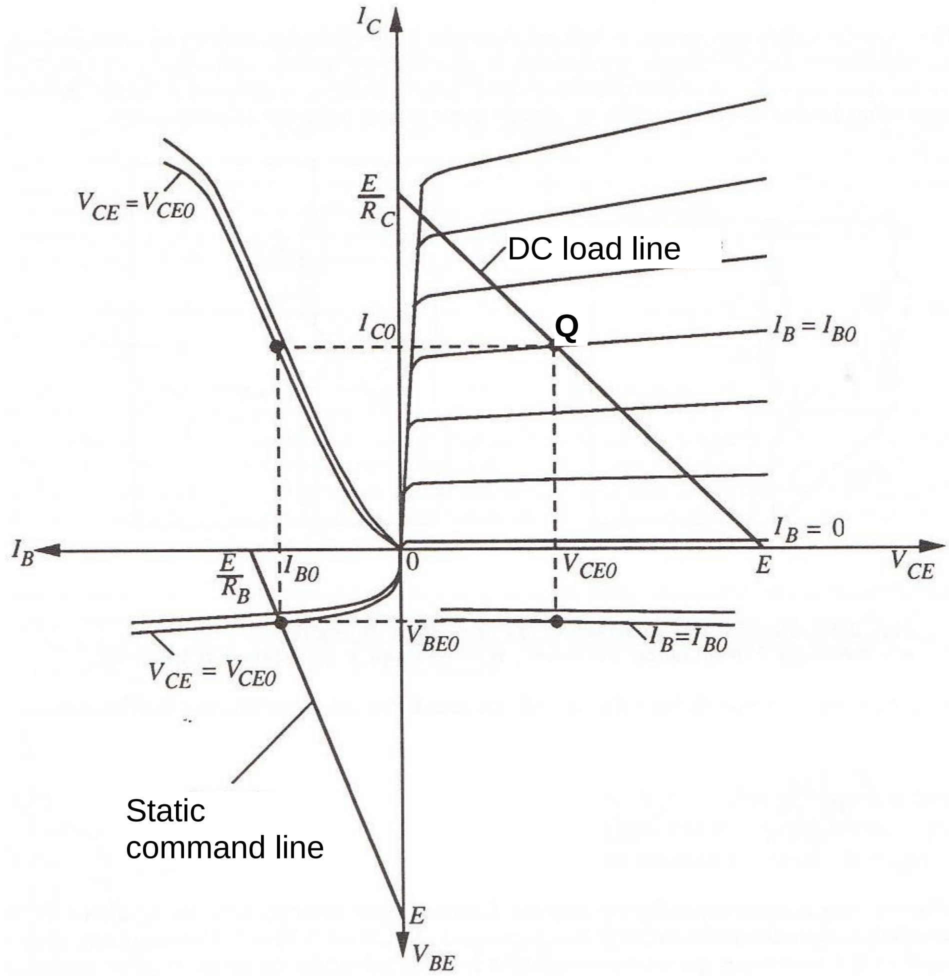
The current I_C and voltage V_{CE} conditions in the transistor circuit are represented by some point on the output characteristics. The same information can be obtained from the load line. Thus when I_C is maximum (= $\frac{V_{CC}}{R_C}$), when $V_{CE}=0$ as shown in above Fig.

If $I_C=0$, then V_{CE} is maximum and is equal to V_{CC}.

For any other value of collector current say *OC*, the collector-emitter voltage *V_CE = OD*. It follows, therefore, that load line gives a far more convenient and direct solution to the problem.

> ***Note.*** *If we plot the load line on the output characteristic of the transistor, we can investigate the behavior of the transistor amplifier. It is because we have the transistor output current and voltage specified in the form of load line equation and the transistor behavior itself specified implicitly by the output characteristics.*
>
> ***Why load line ?*** *The resistance RC connected to the device is called load or load resistance for the circuit and, therefore, the line we have just constructed is called the load line.*

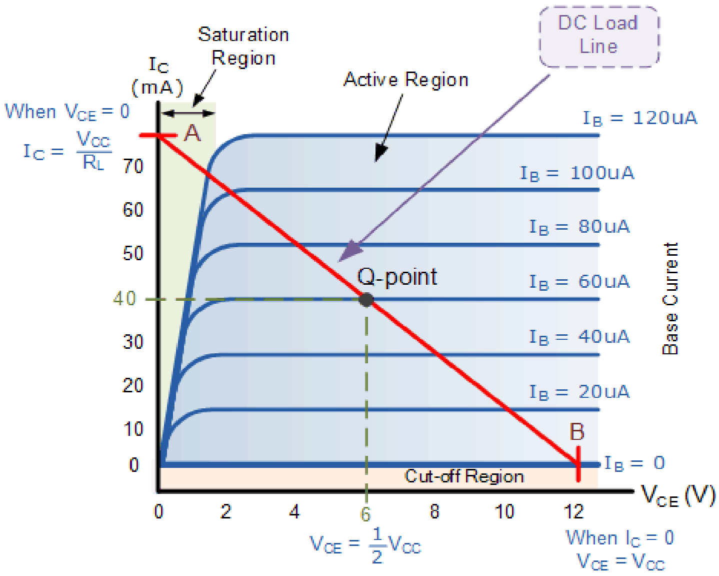
We can summarize this whole stage of polarization on a single graph:



We will recognize here the three characteristics of the transistor (input, transfer, output) joined on the same graph. Warning: it should be noted that the axes are different on both sides of the zero!

6. Saturation, cut-off and active regions

A transistor is essentially like a valve. A transistor is said to be **cut-off** when the valve is completely closed. It is said to be **saturated** when the valve is wide open.



6.1. Cut-off

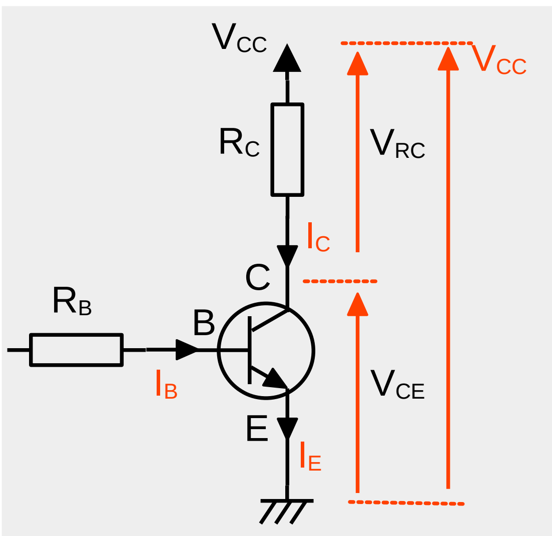
A transistor is cutoff when V_{BE} < cut-in voltage. **A silicon transistor is cutoff when V_{BE} < 0.7 volts.** When V_{BE} < cut-in voltage, I_B = 0. This makes I_C = 0.

When I_B and I_C are both zero, then I_E = 0 as well.

In cut-off: $\boxed{I_B = I_C = I_E = 0}$.

6.2. Saturation

Saturation is when the valve is wide open. The valve is opened wider and wider by increasing the base current. Think about what happens in a circuit when we increase the base current more and more.



If we increase I_B, I_C will increase, since $I_C = \beta . I_B$. And V_{RC} will increase too, since $V_{RC} = I_C . R_C$.

is maximum When V_CE is null.

By KVL we have $V_{CE}+V_{VRC}-V_{CC}=0$, then $V_{RC}=V_{CC}-V_{CE}$ and as V_{CC} is constant, if V_{RC} increase, V_{CE} will decrease.

V_{CE} can not decrease more than 0 and the limit for V_{RC} is then V_{CC}. And finally, from $V_{RC}=I_C.R_C$ we deduce a maximum value of I_C called I_{CMAX} or I_{CSAT} equal to $\frac{V_{CC}}{R_C}$.

$$I_{CMAX} = I_{CSAT} = \frac{V_{CC}}{R_C}.$$

from this point the increase of I_B will not produce an increase of I_C: We reached the saturation state of the transistor.

In saturation we have:

$$\boxed{I_C=I_{CMAX}=I_{CSAT}=\frac{V_{CC}}{R_C}}$$

$$\boxed{V_{CE}=0}$$

$$\boxed{I_C\neq\beta.I_B}$$

> ***Important Note:*** *If you calculate I_B and then $I_C=\beta.I_B$ and find that it's higher than the maximum I_C current (I_{CSAT}), you can deduce that the transistor is saturated.*

Summary:

A transistor is said to be saturated when $I_C=\beta.I_B$ stops being true because it would require V_{CE} to be less than 0.2 volts.

When a transistor becomes saturated, V_{CE} stops changing. It just stays about 0.2 volts (≈ 0) as I_B continues to increase.

Notice that $V_B>V_C$ when the transistor is saturated. $V_B\approx 0.7\,volts$ and V_C ≈ 0.2 volts.

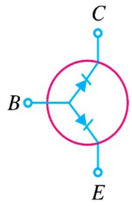
V_C ≈ 0.5 V. The Base–Collector diode junction has a forward voltage in saturation

6.3. Active region

The region between cut off and saturation is known as *active region*. In the active region, collector-base junction remains reverse biased while base-emitter junction remains forward biased. Consequently, the transistor will function normally in this region.

> ***Note.*** *We provide biasing to the transistor to ensure that it operates in the active region. Detailed discussion on transistor biasing is in the next chapter.*

6.4. Summary



As we know, transistor has two PN junctions *i.e.*, it is like two diodes:

- The junction between base and emitter may be called *emitter diode.*
- The junction between base and collector may be called *collector diode.*

We have seen above that transistor can act in one of the three states: **cut-off, saturated** and **active**. The state of a transistor is entirely determined by the states of the emitter diode and collector diode. The relations between the diode states and the transistor states (modes) are:

- **CUT-OFF** mode**:** Emitter diode and collector diode are **OFF (polarized in reverse).** If the transistor is cut-off, there is no base current, so there is no collector or emitter current. That is collector emitter pathway is open.

  When it is blocked, it represents an open switch.

- **SATURATED** mode **:** Emitter diode and collector diode are **ON (forward biased).** In saturation, the collector and emitter are, in effect, shorted together. That is the transistor behaves as though a switch has been closed between the collector and emitter.

  In saturation, the transistor plays the role of a closed switch (resistance between Emitter and weak collector).

- If it becomes alternately blocked and saturated, it is said to work in switching. It is an electrical switch controlled by the signal sent to the base.

- **ACTIVE** mode**:** Emitter diode is **ON** and collector diode is **OFF** (the emitter junction is polarized forward and the collector junction reverse). This is also called normal mode. In the active state, collector current is β times the base current (*i.e.* $I_C = \beta . I_B$)**.**

  In normal conditions, the transistor is used as an amplifier of signal power.

- When the emitter junction is polarized in reverse and the collector junction in direct, the transistor works in reverse mode. The reverse mode is rarely used.