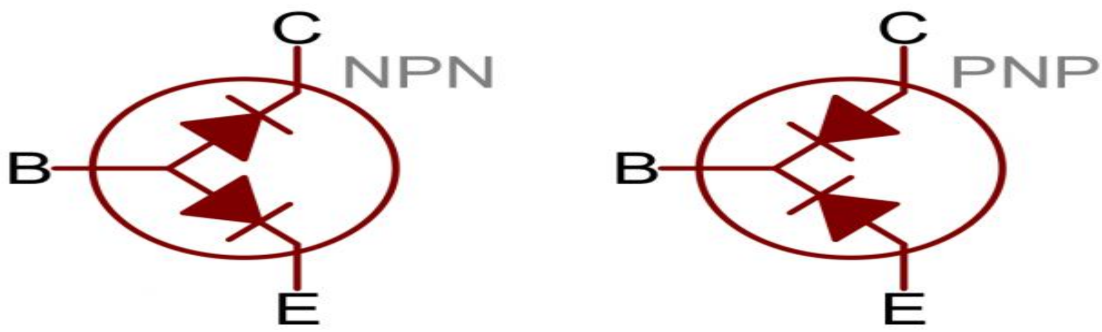
Chapiter 3: Bipolar junction transistor (BJT)

1. BJT construction and symbols

- ✓ The bipolar junction transistor (BJT) is a three-element (emitter, base, and collector) device
- ✓ Its operation involves conduction by two carriers, electrons and holes in the same crystal.
- ✓ Made up of alternating layers of N- and P-type semiconductor materials joined metallurgically.
- ✓ The transistor can be of PNP type (principal conduction by positive holes) or of NPN type (principal conduction by negative electrons), as shown in in the figure bellow:
- ✓ There are two types of bipolar junction transistors:
  - PNP bipolar junction transistor
  - NPN bipolar junction transistor
- ✓ Transistors are just two diodes with their cathodes (or anodes) tied together



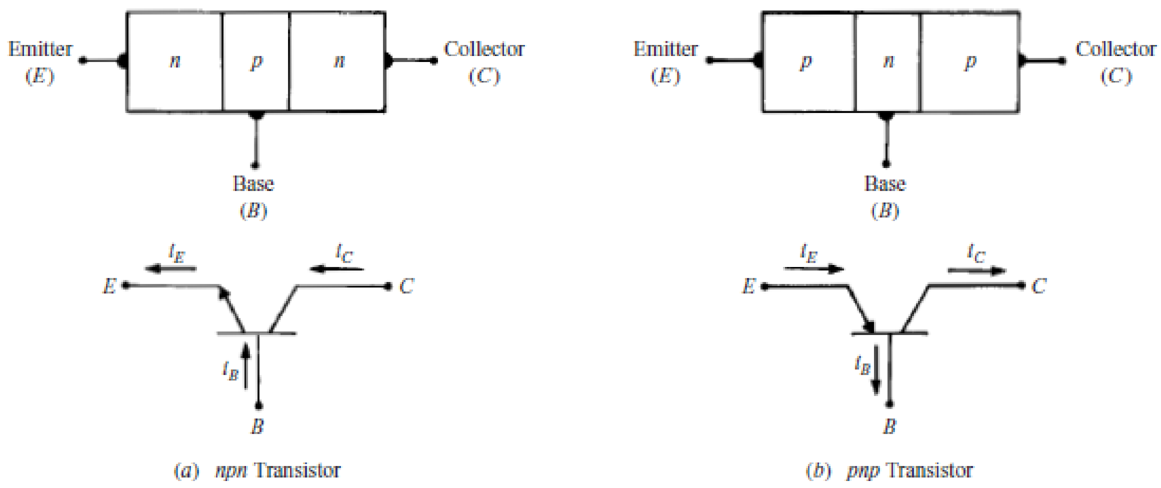


Figure 1: Equivalent model for BJT transistor: a) NPN transistor; b): PNP transistor

On the symbol of a transistor, an arrow is carried by the emitter; the direction of the arrow identifies the type of transistor.

The ratio between the collector current IC and the current IB is called the gain β(betat) such that:

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

- ✓ $I_E = I_C + I_B$
- ✓ $V_{CE} = V_{BE} + V_{CB}$

Then bipolar transistors have the ability to operate within three different modes:

1. Active Region - the transistor operates as an amplifier and Ic = β.Ib

2. Saturation - the transistor is "fully-ON" operating as a switch and Ic = I(saturation)

3. Cut-off - the transistor is "fully-OFF" operating as a switch and Ic = 0

2. BJT Working Principle

Usually, the base of NPN transistors are thin and lightly doped, so it has fewer holes while compared with the electrons in the emitter. The recombination of holes in the base with electrons in the emitter region will constitute the flow of the base current. Usually, the direction of conventional current flow will remain opposed to the flow of electrons.

The two PN junctions must be properly biased with voltages to work correctly.

For the transistor NPN:

- ✓ The BE junction is forward biased :$VB > VE$.
- ✓ The BC junction is reverse biased :$VB < VC$.

Conditions : ⇔VC>VB>VE

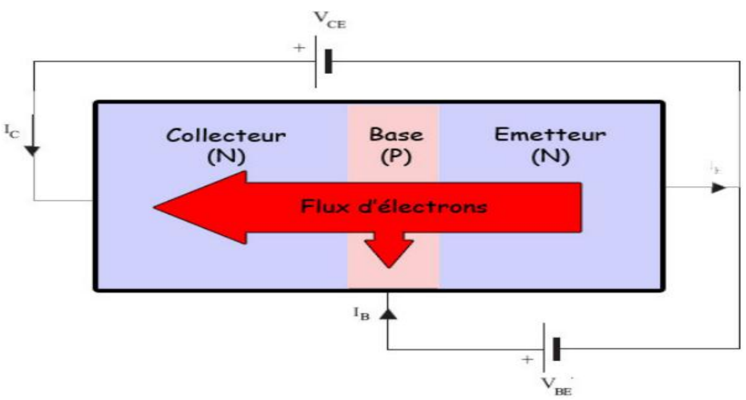
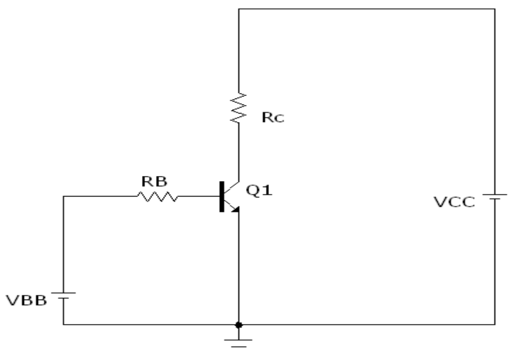


Figure 2 : Transistor biasing

Example

Consider the circuit based on a bipolar transistor given in the figure below:



Given : VBB=5V, RB=10KΩ, RC=100Ω, VCC=10V, VBE=0.7V, β=150.

1. Determine the collector, base, and emitter currents $I_B,\ I_C, I_E$.
2. Determine the voltages: V_{CE}, V_{CB}.

Solution

I_B =?, I_C =? , I_E =? , V_{CE} =? , V_{CB} =?

$$I_B = \frac{\text{VBB} - \text{VBE}}{\text{RB}} = \frac{5 - 0.7}{10\text{K}} = 430\mu\text{A}$$

$$I_c = \beta\text{IB} = 150(430\mu\text{A}) = 64.5\text{mA}$$

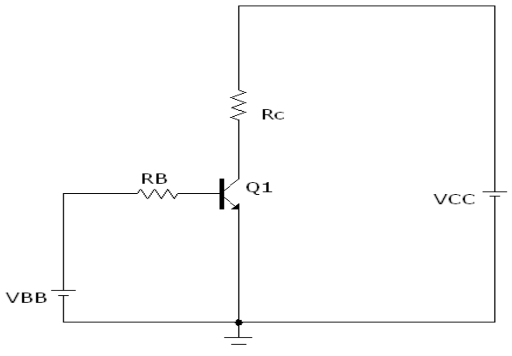
$$I_E = \text{IC} + \text{IB} = 150(430\mu\text{A}) = 64.5\text{mA} + 430\mu\text{A} = 64.9\text{mA}$$

$$\text{VCE} = \text{VCC} - \text{RCIC} = 10 - (64.5)(100) = 3.55\text{V}$$

$$\text{VCB} = \text{VCE} - \text{VBE} = 3.55 - 0.7 = 2.85\text{V}$$

3. Characteristics of bipolar junction transistors

Manufacturers provide a series of curves for each type of transistor. We will mainly focus on the characteristics of the common emitter circuit shown in the following figure:



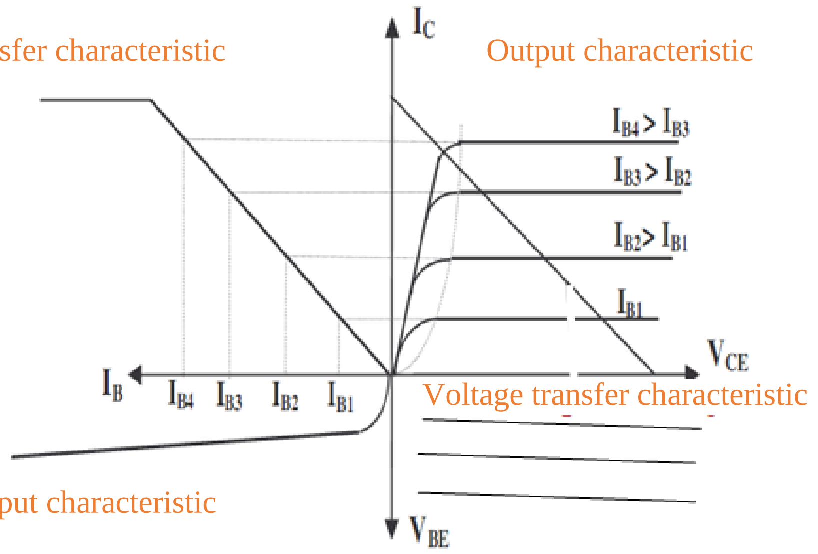


Figure 3 : Bipolar Juntion Transistor characteristics

3.1. Output characteristic Ic = f(VCE)

Output characteristic curves, are the curves IC = f(VCE) with IB = Cte. The IC = f(VCE) curves are plotted for different values of IB to define the behavior of the transistor output and the circuit that charges it.

There are **three operating regions** of a bipolar junction transistor:

1) **Active region**: The region in which the transistors operate as an amplifier.
2) **Saturation region**: The region in which the transistor is fully on and operates as a switch such that collector current is equal to the saturation current.

3) **Cut-off region**: The region in which the transistor is fully off and collector current is equal to zero.

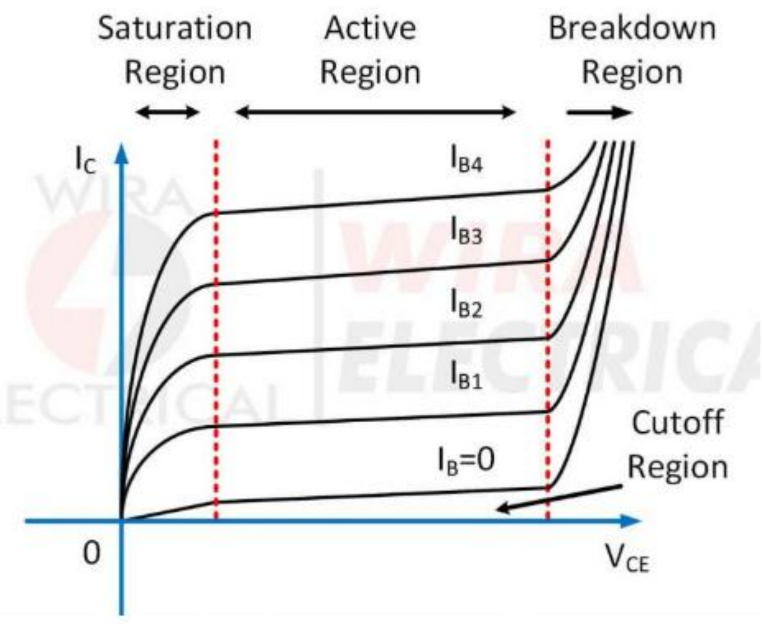


Figure 4: The output characteristic

3.2. Input characteristic $I_B = f(V_{BE})$

Input characteristic curves, are the curves IB = f(VBE) for different values of VCE.

Almost all curves are confused. The curve is identical to the characteristic of a diode (basic emitter junction). For a silicon transistor VBE varies very little and remains near the threshold voltage of the base-emitter junction, i.e. 0.7V.

3.3. Current transfer characteristic

The curve IC = f(IB) is a current transfer network, the curve is linear and passes through the point IB =0 and ICEO.

3.4. Voltage transfer characteristic

The VBE = f(VCE) curves for different values of IB give the reaction of the output circuit on the input circuit.

4. DC load line and attack line

4.1. DC load line

The DC load line of a transistor shows the relationship between the current I_C and voltage V_{CE} of the circuit under consideration for a given load.

4.2. Attack line

The attack line is the equation that relates the input current I_B to the input voltage V_{BE}.

4.3. Q-point

Q-point or quiescent (silent) point is a point in transistor characteristics in which the transistor works. Variations of currents and voltages takes place around this point when input AC signal is applied.

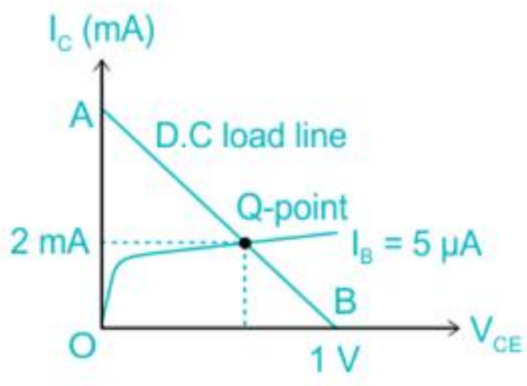
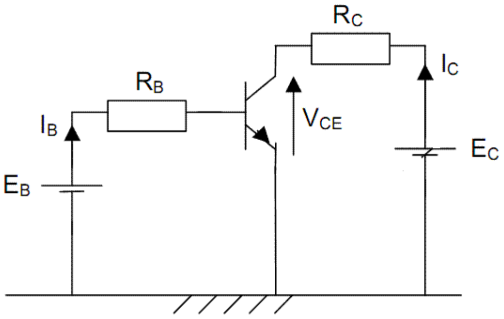


Figure 5: The DC load line and the operating point

5. BJT Biasing circuits

Biasing a transistor means defining the continuous (static) quantities IB, IC, VCE and VBE. Knowing the value of these parameters makes it possible to set an operating (rest) point Q.

5.1. The Fixed-Bias Circuit



1. Find the load and attack line equation.

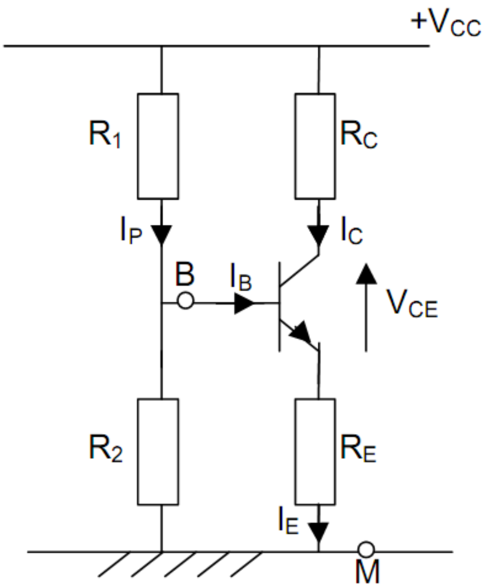
- The line load equation is: $I_C = \frac{V_{CC}}{R_C} - \frac{V_{CE}}{R_C}$

- The line attack equation is: $I_B = \frac{V_{BB}}{R_B} - \frac{V_{BE}}{R_B}$

5.2. The voltage-divider bias circuit

1) In this configuration we use only one supply.

2) The resistors R1 and R2 are chosen in which the current IB is negligible compared to the current passing through these resistors.



β=100, Vcc=10V and we want an operating point Q(Ic=5mA, VCE=5V), RE=495Ω, R2=6.8K Ω, VBE=0.6V.

Determine the value of R1.

Solution

$VB = \frac{R2}{R1+R2} Vcc$ (1)

VE=Re.IE=RE(1+1/β)Ic (2)

VBE=VB-VE=0.6V (3)

NA :

Equation 2 →VE=495(1+1/100).5.10^{-3}=2.49V

Equation 3 → VB=0.6+VE=0.6+2.49=3.1V

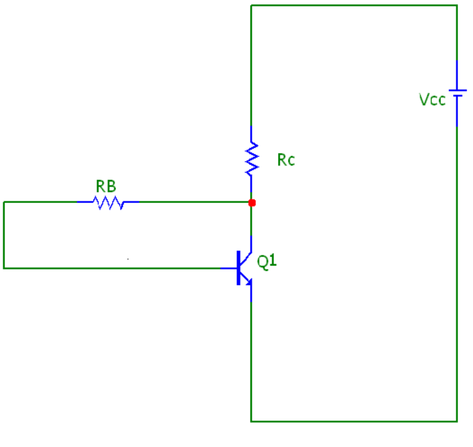
Equation 1 → R2VCC=(R1+R2)×3.1

R1=2.22×R2

NA:

R1=2.22×R2=2.22 ×6.8 10=15KΩ

5.3. Biasing by base-collector resistance



Vcc=10V, V_{CE0}=5V ; I_{C0}=5mA ; β=200, VBE=0.6V.

R_C= ?; R_B= ?.

Solution

Rc=?

VCC=RC(ICQ+IB)+VCQ=RC(1+1/β)ICQ+VCEQ

$$\Rightarrow RC = \frac{VCC-VCEQ}{(1+1/\beta)\text{ICQ}}$$

NA:

$$\Rightarrow RC = \frac{10-5}{(1+1/200)5\times10^{-3}} = 995\Omega$$

RB=?

$$VCE = VBE + RBIB = VBE + RB.\frac{ICQ}{\beta} \rightarrow RB = \frac{(VCEQ-VBE)}{ICQ}\beta$$

NA:

$$RB = \frac{(5-0.6)}{5\times10^{-3}}200 = 176\ \text{K}\Omega$$

6. Applications of BJTs

BJTs have a wide range of applications due to their versatile properties. This makes them useful as switches or amplifiers. Here are some of the key areas where they are used:

- **Amplification:** BJTs can be used in various circuits to amplify small signals, thanks to their property of transforming a low-power input into a high-power output. This is particularly useful in audio and radio frequency applications.

- **Switching:** BJTs can also function as electronic switches. When a BJT is in the cut-off region, it behaves as an open switch, while in the saturation region it acts as a closed switch.

- **Regulation:** BJTs are integral components in voltage regulation circuits, including the design of power supplies.

6.1. Transistors BJT as amplifier

The transistor will operate as an amplifier or other linear circuit if the transistor is biased into the linear region.

We add to the continuous regime (DC) a signal which varies over time (Vin(t)), with use the connection capacitors (C1 and C2) and decoupling capacitor (CE) as shown in figure below (common emitter amplifier).

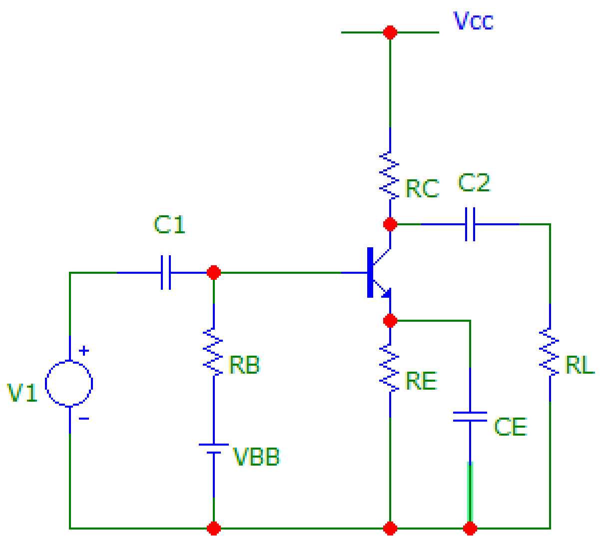


Figure 6: Common Emitter (CE) Configuration

The electrical values envisaged depend on time (e.g. emitter-base voltage vbe(t), collector current ic(t)).

A dynamic regime is the small signal regime where the electrical quantities are formed by adding a small dynamic variation to a static value around this value:

$$\begin{cases} VBE(t) = VBE + vbe\,(t) = VBE + \Delta vbe \sin(wt) \\ IC(t) = IC + ic\,(t) = IC + \Delta ic \sin(wt) \end{cases}$$

Note :

- The continuous quantities, noted in uppercase (capita) letters, (VBE, IC, ...) define the static operating point.

- The dynamic quantities, noted in lowercase, (vbe, ic....) define the dynamic operation.

- The small signal regime is always characterized by peak amplitudes of dynamic quantities much smaller than the values of static quantities (Δvbe << VBE, Δic << IC ....)

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6.1.1. BJT in small-signal dynamic

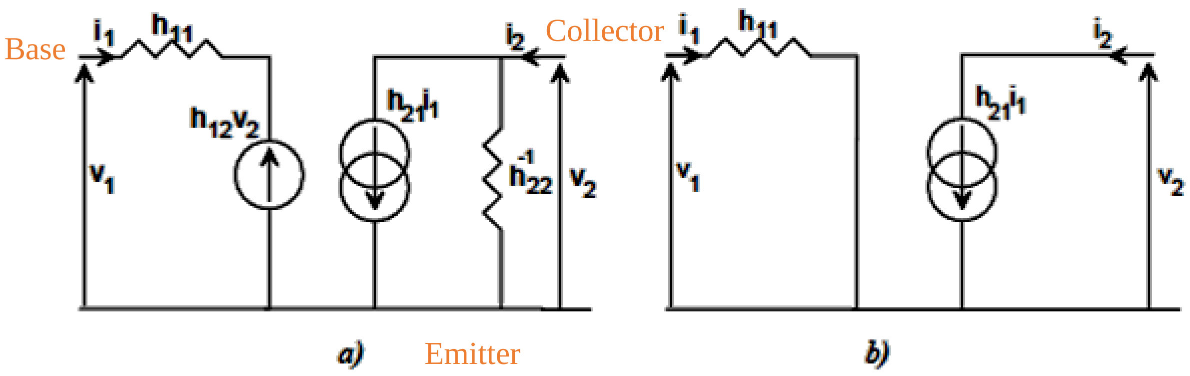


Figure 7: Low-frequency small-signal equivalent circuits of a BJT (a): Complete Scheme; (b) Simplified Scheme

$\boldsymbol{h11}$: input impedance; $\boldsymbol{h12}$: Reverse transfer ratio; $\boldsymbol{h22}$: Output conductance ;$\boldsymbol{h21}$: current gain.

The exploitation of the equivalent model of the transistor will make it possible to calculate the following quantities:

- Current amplification $A_i = \frac{i_2}{i_1}$

- Voltage amplification $A_v = \frac{v_2}{v_1}$

- Input impedance $Z_e = \frac{v_1}{i_1}$

- Output impedance $Z_s = \frac{v_2}{i_2}$

Notes :

In the dynamic regime:

 The capacitors C are replaced by short circuits at the signal frequency.

 DC source is replaced by a ground.

6.1.2. Bipolar Transistor Configurations

A BJT can be configured into three types, they are a common collector configuration, common base configuration and common emitter configuration.

AC equivalent of a network

• AC equivalent of a network is obtained by:

• Setting all dc sources to zero and replacing them by a short – circuit equivalent

• Replacing all capacitors by short – circuit equivalent

• Removing all elements bypassed by the short – circuit equivalents

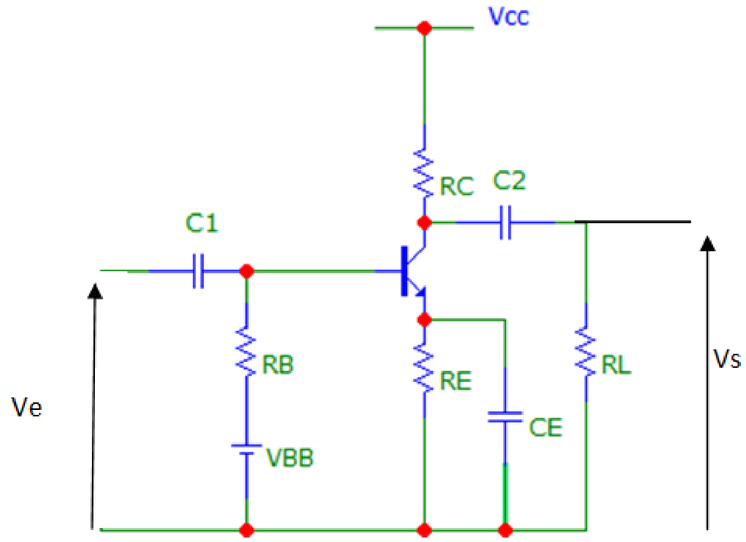
• Redrawing the network in a more convenient and logical form.

In all the figuration determine the four parameters:

- Current amplification $A_i = \frac{i_2}{i_1}$
- Voltage amplification $A_v = \frac{v_2}{v_1}$
- Input impedance $Z_e = \frac{v_1}{i_1}$
- Output impedance $Z_s = \frac{v_2}{i_2}$

a) Common-Emitter configuration

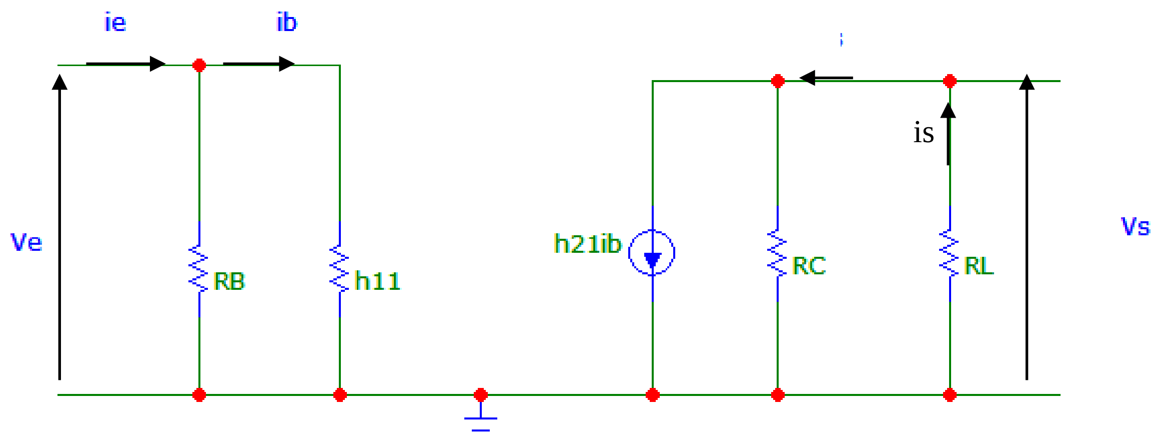
➢ Montage



In dynamic mode the capacitors C1, C2 and CE are replaced by short circuits

En régime dynamique les condensateurs C_1, C_2 et C_E sont remplacés par des court circuits

The equivalent dynamic scheme is represented in the figure bellow:



- The voltage gain of the circuit: $G_V = \frac{V_s}{V_e}$

$v_s = -h_{21}\frac{R_c R_L}{R_c+R_L}i_b$ (1)

$v_e = h_{11}i_b \Rightarrow$ (2)

We take the ratio eq1/eq2 we obtain:

$$G_V = \frac{v_s}{v_e} = -h_{21}\frac{R_C R_L}{(R_C + R_L)h_{11}}$$

- The current gain of the circuit : $A_i = \frac{i_s}{i_e}$

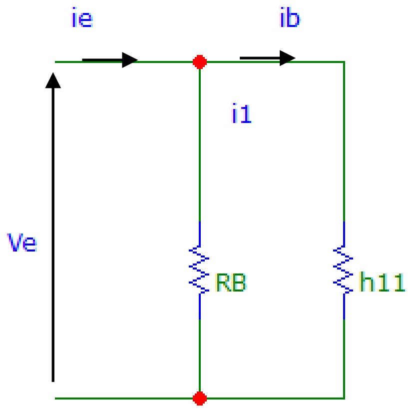
$i_s = \frac{R_c}{R_c + R_L} h_{21} i_b$ (3)

$i_b = \frac{R_B}{R_B + h_{11}} i_e \Rightarrow i_e = \frac{R_B + h_{11}}{R_B} i_b$ (4)

then :

$$A_i = \frac{i_s}{i_e} = \frac{R_c}{R_c + R_L} \cdot \frac{R_B}{R_B + h_{11}} h_{21}$$

- The input impedance



$$z_e = \frac{v_e}{i_e}$$

$v_e = h_{11} i_b$ (5)

$i_b = \frac{R_B}{R_B + h_{11}} i_e \Rightarrow i_e = \frac{R_B + h_{11}}{R_B} i_b$ (6)

$$\frac{i_e}{v_2} = \frac{1}{R_b} + \frac{1}{h_{11}} = R_b // h_{11}$$

$$z_e = R_B // h_{11}$$

- The output impedance

$$z_s = \left.\frac{Vs}{i_s}\right|_{eg=0}$$

$z_s = \frac{v_s}{i_s}$ with $\begin{cases} R_L & \boldsymbol{disconnected} \\ & v_e = 0 \end{cases}$

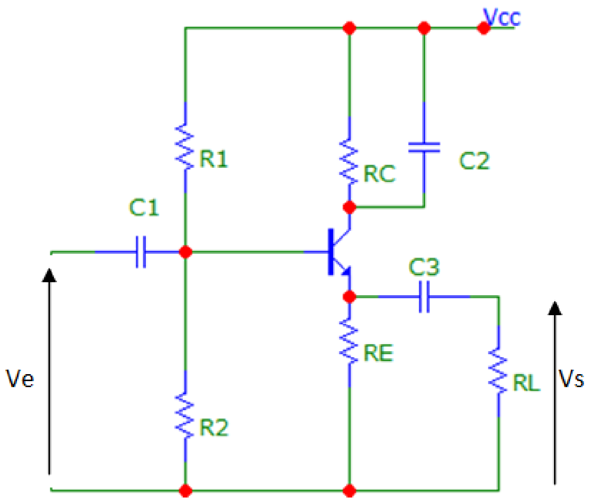
$v_e = 0 \Rightarrow i_e = 0 \Rightarrow i_b = 0 \Rightarrow h_{21} i_b = 0 \Rightarrow$

$$z_s = R_c$$

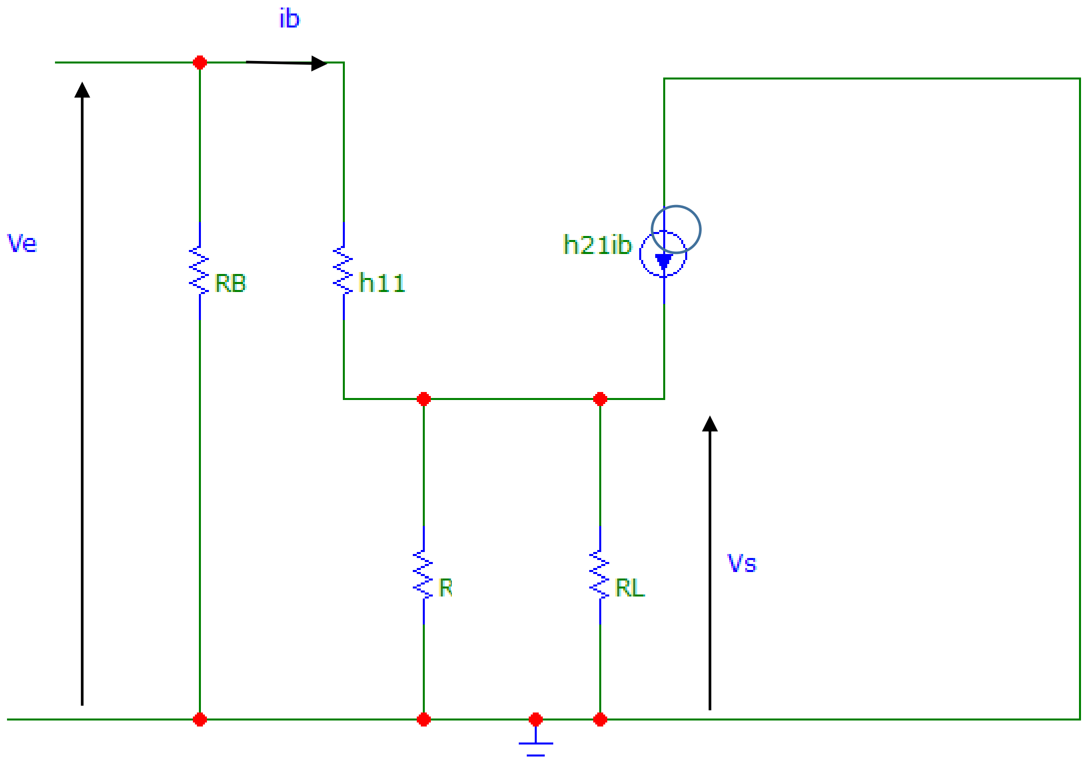
b) Common Collector Configuration

- Montage

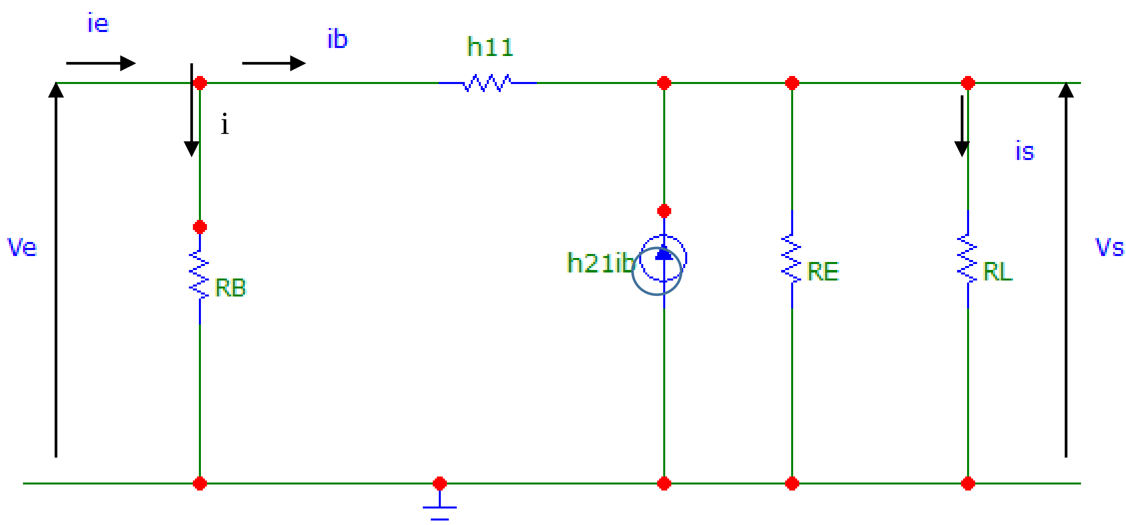
The corresponding circuit to the common collector configuration is given in the figure bellow:



- The equivalent scheme:



we pose RB=R1//R2



- The voltage gain: $G_v = \frac{V_s}{V_e}$

$V_S = (R_E//R_L)(1 + h_{21})i_b$ (1)

$V_e = h_{11}i_b + V_s = [h_{11} + (R_E//R_L)(1 + h_{21})]i_b$ (2)

L'équation (1)/(2) donne :

$$G_v = \frac{(R_E//R_L)(1+h_{21})}{h_{11}+(R_E//R_L)(1+h_{21})}$$

- The input imedance :

$$i_e = i + i_b = \frac{V_e}{R_B} + i_b \qquad (3)$$

From equation (2) ⇒ $i_b = \frac{V_e}{h_{11}+(R_E//R_L)(1+h_{21})}$ (4)

Eq (4) in eq (3), we obtain:

$$i_e = \frac{V_e}{R_B} + \frac{V_e}{h_{11}+(R_E//R_L)(1+h_{21})}$$

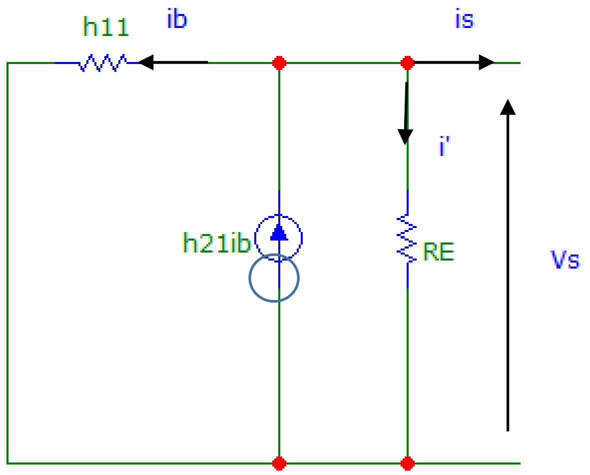
$$\frac{i_e}{V_e} = \frac{1}{R_B} + \frac{1}{h_{11}+(R_E//R_L)(1+h_{21})}$$

SO

$$Z_e = R_B//[h_{11}+(R_E//R_L)(1+h_{21})]$$

- The output impedance

$z_s = \frac{V_S}{i_s}\Big|_{V_e(t)=0}$ and R_L disconnected (see figure below)



Disconnect the load

Shorted the Ve input

$$i_s = i' - (1+h_{21})i_b = \frac{V_s}{R_E} - (1+h_{21})i_b \qquad (5)$$

$$V_s = -h_{11}i_b \qquad (6)$$

We replace equation 5 in equation 6 we obtain:

$$i_s = \frac{V_s}{R_E} + \frac{V_s}{h_{11}}(1+h_{21})$$

$$\frac{i_s}{V_s} = \frac{1}{z_s} = \frac{1}{R_E} + \frac{(1+h_{21})}{h_{11}}$$

$$Z_s = R_E//(h_{11}/1+h_{21})$$

- The current gain of the circuit : $G_i = \frac{i_s}{i_e} = \frac{i_s}{i_b}.\frac{i_b}{i_e}$

Using the current divider:

$$i_s = \frac{R_E}{R_E+R_L}(1+h_{21})i_b \Rightarrow \frac{i_s}{i_b} = \frac{R_E}{R_E+R_L}(1+h_{21}) \qquad (7)$$

You have to search $i_e = f(i_b)$

$\frac{1}{z_e} = \frac{1}{R_B} + \frac{1}{h_{11}+(R_E//R_L)(1+h_{21})}$ (see the section Ze)

$$V_e = h_{11}i_b + (1+h_{21})(R_E//R_L)i_b \Rightarrow \frac{V_e}{i_b} = h_{11} + (R_E//R_L)(1+h_{21})$$

$$V_e = z_e i_e \Rightarrow i_e = \frac{V_e}{z_e} = [h_{11} + (RE \parallel RL)(1+h_{21})].ib/Ze$$

$$\frac{i_e}{i_b} = [h_{11} + (R_E//R_L)(1+h_{21})]/z_e \Rightarrow$$

$$\frac{i_e}{i_b} = \frac{[h_{11}+(R_E//R_L)(1+h_{21})]}{R_B//[h_{11}+(R_E//R_L)(1+h_{21})]} \qquad (8)$$

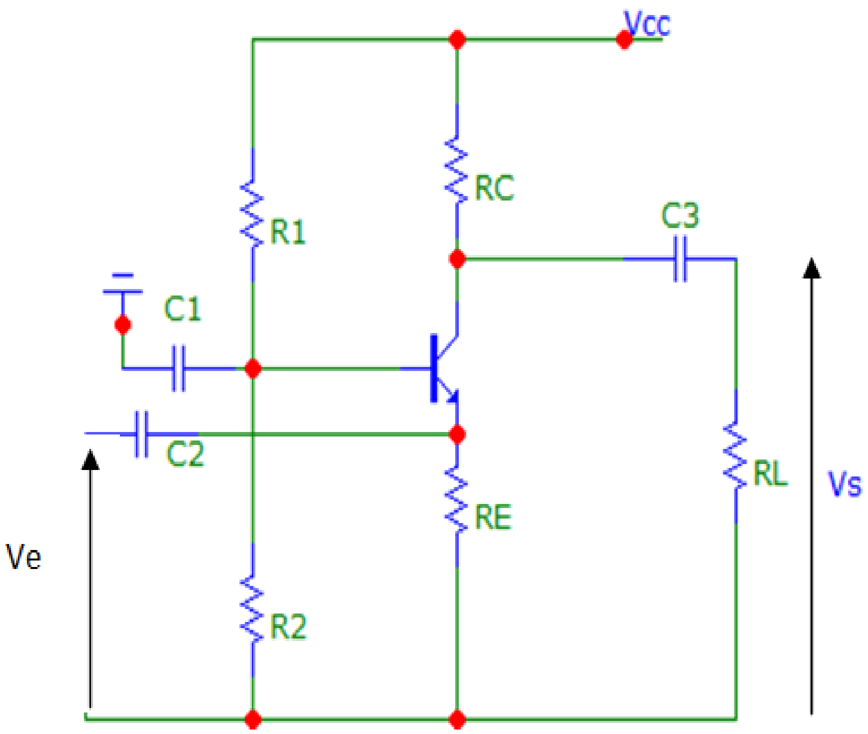
The multiplication of eq (7) and (8) gives :

$$G_i = \frac{R_E(1+h_{21})}{R_E+R_L} \cdot \frac{R_B//[h_{11}+(R_E//R_L)(1+h_{21})]}{[h_{11}+(R_E//R_L)(1+h_{21})]}$$

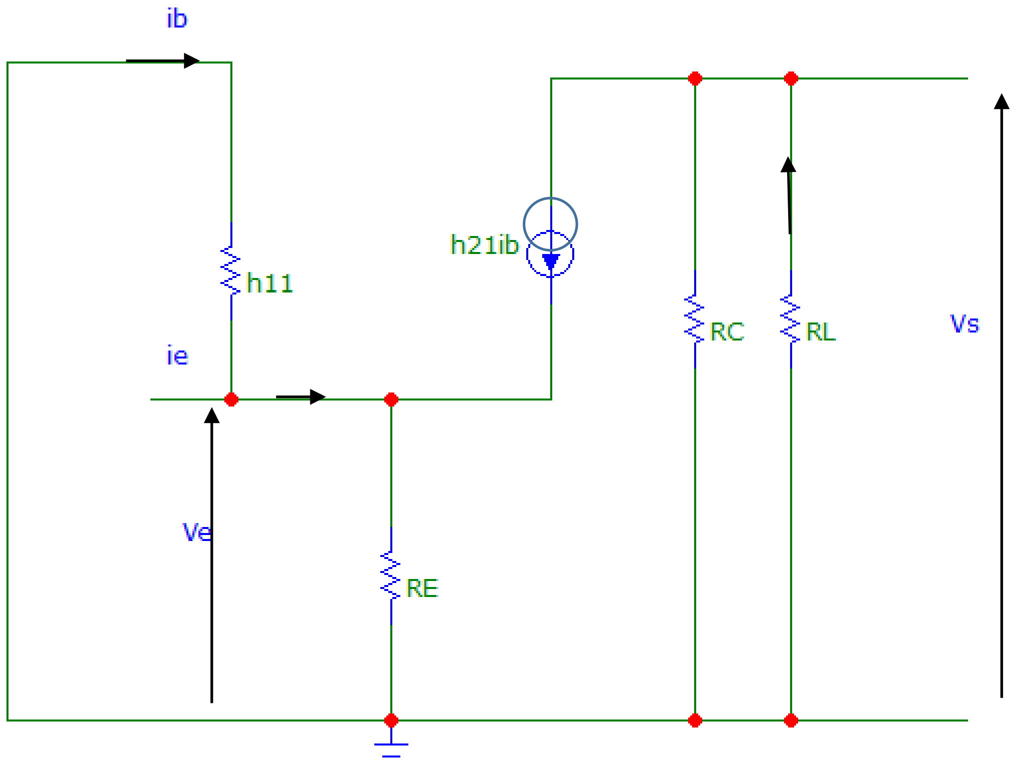
c) Common Base Configuration

In this configuration, the base terminal is grounded and remains common to both the input and the output of the transistor. Emitter–base section is the input where the signal to be amplified is connected and the output signal is drawn across the collector and base as shown in Figure below.

- Montage



- The equivalent scheme



- The voltage gain of the circuit : $G_v = \frac{V_s}{V_e}$

$v_s = -(R_c//R_L)h_{21}i_b$

$v_e = -h_{11}i_b \Rightarrow$

$$G_v = h_{21}\frac{(R_c//R_L)}{h_{11}}$$

- The current gain of the circuit : $G_i = \frac{i_s}{i_e}$

$ve = RE(ie + ib(1 + h21))$ (1)

$ve = -h11ib$ (2)

We replace equation (2) in (1), we obtain:

$ie = -ib(\frac{h11}{RE} + 1 + h21)$ (3)

We apply the current divider :

$i_s = \frac{-R_c}{R_c+R_L} h_{21} i_b$ (4)

$eq(4)/eq(3) = G_i = \frac{R_c h_{21}}{R_c+R_L} \cdot \frac{R_E}{h_{11}+R_E(1+h_{21})}$

- Input impedance $z_e = \frac{v_e}{i_e} = ?$

$ve = RE(ie + ib(1 + h21))$ (5)

$ve = -h11ib \Rightarrow ib = -\frac{ve}{h11}$ (6)

Equation (5) in (6), we obtain:

$i_e = \frac{ve}{R_E} - i_b(1 + h_{21})$ avec $Ve = -h_{11} i_b$

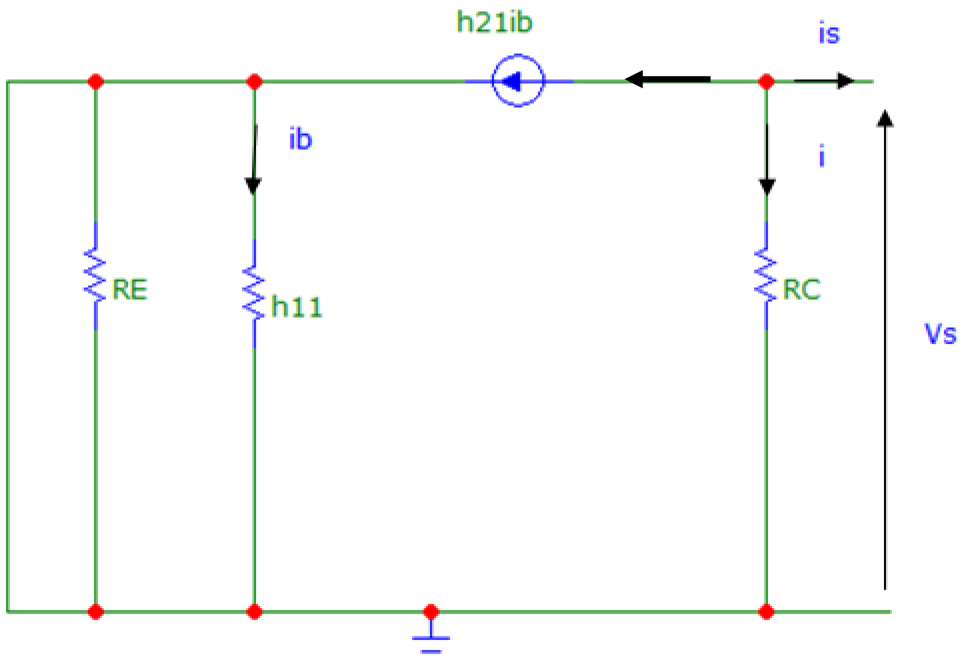
Alors : $ve \left(1 + \frac{RE}{h11}(1 + h21)\right] = REie$

$\frac{i_e}{v_e} = \frac{1}{z_e} = \frac{1}{R_E} + \frac{(1+h_{21})}{h_{11}} = \frac{1}{R_E} + \frac{1}{h_{11}/(1+h_{21})} \Rightarrow$

$z_e = R_E // \left(h_{11}/(1 + h_{21})\right)$

- The output impedance:

$z_s = -\frac{s}{i_s}\Big|_{V_e=0}$ with R_L disconnected (see the figure below)



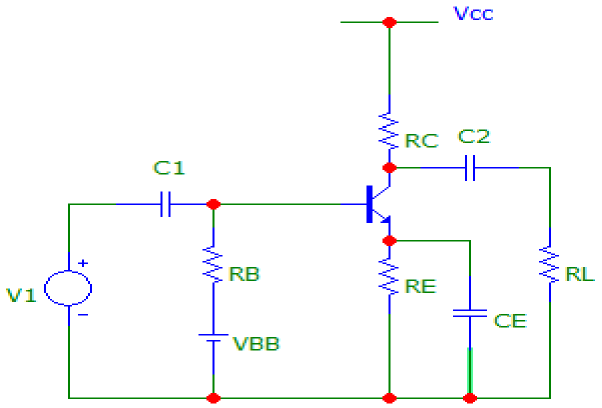
$i_s = \frac{V_s}{R_c} + h_{21} i_b$ since $h_{11} i_b = 0 \Rightarrow i_b = 0$ alors

$\frac{V_s}{i_s} = R_c \Rightarrow$

$z_s = R_c$

d) Example

Consider the circuit in the figure below:



1. Represent the equivalent diagram of the simplified transistor alone.

2. Establish the small low frequency signal equivalent diagram of the complete stage.

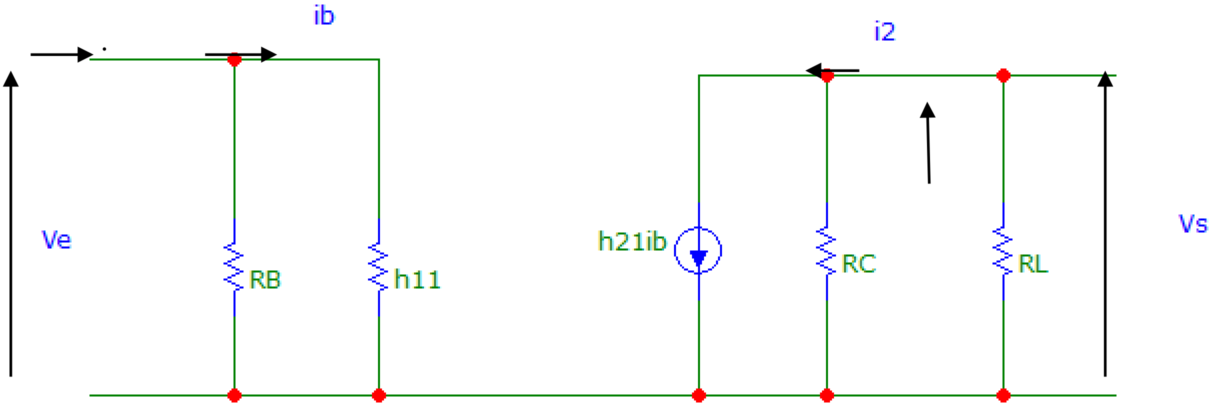
3. Calculate the voltage amplification Av, the current amplification Ai as well as the input impedances Ze and output Zs of the stage.

4. CE is disconnected, repeat the same questions.

Solution

1. The equivalent alternative diagram

The capacitors C1, C2 and CE are replaced by short circuits



2. The voltage gain of the assembly : $G_V = \frac{V_s}{V_e}$

$v_s = -h_{21}.\frac{R_C R_L}{R_c+R_L} i_b$ et $v_e = h_{11} i_b \Rightarrow$

$$G_V = \frac{v_s}{v_1} = -h_{21}\frac{R_C R_L}{(R_C + R_L)h_{11}}$$

3. The current gain of the assembly : $A_i = \frac{i_s}{i_e}$

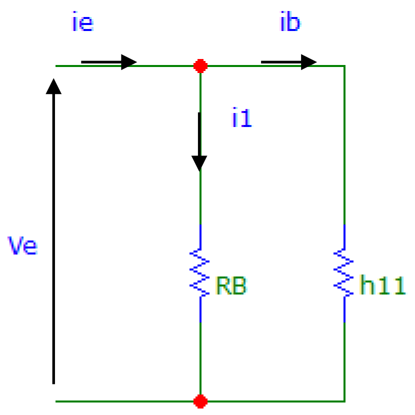
$v_s = -R_L i_s = -\frac{R_C R_L}{R_c+R_L} h_{21} i_b \Rightarrow i_s = \frac{R_C}{R_c+R_L} h_{21} i_b$ avec

$i_b = \frac{R_B}{R_B+h_{11}} i_e \Rightarrow i_e = \frac{R_B+h_{11}}{R_B} i_b$

So :

$$A_i = \frac{i_s}{i_e} = \frac{R_c}{R_c + R_L} \cdot \frac{R_B}{R_B + h_{11}} h_{21}$$

4. The input impedance Ze



$$z_e = \frac{v_e}{i_e}$$

$$v_e = h_{11} i_b$$

$$i_e = i_1 + i_b = \frac{v_e}{R_B} + \frac{v_e}{h_{11}}$$

$$\frac{i_e}{v_2} = \frac{1}{R_B} + \frac{1}{h_{11}} = R_B // h_{11}$$

$$z_e = R_B // h_{11}$$

1. The output impedance Ze

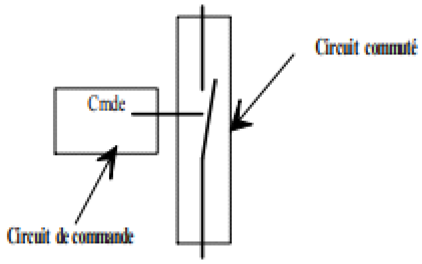
$$z_s = \frac{v_2}{i_2} \text{ avec } \begin{cases} R_L & disconnected \\ & v_e = 0 \end{cases}$$

$$v_e = 0 \Rightarrow i_1 = 0 \Rightarrow i_b = 0 \Rightarrow \beta i_b = 0 \Rightarrow$$

$$z_s = R_c$$

6.2. Transistor BJT as switch

The switching transistor is used to open or close a circuit. Thus it can control an LED, a relay, a motor...etc... We generally compare the transistor output circuit to a switch which is controlled either by a voltage or by a current depending on the type of transistor chosen.



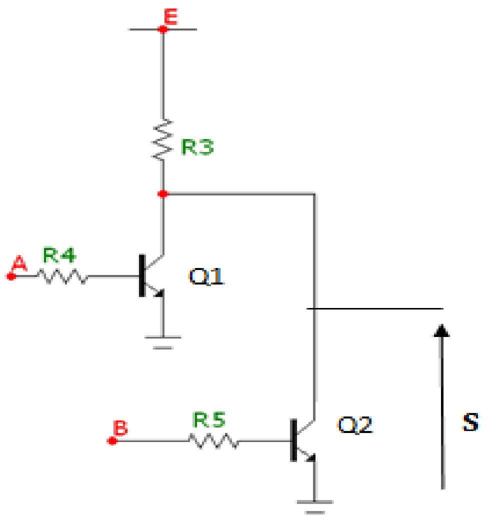
The transistor behaves like a switch between C and E controlled by the base.

- ✓ Transistor blocked if (Vbe=0), Ib is zero →Ic=0, BJT "off" ⇔ open switch;
- ✓ Vbe≥0.7V⇔ closed switch ; BJT " on": Ib>Ic/Bmin (Vcesat=0V).

Example

We consider the two transistors Q1 and Q2 operate in switching mode.

- Analyze the operation of the circuit in the figure below, and deduce the logical function performed.



Solution

Analysis of operation :

- if VA=VB=0V both transistors are "OFF"⟹S=E.

- - If one of the input voltages (or both) is equal to E, the corresponding transistor "ON" $\Longrightarrow$S=0.

- $S = \overline{A + B}$

B	A	S
0	0	1
0	1	0
1	0	0
1	1	0

The logical function performed : **NOR**