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15EC202 Electronic Circuits

Unit - I : BJT Amplifiers

1. DC analysis & DC load line of BJT ckts
2. AC analysis & AC load line of BJT ckts
3. Small-signal operation & hybrid-π model
4. T-Model
5. Characterizing amplifiers
6. Single-Stage BJT amplifiers
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   b. CB amps.
   c. CC amps.
7. Multi-Stage BJT amplifiers
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   b. CE + CB (Cascode)
   c. CE + CC
   d. CC + CC (Darlington)
8. Single-Tuned Amps.
9. Freq. Response of CE amps. — Low-freq response, High-freq response

Analysis of Common-Emitter BJT amplifier

- amplifier is an electronic circuit which provides amplification.
- amplification is a process of raising the strength of a weak signal without any change in the shape of the signal.
- BJT can be employed for amplification.
- BJT can be connected in circuit in 3 ways
  1. CE connection
  2. CB connection
  3. CC connection.

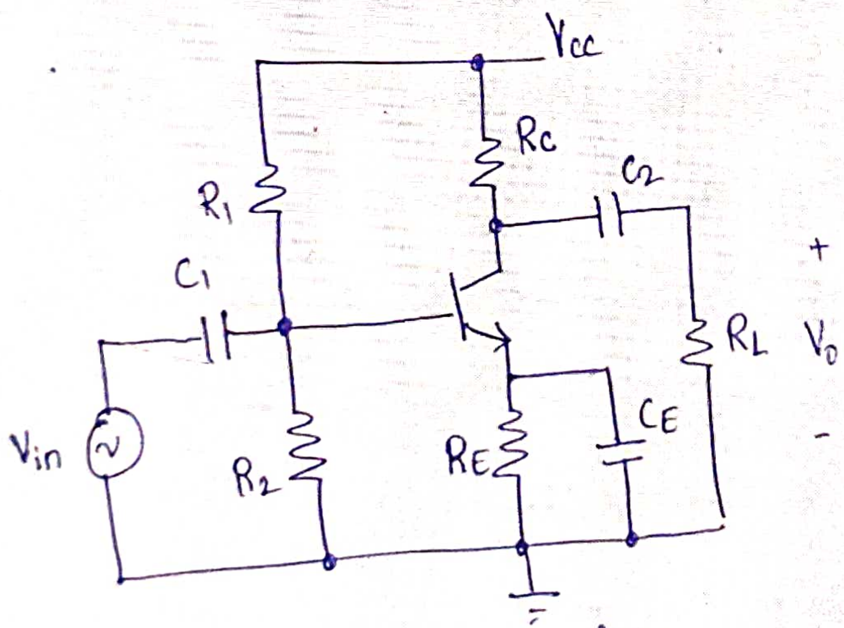

Fig.1 : CE BJT amplifier.

- Signal source is capacitor-coupled to the circuit i/p terminal
- a load resistor is also capacitor coupled to the circuit o/p terminal.

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- Capacitor-coupling ensures that the source and the load do not affect the dc bias conditions in the circuit.
- Emitter resistor R_E is bypassed using a capacitor C_E to prevent ac degeneration (ie, loss in voltage gain of the circuit due to negative feedback)
- analysis is of two types: dc analysis and ac analysis.

DC analysis

- To Perform DC analysis
  1. Turn-off AC sources
  2. open-circuit all the capacitors
- the resultant n/w is a DC n/w, and only dc conditions (ie, dc voltages and dc currents) prevail in the n/w.

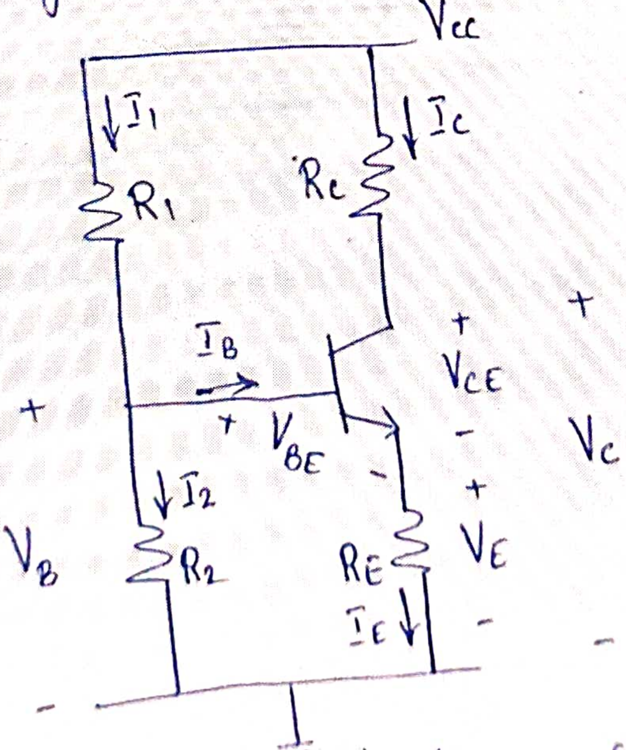


Fig. 2: voltage-divider biasing circuit

- This ckt. is called voltage-divider bias circuit for BJT
- The basis for the name of the ckt. stems from the fact that resistors R_1 and R_2 consitute a voltage divider that devides the supply voltage V_{cc} to produce base voltage V_B.

Applying KVL in the i/p loop,

$$V_B = V_{BE} + V_E \quad \text{--- (1)}$$

ie, $$V_E = V_B - V_{BE} \quad \text{--- (2)}$$

ie, $$I_E = \frac{V_B - V_{BE}}{R_E} \quad \text{--- (3)} \quad \text{where } V_B = \frac{V_{cc} \times R_2}{R_1 + R_2} \quad \text{--- (4)}$$

and, $$I_c \simeq I_E \quad \text{--- (5)}$$

$$I_B = \frac{I_c}{\beta} \text{ where } \beta \text{ is the dc current gain.}$$

Applying KVL in the o/p portion of the n/w,

$$V_{cc} = I_c R_c + V_{CE} + I_E R_E$$

ie, $$V_{CE} = V_{cc} - I_c (R_c + R_E) \text{ if } I_E \simeq I_c \quad \text{--- (6)}$$

The other transistor branch currents and voltages can be computed as:

$$\left.\begin{aligned} V_c &= V_{CE} + V_E \\ V_{BC} &= V_B - V_c \\ V_E &= I_E R_E \simeq I_c R_E \end{aligned}\right\} \quad \text{--- (7)}$$

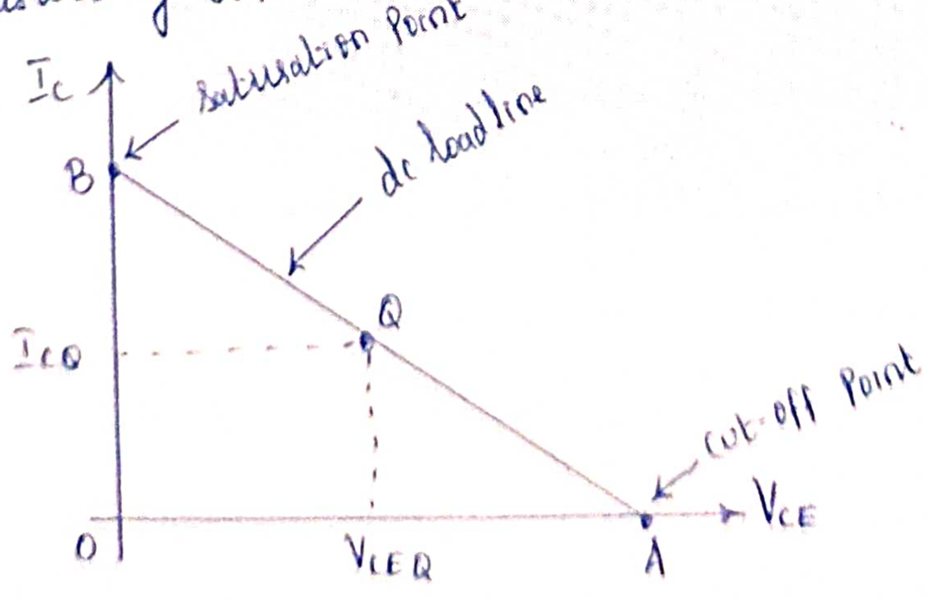
- The zero-signal (Pl. note the absence of signal source) values of transistor current and voltages is called Quiscent current and voltages.
- Particularly, the zero-signal values of V_{CE} and I_C is called Quisent point, or Q-point, or Silent point.
- Quiscent means 'Silent'; Silent means 'no signal'.
- Q-point is also called as operating point.

Dc load line

Recall the expression

$$V_{CE} = V_{CC} - I_C(R_C + R_E) \quad \text{—} \quad (6)$$

- When I_B changes, I_C changes and V_{CE} changes
- ie, when I_B changes, Q-point changes but along a sloping straight line, since eq. (6) is an eq. of a st. line.
- this st. line is called dc loadline, and is draw on the o/p characteristics of BJT.



To draw DC load line,

* Put $I_C = 0$ in eq. 6

$$\Rightarrow V_{CE_{(off)}} = V_{CC}$$

This Point $(V_{CC}, 0)$ on the characteristics curve of the BJT is called cut-off point, meaning that transistor is off because of $I_C = 0$. This pt. is marked 'A'.

* Put $V_{CE} = 0$ in eq. 6

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

This pt. $\left(0, \frac{V_{CC}}{R_C+R_E}\right)$ on the charac. curve is called saturation point, meaning that the voltage drop across the transistor (ie, between C & E terminals) is zero, and hence transistor is saturated by a large current flow thro it. This point is marked 'B'.

* Connect the points A & B using a st. line, which is called dc load line, whose slope is $-\frac{1}{R_C + R_E}$.
* Q-Point can be plotted, and is on the dc load line.
* When I_B changes, Q-point changes and moves along the load line.
* The region along the loadline including all points between saturation and cut-off is generally known as the linear region of the transistor's operation. As long as the tr. is operated in this region, the o/p voltage is ideally a linear reproduction of the i/p.

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Ac analysis

- once the Dc analysis is completed, the ac response can be determined using ac analysis.
- To perform Ac analysis
  * Turn-off V_{cc}, ie, V_{cc} is at ac ground
  * short-circuit all the capacitors, because $X_c \simeq 0$ at signal frequencies (assumed)
- the resultant n/w is called Ac equivalent circuit, and only ac conditions prevail in the circuit.

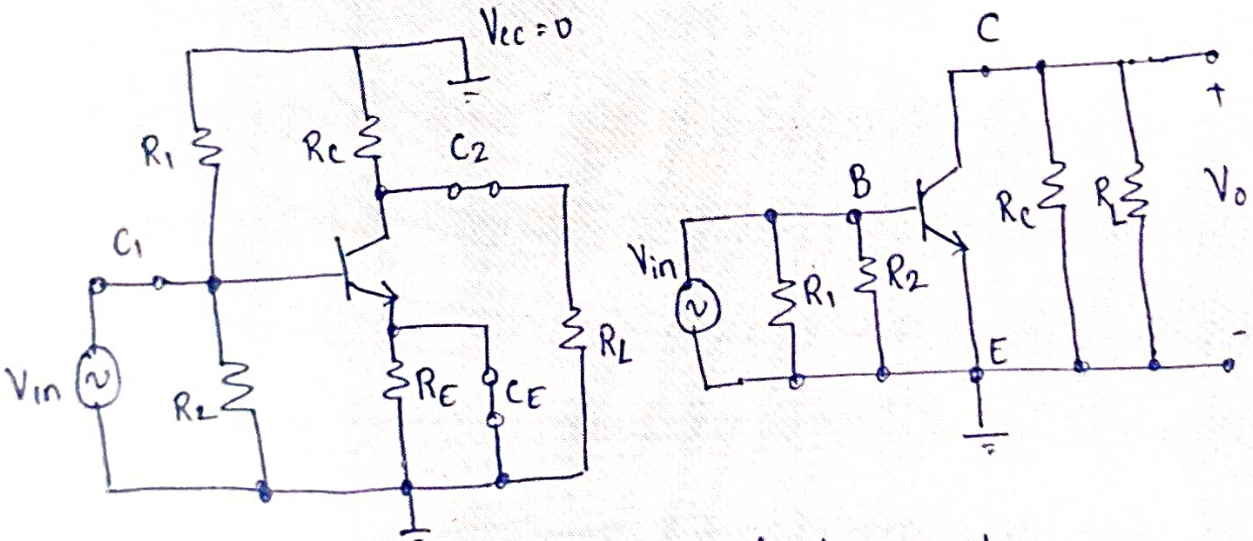
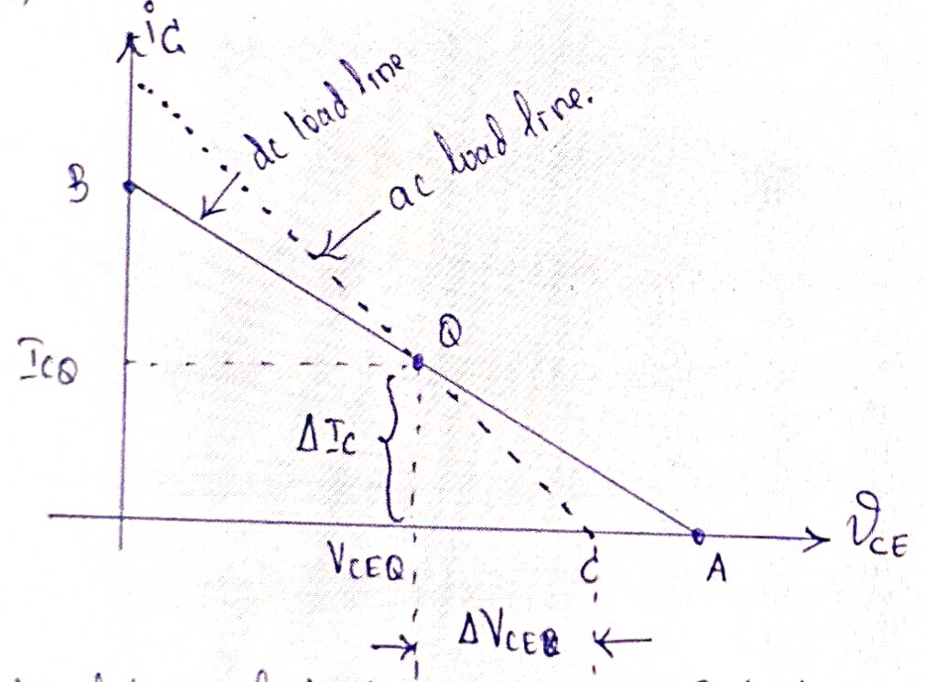


Fig. 3: AC equivalent circuit

- once the ac equivalent circuit is obtained, the BJT device is replaced by its equivalent model and then the circuit analysis is performed to determine the desired quantities of the n/w.
- of the various models available, hybrid-π model is extensively used, and its simplified version is discussed in the next section

Ac load line

- Ac loadline is a new load line drawn on the o/p charac. curve of the transistor to describe the circuit performance when signal is applied.
- Recall that the total dc load of the tr. n/w is $(R_C + R_E)$ and consequently dc load line is drawn with a slope of $\left(-\frac{1}{R_C+R_E}\right)$.
- From fig. 3, it is understood that R_E is not a part of the ac n/w, and hence the ac load of the n/w is $(R_C \| R_L)$.



- When no signal is applied, the tr. current & voltage conditions are as indicated at the Q-pt. on the dc load line. When ac signal is applied, the tr. current and voltage vary above and below Q-pt. So, Q-point is common to both load lines.
- another pt. is found on the ac load line by taking a convenient collector current change (usually $\Delta I_C = I_{CQ}$) and then calculate corresponding collector-emitter voltage $\Delta V_{CEQ} = \Delta I_C \times (R_C \| R_L)$. Mark this pt. as 'C'.
- Connect pts. Q & C to draw ac load line and extend it to meet the y-axis.

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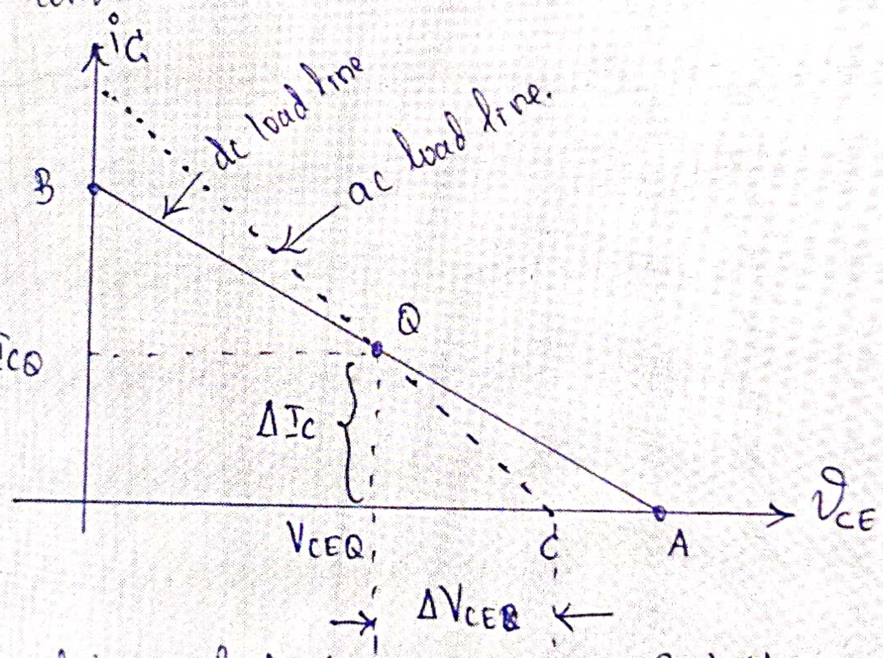

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Small-Signal operation and hybrid-π model

Consider a conceptual circuit to illustrate the operation of the tr. as an ampr.

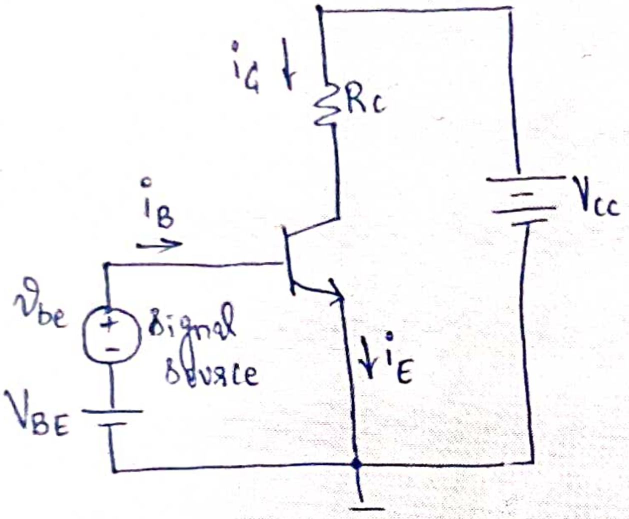

Fig. 4(a): Basic small-signal ampr.

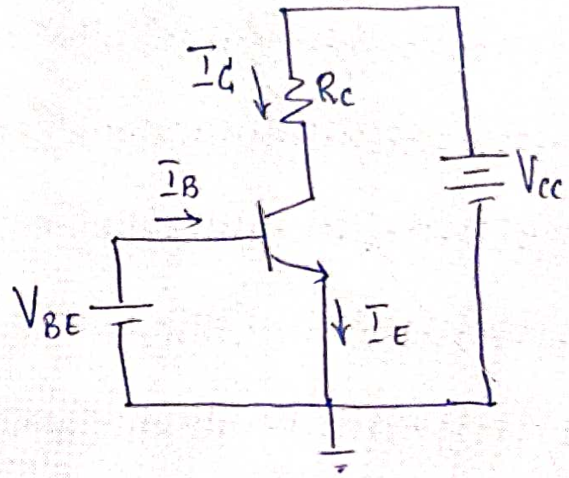

Fig. 4(b): ckt. with signal source eliminated for dc analysis.

- DC power supply voltages V_{BE} and V_{CC} established f/w bias and rev. bias to EB jn and CB jn respectively.
- an i/p signal v_{be} which is to be amplified is superimposed on V_{BE}

When no signal is applied, i.e., $v_{be} = 0V$, we can write the following relationships for the dc currents and voltages.

$$\left.\begin{aligned} I_C &= I_S e^{V_{BE}/V_T} \\ V_C &= V_{CE} = V_{CC} - I_C R_C \\ I_C &= \beta I_B \\ I_C &= \alpha I_E \end{aligned}\right\} \quad — \quad (8)$$

where V_T = volt-equivalent of temperature = $\frac{KT}{q} \simeq 26mV$

α = current gain of CB connected tr.

β = current gain of CE connected tr.

The collector current and the transconductance

When a signal is applied, the total instantaneous base-emitter voltage becomes

$$v_{BE} = V_{BE} + v_{be} \qquad — (9)$$

Correspondingly, the total instantaneous collector current will be

$$i_C = I_S e^{v_{BE}/V_T} = I_S e^{(V_{BE}+v_{be})/V_T}$$

$$= I_S e^{V_{BE}/V_T} e^{v_{be}/V_T}$$

$$= I_C e^{v_{be}/V_T} \qquad — (10)$$

if $v_{be} << V_T$, we can approximate,

$$i_C = I_C\left(1 + \frac{v_{be}}{V_T}\right)$$

$$= I_C + I_C \frac{v_{be}}{V_T}$$

$$= I_C + i_c$$

This approximation $v_{be} << V_T$ ie., $v_{be} < 10mV$ is referred to as small-signal approximation and hence, the name small-signal ampr.

where i_c is the small-signal collector current, and is given by

$$i_c = I_C \frac{v_{be}}{V_T} \qquad — (11)$$

ie., $$\boxed{i_c = g_m v_{be}} \qquad — (12)$$

where g_m is the transconductance, and is given by

$$\boxed{g_m = \frac{I_C}{V_T}} \qquad — (13)$$

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The base current and the i/p resis. @ the base

The total instantaneous base current is given by

$$i_B = \frac{i_C}{\beta} = \frac{I_C + i_c}{\beta} = \frac{I_C}{\beta} + \frac{i_c}{\beta} = I_B + i_b$$

where i_b is the small-signal base current, and is given by

$$i_b = \frac{i_c}{\beta} = \frac{1}{\beta} I_C \frac{v_{be}}{V_T} \quad \text{from eq. (11)}$$

ie, $$i_b = \frac{g_m v_{be}}{\beta} \quad \text{— (14)}$$

ie, $$\boxed{r_\pi = \frac{v_{be}}{i_b} = \frac{\beta}{g_m}} \quad \text{— (15)}$$

where r_π is the small-signal i/p resistance between base and emitter

also, $$\boxed{r_\pi = \frac{\beta}{I_C/V_T} = \frac{V_T}{I_B}} \quad \text{— (16) from eq. (13)}$$

The emitter current and the i/p resis. @ the emitter

The total instantaneous emitter current is given by

$$i_E = \frac{i_C}{\alpha} = \frac{I_C + i_c}{\alpha} = \frac{I_C}{\alpha} + \frac{i_c}{\alpha} = I_E + i_e$$

where i_e is the small-signal emitter current, and is given by

$$i_e = \frac{i_c}{\alpha} = \frac{1}{\alpha} \frac{I_C}{V_T} v_{be} \quad \text{— (17) from eq. (13)}$$

ie, $$i_e = \frac{g_m v_{be}}{\alpha}$$

ie, $$\boxed{r_e = \frac{v_{be}}{i_e} = \frac{\alpha}{g_m} \approx \frac{1}{g_m}} \quad \text{— (18)}$$

where r_e is called emitter resistance

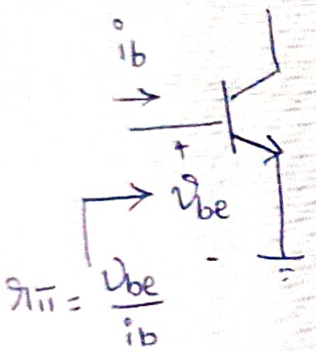
also. $r_e = \frac{\alpha}{g_m} = \frac{\alpha}{I_C/V_T} = \frac{V_T}{I_E}$ — (19) from eq. (13)

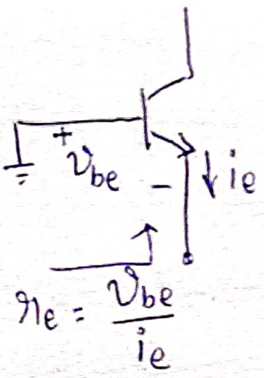
from equations (14) and (18),

$$v_{be} = i_b r_\pi = i_e r_e$$

ie, $r_\pi = \frac{i_e}{i_b} r_e = \frac{i_b + i_c}{i_b} r_e$

ie, $\boxed{r_\pi = (1+\beta) r_e}$ — (20)





Voltage gain

Eq. (12) ⇒ $i_c = g_m v_{be}$

ie., the transistor produces an o/p collector current proportional to the changes in the i/p base-emitter voltage. To obtain an o/p voltage, force this o/p current to flow thro the resistor R_C. So,

$$v_C = V_{CC} - i_C R_C = V_{CC} - (I_C + i_c) R_C$$

$$= (V_{CC} - I_C R_C) - i_c R_C$$

$$= V_C - v_c$$

where v_C is the total instantaneous o/p collector voltage, given by

$$v_c = -i_c R_C$$

$$= -g_m v_{be} R_C \quad \text{from eq. (12)}$$

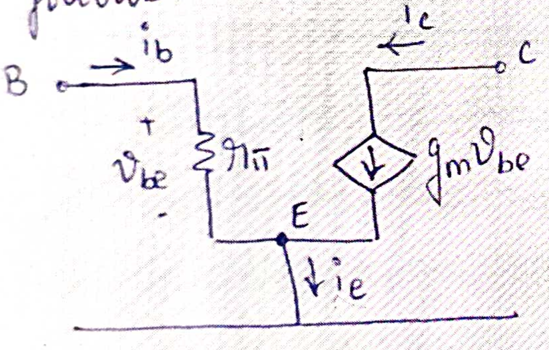
ie, $\boxed{A_v = \frac{v_c}{v_{be}} = -g_m R_C}$ is the voltage gain of this ampr.

Because g_m is directly proportion to collector bias current, the voltage gain of the ampr will be as stable as the collector current.

also, $\boxed{A_v = -g_m R_C = -\frac{I_C R_C}{V_T}}$

The Hybrid-π model

- In the previous section, we have developed AC equivalent circuit of the CE BJT amplifier.
- The BJT in that circuit is replaced by its small-signal equivalent model.
- One such model is the hybrid-π model, which is closely related to the physics of the transistor.
- Using the parameters g_m, r_π, r_e, β and α, ~~discusse~~ as discussed in the previous section, we can develop a simplified small-signal hybrid π equivalent circuit as follows:



$$r_\pi = \frac{\beta}{g_m}$$

$$g_m = \frac{I_C}{V_T}$$

This model

- represents BJT as a voltage-controlled current source, and
- includes the i/p resistance looking into the base, r_π

An expression for i_e can be found as

$$i_e = i_b + i_c = \frac{v_{be}}{r_\pi} + g_m v_{be} = \frac{v_{be}}{r_\pi}(1 + g_m r_\pi)$$

$$= \frac{v_{be}}{r_\pi}(1+\beta) = \frac{v_{be}}{\left(\frac{r_\pi}{1+\beta}\right)}$$

$$= \frac{v_{be}}{r_e}, \text{ where } r_e = \text{emitter resistance} = \frac{r_\pi}{1+\beta}$$

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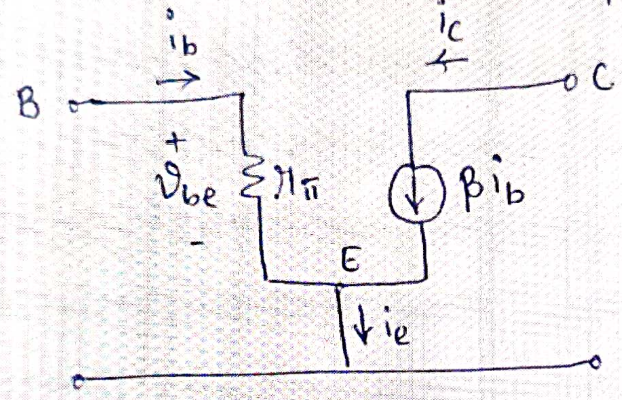
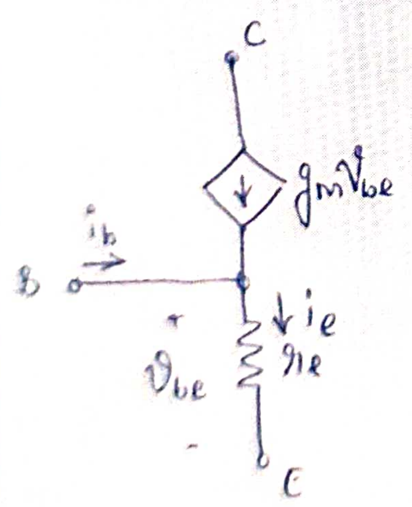
A slightly different eq. ckt. can be obtained by replacing voltage-controlled current source with a current-controlled current source, as follows:

$$g_m v_{be} = g_m (i_b r_\pi) = (g_m r_\pi)\, i_b$$
$$= \cancel{\beta I_b}$$
$$= \beta i_b$$



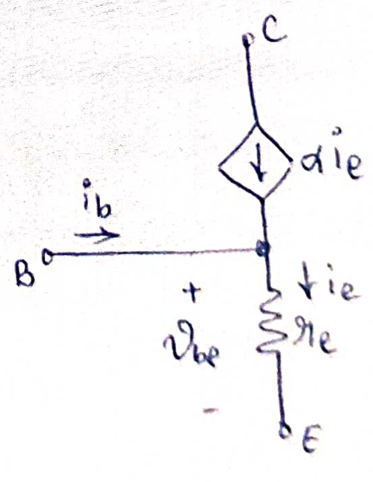
The T-model

Although the hybrid-π model can be used to carry out small-signal analysis of transistor circuits, there are situations in which an alternative model, known as T-model is much more convenient.



$$g_m = \frac{I_C}{V_T}$$

$$r_e = \frac{V_T}{I_E} = \frac{\alpha}{g_m}$$



This model
- represents BJT as a voltage-controlled current source, $g_m v_{be}$
- includes resis. bet. base and emitter, r_e

An expression for i_b can be found as

$$i_b = i_e - i_c = \frac{v_{be}}{r_e} - g_m v_{be} = \frac{v_{be}}{r_e}(1 - g_m r_e)$$

$$= \frac{v_{be}}{r_e}(1-\alpha) = \frac{v_{be}}{r_e}\left(1 - \frac{\beta}{\beta+1}\right)$$

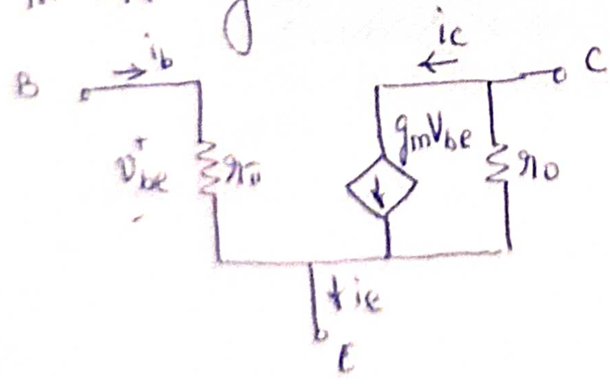
$$= \frac{v_{be}}{(\beta+1) r_e} = \frac{v_{be}}{r_\pi}$$

In the model, the current of the controlled source can also be expressed ~~as~~ in terms of the emitter current as follows:

$$g_m v_{be} = g_m (i_e r_e)$$
$$= (g_m r_e)\, i_e$$
$$= \alpha i_e$$

The Early Effect : Its impact on the small-signal analysis

The Early effect causes the I_C to depend not only on V_{BE} but also on V_{CE}. The dependence on V_{CE} can be modeled by assigning a finite o/p resistance r_o to the controlled current-source in the hybrid-π model as follows:



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Its value is given by $r_o = \frac{V_A + V_{CE}}{I_C} \approx \frac{V_A}{I_C}$ where V_A = early voltage whose values ranges between 30V and 100V.

In the analysis of transistor circuits, r_o will not be included because it would complicate the analysis considerably. Also, it can be proved that the effect of r_o on the performance of discrete amplifier circuits is very small. This is not the case, however, for the IC form of the amplifier circuits, where effect of r_o is significant.

Relationship between various small-signal parameter - a summary

Model parameters in terms of DC bias currents

$$g_m = \frac{I_C}{V_T}, \quad r_e = \frac{V_T}{I_E} = \alpha \frac{V_T}{I_C}, \quad r_\pi = \frac{V_T}{I_B} = \beta \frac{V_T}{I_C}, \quad r_o = \frac{V_A}{I_C}$$

In terms of g_m

$$r_e = \frac{\alpha}{g_m}, \quad r_\pi = \frac{\beta}{g_m}$$

In terms of r_e

$$g_m = \frac{\alpha}{r_e}, \quad r_\pi = (\beta+1) r_e, \quad g_m + \frac{1}{r_\pi} = \frac{1}{r_e}$$

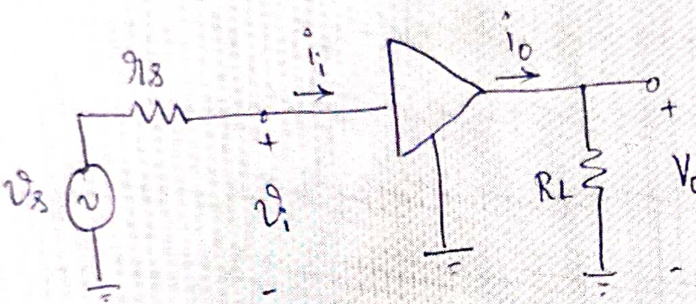
Relationships between α and β

$$\beta = \frac{\alpha}{1-\alpha}, \quad \alpha = \frac{\beta}{\beta+1}, \quad \beta+1 = \frac{1}{1-\alpha}$$

Characterizing Amplifiers

Before the analysis of different BJT ampr. configurations can be carried out, we shall understand how to characterize the performance of an ampr. ckt.

Let us consider an ampr. ckt represented by the block schematic as shown below:



- r_s is the internal resistance of the source v_s.
- R_L is the load resis. connected to the o/p terminal.
- R_L can be actual load resistance or the i/p resistance of a succeeding ampr. stage.

The performance of the transistor can be characterized by using the following parameters:

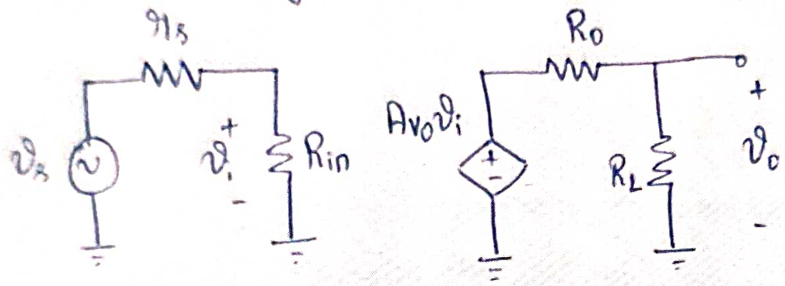
1. The i/p resistance, R_{in}

$$R_{in} = \frac{v_i}{i_i}$$

This R_{in} together with r_s forms a voltage-divider which divides the source voltage v_s, producing v_i.

$$v_i = \frac{R_{in}}{R_{in} + r_s} v_s.$$

The ampr. block in the ampr. block circuit shown above can be replaced by Thevenin's equivalent circuit model.

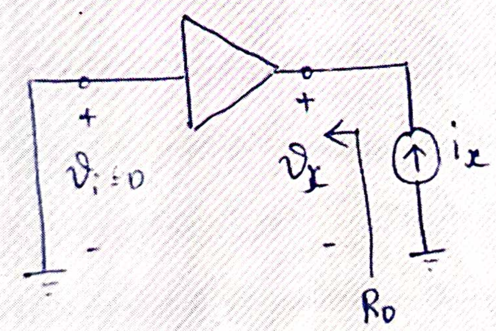


2. Open-Circuit Voltage gain, A_{vo}

$$A_{vo} = \left.\frac{v_o}{v_i}\right|_{R_L = \infty}$$

3. The o/p resistance, R_o

R_o is the resistance seen looking back into the ampr. o/p terminal with v_i set to zero. conceptually,



$$R_o = \frac{v_x}{i_x}$$

— * —

From the eq. ckt. of the ampr., we can also note that

$$v_o = A_{vo} v_i \times \frac{R_L}{R_o + R_L}$$

Thus, the voltage gain of the ampr. can be given by

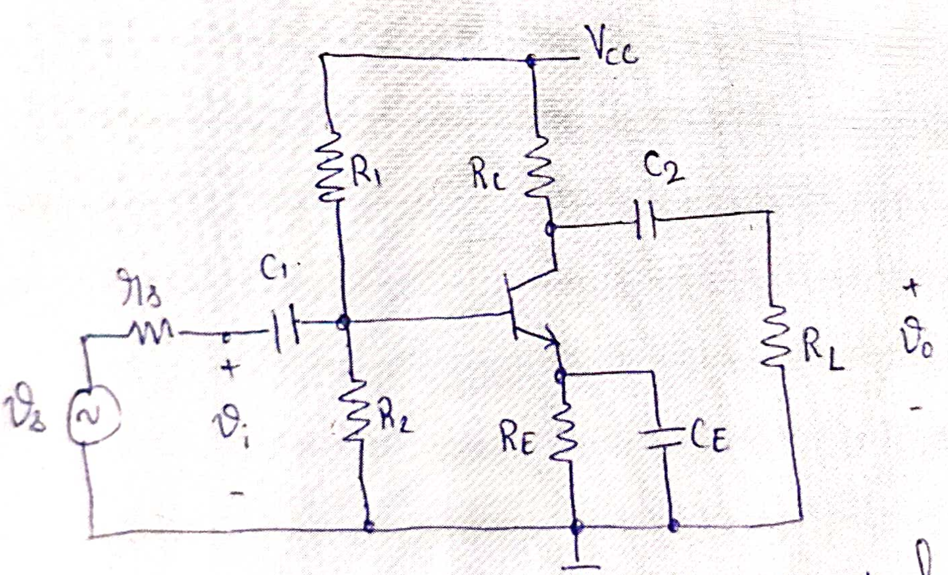
$$A_v = \frac{v_o}{v_i} = A_{vo} \cdot \frac{R_L}{R_L + R_o}$$

The overall voltage gain, A_{vs} of the ampr. ckt can be given by

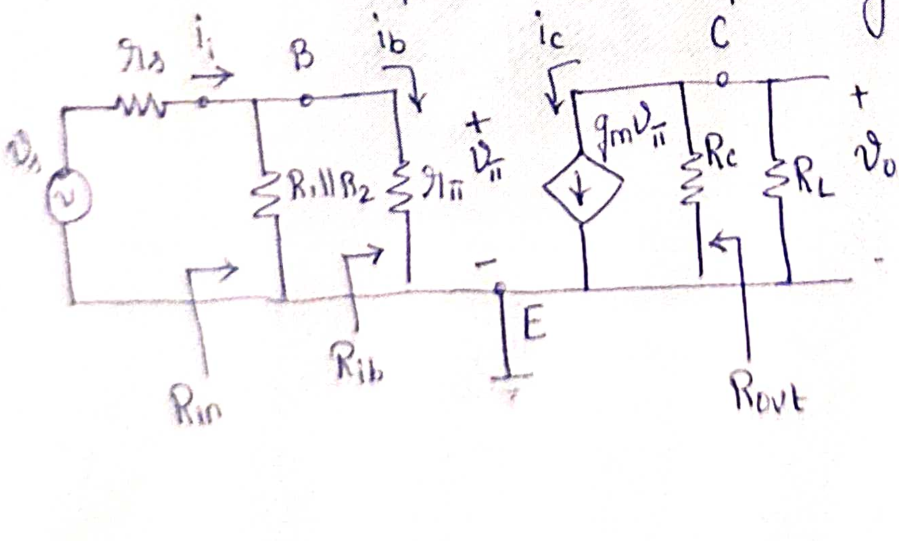
$$A_{vs} = \frac{v_o}{v_s} = \frac{v_o}{v_i} \times \frac{v_i}{v_s}$$

$$= A_v \cdot \frac{R_{in}}{R_{in} + r_s}$$

The Common-Emitter (CE) Amplifier



The BJT in the ampr. ckt. can be replaced by its hybrid-π model.



Input Resistance, R_{in}

$$R_{in} = \frac{v_i}{i_b} = R_1 \| R_2 \| R_{ib}$$

where R_{ib} is the resis. looking into the base.

$$R_{ib} = r_\pi$$

Normally, we select $R_1 \| R_2 >> r_\pi$, resulting

$$R_{in} \simeq R_{ib} = r_\pi$$

Output Resistance, R_{out}

The o/p resis can be found from the eq. ckt. by looking back into the o/p terminal with $v_s = 0$. This will result in $V_\pi = 0$, so

$$R_{out} = R_c \| R_L$$

Voltage Gain

Open circuit voltage gain, $A_{vo} = \left.\frac{V_o}{v_i}\right|_{R_L = \infty}$

$$= \frac{-g_m V_\pi R_c}{V_\pi}$$

$$= -g_m R_c$$

Voltage gain of the ampr. block, $A_v = A_{vo} \cdot \frac{R_L}{R_o + R_L}$

$$= -g_m R_c \times \frac{R_L}{R_c + R_L}$$

∴ The overall voltage gain of the ampr. ckt. is given by

$$A_{vs} = \frac{v_o}{v_s} = A_v \times \frac{R_{in}}{R_{in} + r_s} = \left(-g_m R_c \times \frac{R_L}{R_c + R_L}\right) \times \frac{r_\pi}{r_\pi + r_s}$$

ie, $A_{vs} = \dfrac{-g_m (R_c \| R_L)\, r_\pi}{r_\pi + r_s}$

$$= \frac{-\beta (R_c \| R_L)}{r_\pi + r_s}, \quad \text{since } \beta = g_m r_\pi$$

Current gain, A_{is}

$$A_{is} = \frac{i_o}{i_i} = \frac{v_o / R_o}{v_s / R_i} = \frac{v_o}{v_s} \times \frac{R_i}{R_o} = |A_{vs}| \times \frac{R_i}{R_o}$$

$$\simeq \frac{\cancel{-}\beta (R_c \| R_L)}{r_\pi + r_s} \times \frac{r_\pi}{(R_c \| R_L)}$$

$$\simeq \frac{\cancel{-}\beta\, r_\pi}{r_\pi}, \quad \text{if } r_s << r_\pi$$

$$= \cancel{-}\beta$$

Inferences or observations

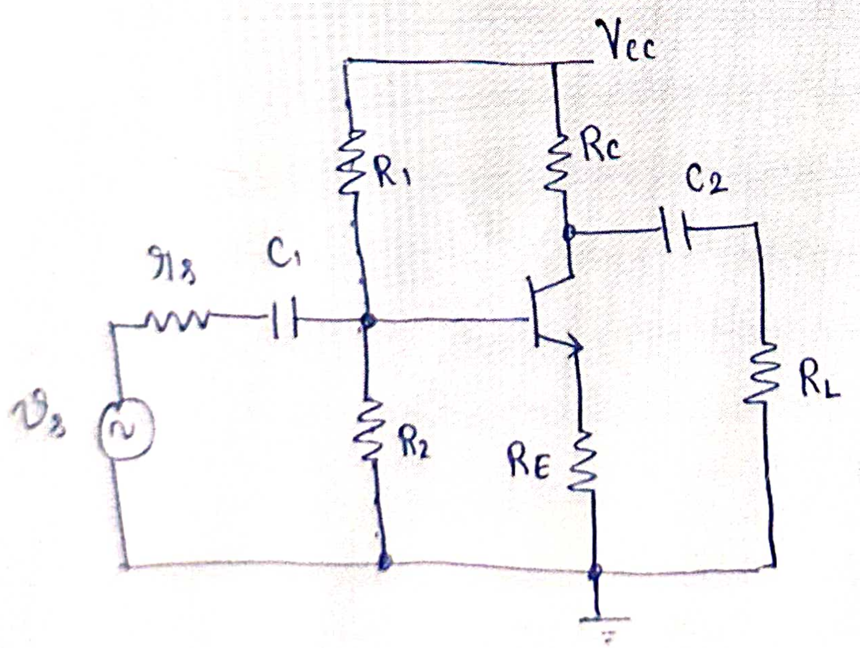
1. The i/p resistance $R_{in} = r_\pi = \dfrac{\beta}{g_m} = \dfrac{\beta V_T}{I_C}$ is moderate to low in value (typically, in the kiloohm range). R_{in} is directly dependent on β and is inversely proportional to I_C. To obtain a higher i/p resis., the bias current I_C can be lowered, but this also lowers the gain. This is a significant design trade-off. If a much higher i/p resis. is desired, then a modification of the CE configuration, or an emitter-follower stage can be used.
2. R_{in} does not depend on the o/p side of the ampr. Hence, this ampr. is said to be unilateral.

3. The o/p resis. $R_o \simeq R_C$ is moderate to high in value (typically in kilo ohm range). To obtain a lower o/p resis., R_C can be lowered, but this is not a viable solution because the voltage gain is also lowered. If a much lower o/p resis. is desired, then an emitter-follower stage can be used.

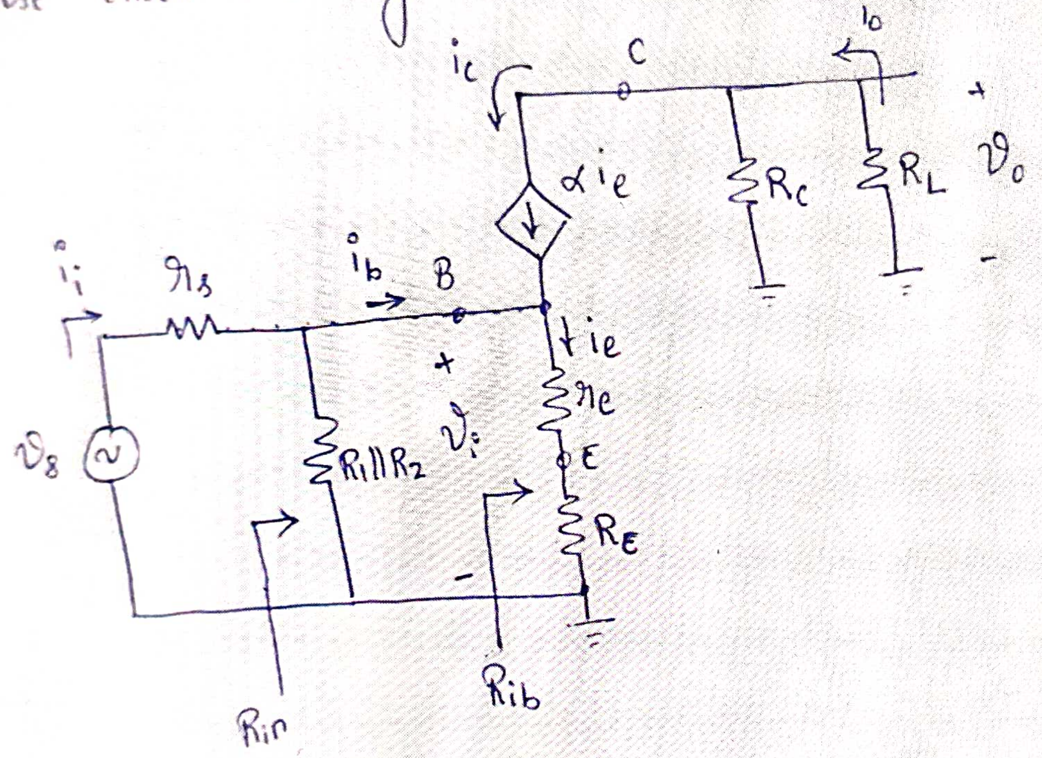
4. The open-ckt voltage gain, A_{vo} is high, thus making CE configuration widely used for voltage amplification. Unfortunately, however, the bandwidth of CE ampr. is severely limited.

5. To maintain a reasonably linear operation, v_i should not exceed about 5 mV to 10 mV, which poses a contraint on the value of v_s.

The Common-Emitter Amplifier with unbypassed R_E



Although hybrid-π model can be used to perform ac analysis of this amp. ckt., T-model is the most convenient for this type of circuit because R_E will appear in series with emitter resis. r_e of the T-model. In fact, whenever there is resistance in the emitter lead, the T-model should be more convenient to use than the hybrid-π model.



Input Resistance, R_{in}

$$R_{in} = \frac{v_i}{i_i} = R_1 \| R_2 \| R_{ib}$$

where R_{ib} = resis. looking into the base terminal.

To determine R_{ib}, apply KVL in the loop consisting of v_i, r_e & R_E.

$$v_i = i_e (R_E + r_e)$$
$$= (\beta+1) i_b (R_E + r_e)$$
$$\Rightarrow R_{ib} = \frac{v_i}{i_b} = (\beta+1)(R_E + r_e)$$
$$R_{in} = R_1 \| R_2 \| [(\beta+1)(R_E + r_e)]$$
$$\simeq (\beta+1)(R_E + r_e), \text{ if } (R_1 \| R_2) >> R_{ib}$$
$$\simeq \beta(R_E + r_e) \simeq \beta R_E, \text{ if } R_E >> r_e$$

Output Resistance, R_{out}

The o/p resis. can be found from the eq. ckt by looking back into the o/p terminal with $v_s = 0$. This will result in $i_i = 0$, $i_b = 0$, $i_E = 0$, and hence $\alpha i_e = 0$. So,

$$R_{out} = R_C \| R_L$$

Voltage gain

open-circuit voltage gain, $A_{vo} = \left.\frac{v_o}{v_i}\right|_{R_L = \infty}$

$$= \frac{-i_c R_C}{(\beta+1) i_b (R_E + r_e)}$$

$$= \frac{-\beta R_C}{(\beta+1)(R_E + r_e)}$$

$$\simeq \frac{-R_C}{R_E + r_e}$$

$$\simeq \frac{-R_C}{R_E} \quad \text{if } r_e << R_E$$

If R_L is connected to the ampr., then voltage gain can be found as,

$$A_v = A_{vo} \times \frac{R_L}{R_o + R_L} = -\frac{R_C}{R_E} \times \frac{R_L}{R_C + R_L} = -\frac{R_C \| R_L}{R_E}$$

Taking into account the source resistance, r_s, the voltage gain can be expressed as

$$A_{vs} = A_v \times \frac{R_{in}}{R_{in} + r_s} = -\frac{R_C \| R_L}{\cancel{R_E}} \times \frac{\beta \cancel{R_E}}{\beta R_E + r_s}$$

$$= \frac{-\beta (R_C \| R_L)}{r_s + \beta R_E}$$

Current Gain, A_{is}

$$A_{is} = |A_{vs}| \times \frac{R_{in}}{R_{out}} = \frac{\beta(\cancel{R_C \| R_L})}{r_s + \beta R_E} \times \frac{\beta R_E}{(\cancel{R_C \| R_L})}$$

$$= \frac{\beta}{\beta R_E} \times \beta R_E, \text{ if } r_s << \beta R_E$$

$$\simeq \beta$$

which is same as that of CE ampr with R_E bypassed.

Inferences or Observations

1. $$\frac{R_{ib} \text{ (with } R_E \text{ included)}}{R_{ib} \text{ (without } R_E)} = \frac{(\beta+1)(R_E + r_e)}{r_\pi} = \frac{(\beta+1)(R_E + r_e)}{(\beta+1) r_e}$$

$$= 1 + \frac{R_E}{r_e}$$

$$= 1 + g_m R_E, \text{ since } g_m \simeq \frac{1}{r_e}$$

ie, The i/p resis. R_{ib} is increased by a factor $(1+g_m R_E)$

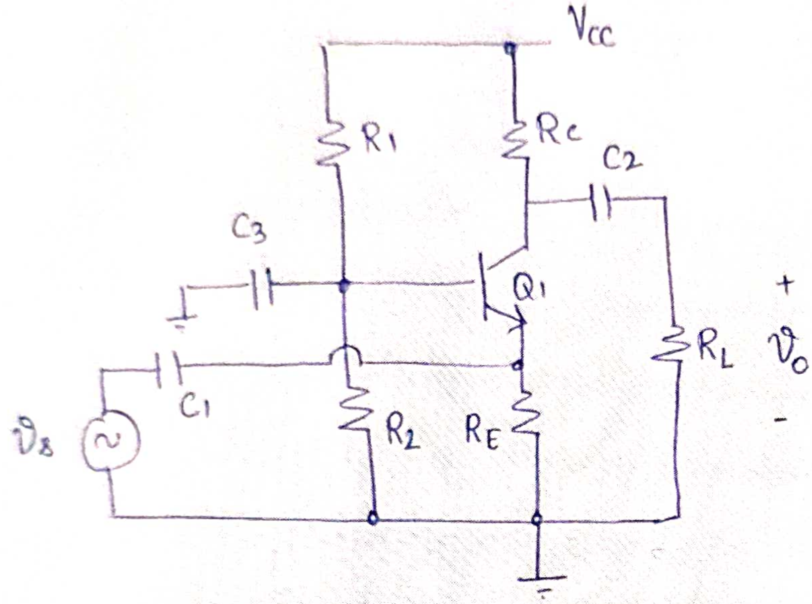
2. $$A_{vo} = -\frac{R_C}{R_E + r_e} = -\frac{1}{r_e} \frac{R_C}{1 + \frac{R_E}{r_e}} = -\frac{g_m R_C}{1 + g_m R_E}$$

when compared to the CE ampr. (without R_E), the open-ckt voltage gain of this ampr is reduced by a factor $(1+g_m R_E)$

3. For the same non-linear distortion, the i/p signal v_i can be increased by a factor $(1+g_m R_E)$
4. The overall voltage gain is less dependent on β
5. The high freq. response is significantly improved.
6. The reduction in gain by a factor of $(1+g_m R_E)$ is due to the -ve feedback action of R_E, giving it the name 'emitter degeneration resistance'

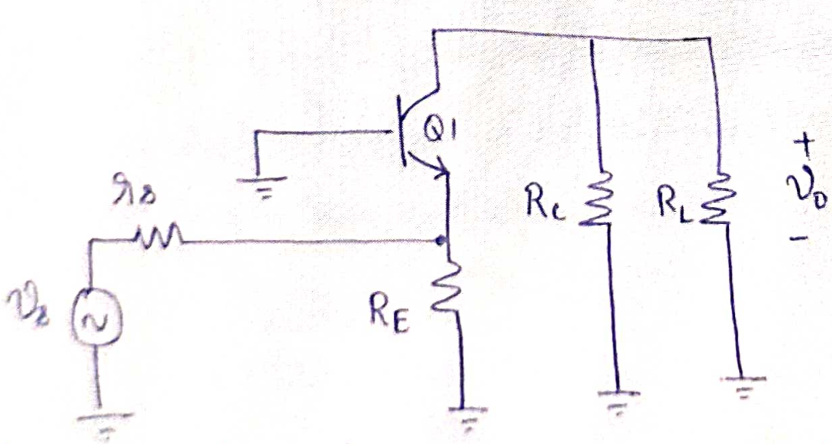
AVM

The Common-Base (CB) Amplifier



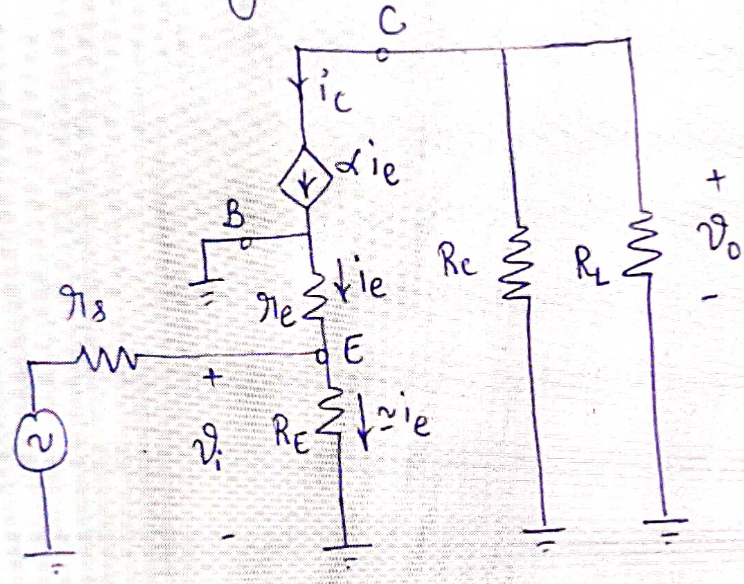
- I/p signal is applied to the emitter, and the O/p is taken at the collector, with the base forming a common terminal between the input and output ports.
- also called as grounded-base amplifier.

The ac equivalent ckt. can be drawn by (i) shorting Vcc to gnd, and (ii) shorting all the capacitors (ideal case of $X_C \simeq 0\Omega$ at mid-frequencies).



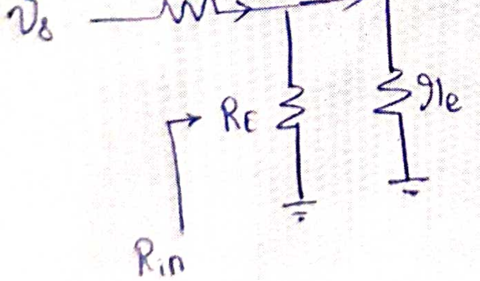
Since both the dc and ac voltages at the base are zero, the base is directly connected to ground, thus eliminating resistors R_1 and R_2 altogether during ac analysis.

Although hybrid-π model can be used to perform ac analysis of this ampr. ckt, T-model is the most convenient for this type of ckt because R_E will appear in series with emitter resis. r_e of the T-model. In fact, whenever there is resis. in the emitter lead, the T-model should be more convenient to use than the hybrid-π model.



Input Resistance, Rin

The i/p part of the small-signal eq. ckt. can be redrawn as



$$\therefore R_{in} = R_E \| r_e$$

$$\simeq r_e \quad \text{if } r_e \ll R_E$$

Typically $r_e \simeq \frac{1}{g_m} = \frac{V_T}{I_C} = \frac{25\,mV}{1\,mA}$ (say for $I_C = 1\,mA$)

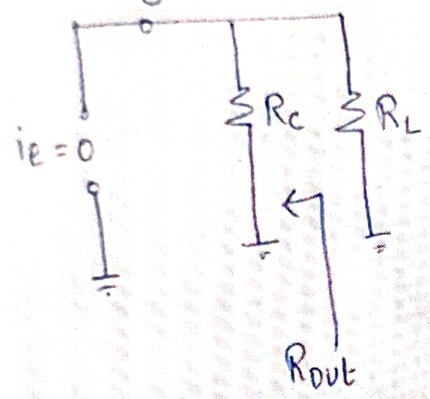
$= 25\,\Omega$.

Thus, CB ampr has a low i/p resistance.

AVM

Output Resistance, Rout

The o/p resis. can be found by inspection from the ckt. as



$\therefore R_{out} = R_C \| R_L$

which is similar to the case of CE ampr.

Voltage Gain

Open-circuit voltage gain, $A_{vo} = \left.\frac{v_o}{v_i}\right|_{R_L=\infty} = \frac{-i_o R_o}{-i_e(r_e \| R_E)}$

$$= \frac{\alpha i_e R_C}{i_e(r_e \| R_E)} \simeq \frac{R_C}{r_e \| R_E} \quad \text{as } \alpha \simeq 1$$

$$\simeq \frac{R_C}{r_e} \quad \text{if } r_e << R_E$$

$$= g_m R_C$$

This is identical to A_{vo} for the CE ampr except that the CB ampr is non-inverting.

By taking into account the effect of R_L, the voltage gain of the ampr can be expressed as

$$A_v = A_{vo} \times \frac{R_L}{R_o + R_L} = g_m R_C \times \frac{R_L}{R_C + R_L} = g_m (R_C \| R_L)$$

By taking into account the effect of r_s, the voltage gain of the CB ampr can be expressed as

$$A_{vs} = A_v \times \frac{R_{in}}{r_s + R_{in}} \simeq g_m (R_c \| R_L) \times \frac{r_e}{r_s + r_e}$$

$$\simeq \frac{R_c \| R_L}{r_s + r_e} \quad \text{since } g_m \simeq \frac{1}{r_e}$$

The overall voltage gain A_{vs} is simply the ratio of the total resis. in the collector circuit to the total resistance in the emitter circuit. Also, the overall voltage gain is independent of β, which is a desirable property.

Current gain, A_{is}

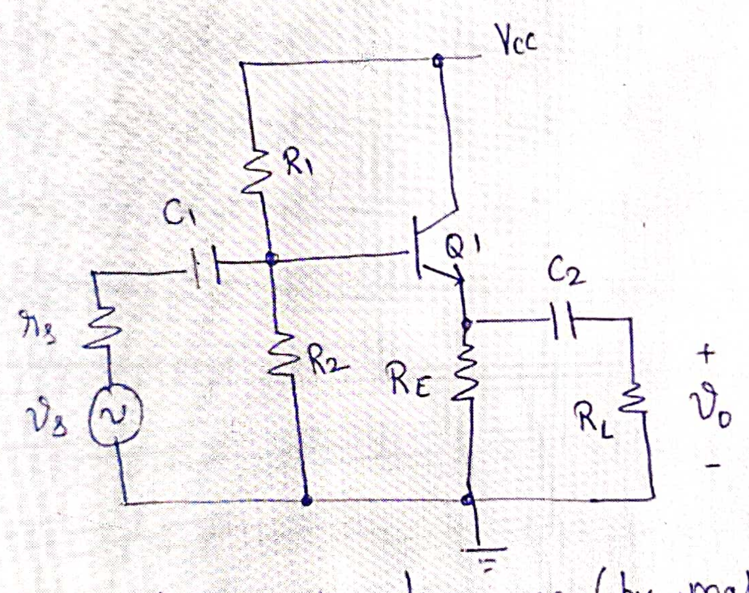
$$A_{is} = A_{vs} \times \frac{R_{in}}{R_{out}} = \frac{R_c \| R_L}{r_s + r_e} \times \frac{r_e}{R_c \| R_L} \simeq 1, \text{ but slightly} < 1$$

Because of this property, the CB circuit can be used as a unity-gain current ampr. or current buffer. It accepts an i/p signal current at a low i/p resistance and delivers a nearly equal current at a very high o/p resis. at the collector.

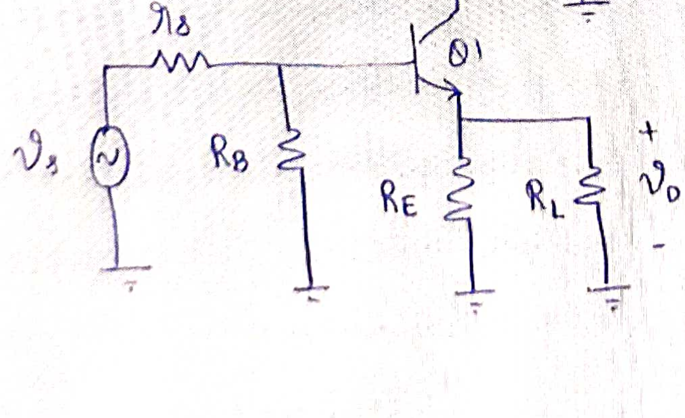
The CB ampr has excellent high-freq performance, making it useful with other circuits in the implementation of high-freq amprs.

The Common-Collector (CC) Amplifier

- The i/p signal is capacitively to the base, and the o/p signal is capacitively coupled from the emitter to a load resis. R_L, with the collector as the common terminal between i/p and o/p ports.
- also called as grounded-collector ampr.
- more commonly known as emitter follower, since the voltage at the emitter (V_o) follows very closely the voltage at the i/p.

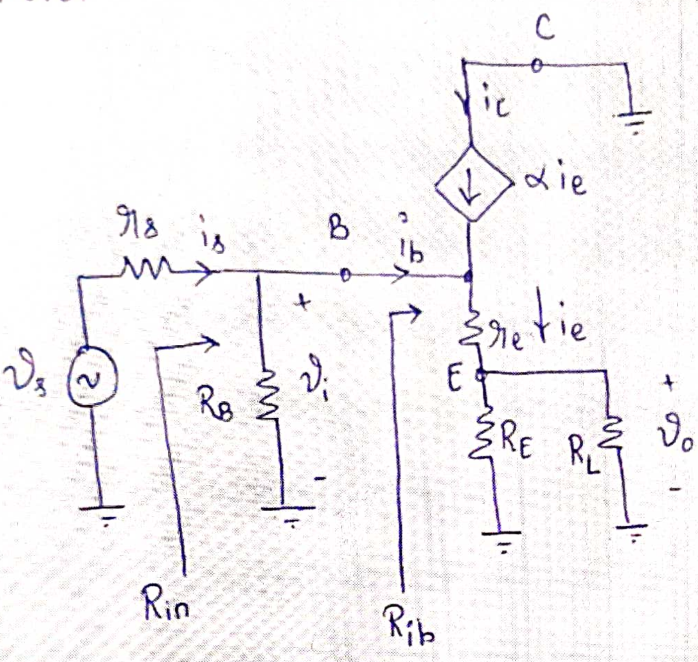


The AC equi. ckt. can be drawn as (by making $V_{CC} = 0$ & $X_C \simeq 0\Omega$)



where $R_B = R_1 \| R_2$

Replace the BJT by its T-model to obtain the small-signal equivalent circuit of the emitter follower. T-model is preferred than hybrid-π model as the T-model is more convenient to use whenever there is resis. in the emitter lead.



Input Resistance, R_{in}

By investigation of the i/p part of the n/w and applying KVL,

$$v_i = i_e\,(r_e + R_E \| R_L)$$

$$= (\beta+1)\, i_b\, (r_e + R_E \| R_L)$$

~~ie, $\frac{v_i}{i_b} = \beta r_e \; 1 + \frac{R_E \| R_L}{}$~~

$$\text{ie.,} \quad \frac{v_i}{i_b} = R_{ib} = \beta r_e + \beta (R_E \| R_L) \quad \text{--- (1)}$$

$$= \beta r_e \left(1 + \frac{R_E \| R_L}{r_e}\right)$$

$$= r_\pi \left[1 + g_m (R_E \| R_L)\right] \quad \text{--- (2)}$$

The factor $(1 + g_m (R_E \| R_L))$ refers to 'amount of -ve feedback' introduced by R_E. By the property of -ve f/b, the i/p imp @ the base (ie, r_π) is increased by a factor of $(1 + g_m (R_E \| R_L))$.

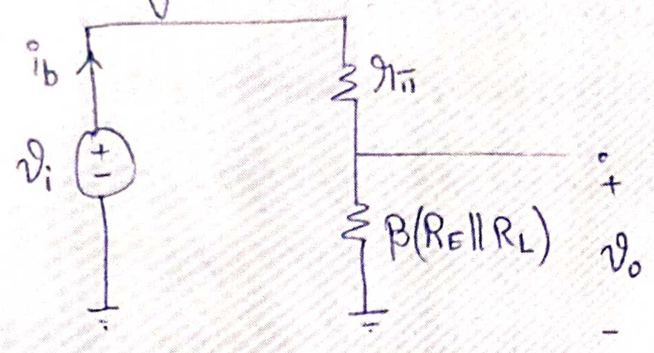
AVM

Voltage Gain

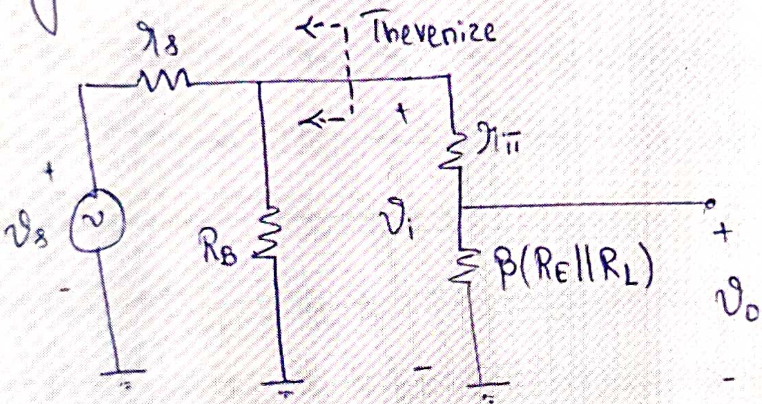
From eq. (2), $v_i = i_b \times [r_\pi + g_m r_\pi (R_E \| R_L)]$

$$= i_b \times [r_\pi + \beta (R_E \| R_L)] \quad \text{--- (3)}$$

The eq. (3) can be synthesized in the circuit form

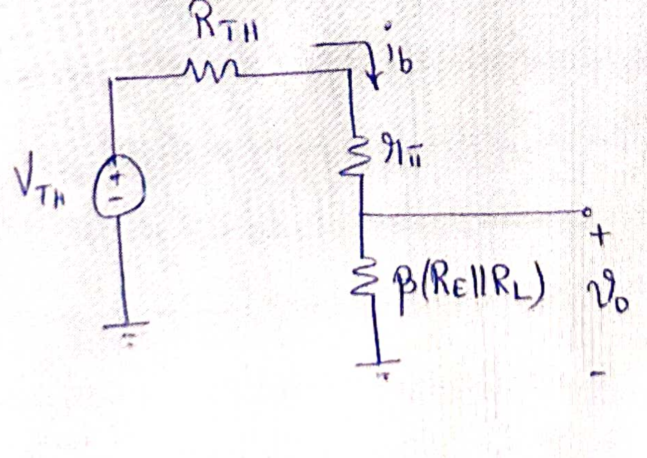


Extending to the i/p part of the ampr.,



Applying Thevenin's theorem,

$$V_{TH} = v_s \times \frac{R_B}{r_s + R_B} \quad \text{and} \quad R_{TH} = r_s \| R_B$$



By voltage divider formula,

$$v_o = \frac{V_{TH} \times \beta(R_E \| R_L)}{R_{TH} + r_\pi + \beta(R_E \| R_L)} = \frac{v_s R_B}{r_s + R_B} \times \frac{\beta(R_E \| R_L)}{(r_s \| R_B) + r_\pi + \beta(R_E \| R_L)}$$

ie, $$\frac{v_o}{v_s} = A_{vs} = \frac{R_B}{r_s + R_B} \times \frac{\beta(R_E \| R_L)}{(r_s \| R_B) + r_\pi + \beta(R_E \| R_L)} \quad \text{--- (4)}$$

where A_{vs} is called overall voltage gain of the CC amplifier by including the effect of r_s and R_L.

If we choose to ignore the effect of r_s, then

$$\cancel{A_{vs}\big|_{r_s=0} = A_v}$$

$$A_v = \frac{v_o}{v_i}\Big|_{r_s=0} = 1 \times \frac{\beta(R_E \| R_L)}{\cancel{r_s} + r_\pi + \beta(R_E \| R_L)} = \frac{R_E \| R_L}{\frac{r_\pi}{\beta} + (R_E \| R_L)}$$

$$= \frac{R_E \| R_L}{\frac{1}{g_m} + (R_E \| R_L)} = \frac{g_m(R_E \| R_L)}{1 + g_m(R_E \| R_L)} \simeq 1, \text{ but slightly } < 1 \quad \text{--- (5)}$$

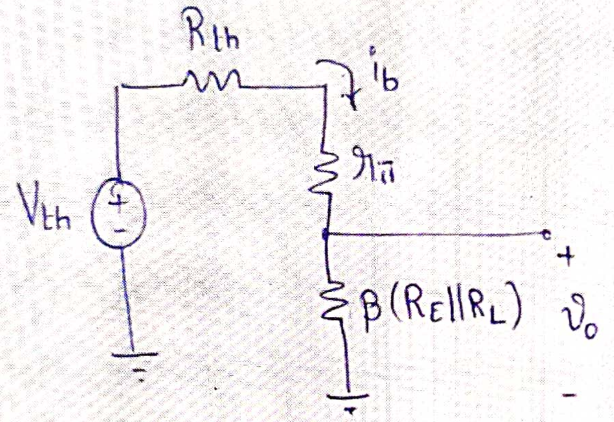
As mentioned earlier, the factor $(1 + g_m(R_E \| R_L))$ refers to the 'amount of -ve f/b' introduced by R_E, and because of this -ve f/b, the gain of the ampr is reduced by a factor of $(1 + g_m(R_E \| R_L))$.

$A_v \simeq 1$ means that the signal at the emitter follows the signal at the base, and hence called as 'emitter follower'.

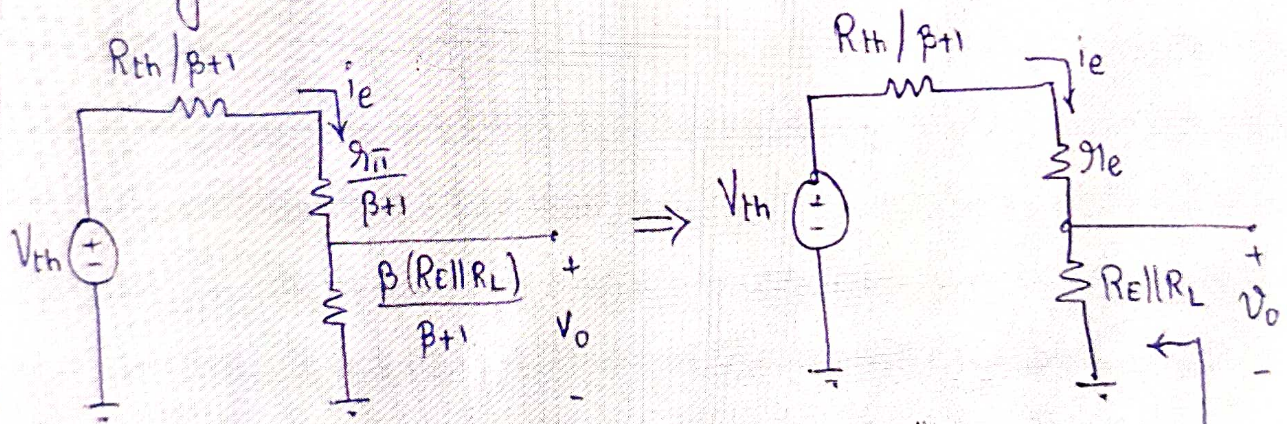
Because of this property, (ie, $A_v \simeq 1$), the CC circuit can be used as a unity gain voltage ampr or voltage buffer. It is useful in connecting a low-resis. load to a high-resis. source.

Output Resistance, R_{out}

The circuit obtained in the derivation of voltage gain of the ampr is redrawn here:



Reflecting all base-circuit resistances to the emitter side,



$$R_{out} = (R_E \| R_L) \| \left(r_e + \frac{r_s \| R_B}{\beta+1}\right) \quad \text{as } R_{th} = r_s \| R_B$$

$$\simeq r_e + \frac{r_s \| R_B}{\beta+1} \quad \text{— (6)}$$

$$\simeq r_e$$

AVM

Typically, $r_e \simeq \frac{1}{g_m} = \frac{V_T}{I_C} = \frac{25\,mV}{1\,mA}$ (say, for $I_C = 1\,mA$)

$\simeq 25\,\Omega$

Thus, the o/p resis of emitter follower is low, again as a result of its impedance transformation or buffering action, which lead to the division of $(r_s \| R_B)$ by $(\beta+1)$.

The o/p resis. of the ckt. can also be infered as follows:

$$R_{out} = \frac{R_E \| R_L}{1 + g_m(R_E \| R_L)} \simeq \frac{R_E \| R_L}{g_m(R_E \| R_L)} = \frac{1}{g_m} \simeq r_e$$

ie., the o/p resis. $(R_E \| R_L)$ is reduced by a factor of $[1 + g_m(R_E \| R_L)]$ due to -ve f/b.

<u>Current gain, A_{is}</u>

$$A_{is} = A_{vs} \times \frac{R_{in}}{R_{out}} \simeq 1 \times \frac{r_\pi(1 + g_m(R_E \| R_L))}{r_e} = \beta(1 + g_m(R_E \| R_L))$$

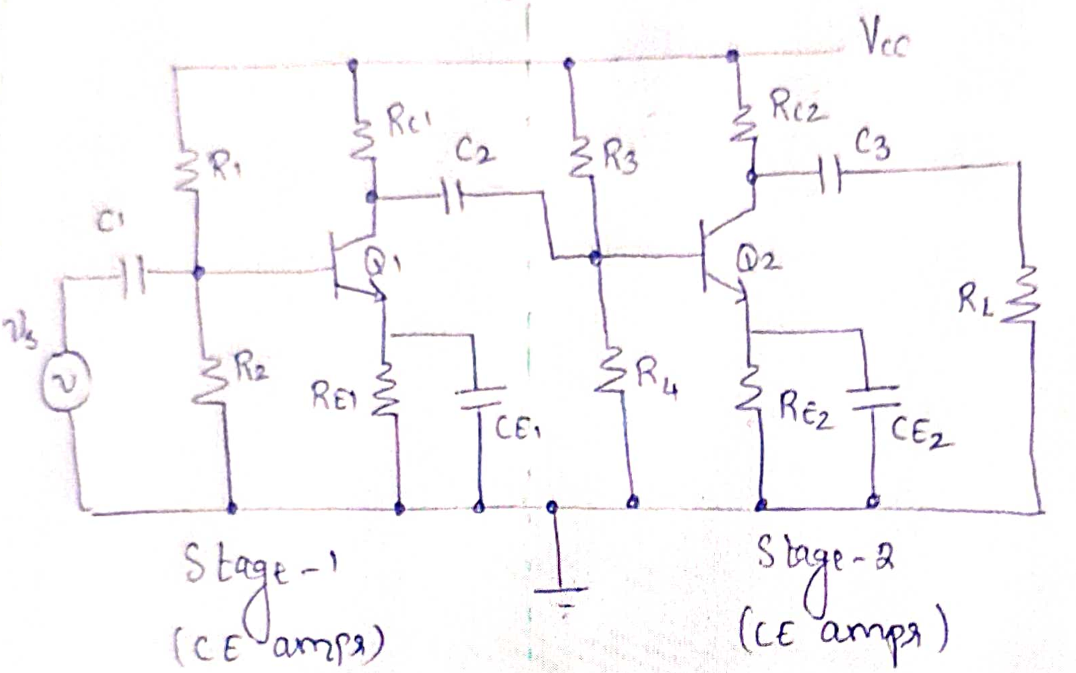
ie, the current gain β of the transistor is increased by a factor of $(1 + g_m(R_E \| R_L))$ due to -ve f/b.

— * —

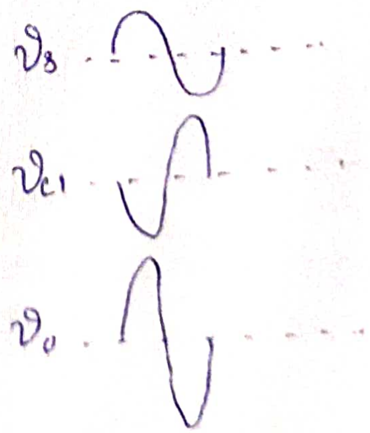
Unlike the CE and CB circuits, the emitter-follower circuit is not unilateral; ie., the i/p resis. depends on R_L, and the o/p resis. depends on r_s. So, enough care must be taken while characterizing the emitter follower.

MULTISTAGE AMPLIFIERS

1. RC coupled Two-stage CE amplifier

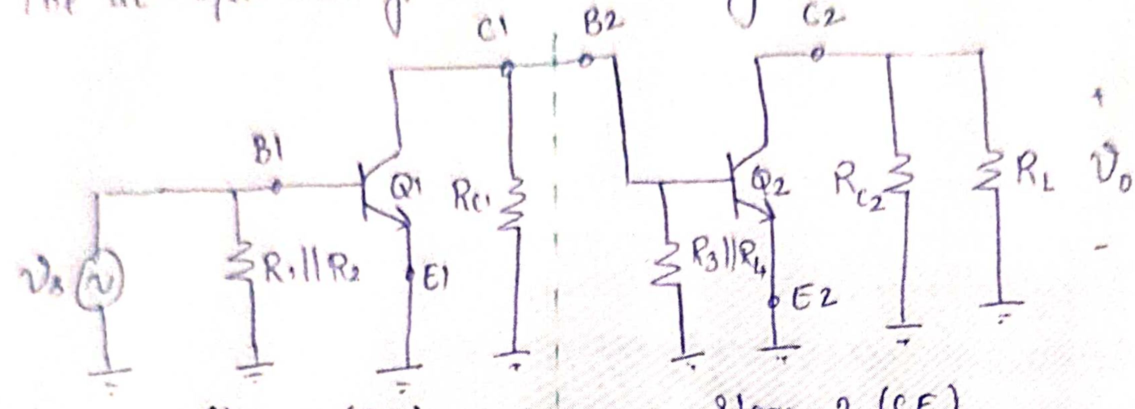


- Stage-1 and stage-2 are similar to single-stage CE circuit
- Stage-1 is capacitor-coupled (Via C2) to the i/p of stage-2
- The i/p signal is applied to the i/p of stage-1 via C1, and the load is coupled to the o/p of stage-2 via C3.
- The signal is first amplified by stage-1, and the o/p of stage-1 is amplified by stage-2, so that the overall gain is much larger than the gain of a single-stage circuit.
- the signal is phase shifted by 180° by stage-1, and then further phase shifted by 180° by stage-2 Consequently, the overall phase shift of the o/p signal is 0° or 360°.



AVM

The ac equi. ckt for the multistage amps can be drawn as



Using the results and discussions done for single-stage circuits, we can summarize the characteristics and parameters of this multistage amps as :

__Input Resistance, Rin__

$R_{in1} = R_1 || R_2 || R_{ib1}$ where $R_{ib1} = r_\pi$

$R_{in2} = R_{C1} || R_3 || R_4 || R_{ib2}$ where $R_{ib2} = r_\pi$

__Output Resistance, Rout__

$R_{out1} = R_{in2}$

$R_{out2} = R_{C2} || R_L$

__Voltage gain__

$A_{v1} = -g_m \times$ effective resis. @ the collector of stage-1

$= -g_m \times (R_{C1} || R_3 || R_4 || R_{ib2})$

$A_{v_2} = -g_m \times$ effective resis @ the collector of stage-2

$= -g_m \times (R_{C2} \| R_L)$

$\therefore$ The overall voltage gain of this multistage ampr. is

$A_V = A_{V_1} \times A_{V_2}$

$= g_m^2 \times (R_{C1} \| R_3 \| R_4 \| R_{ib2}) \times (R_{C2} \| R_L)$

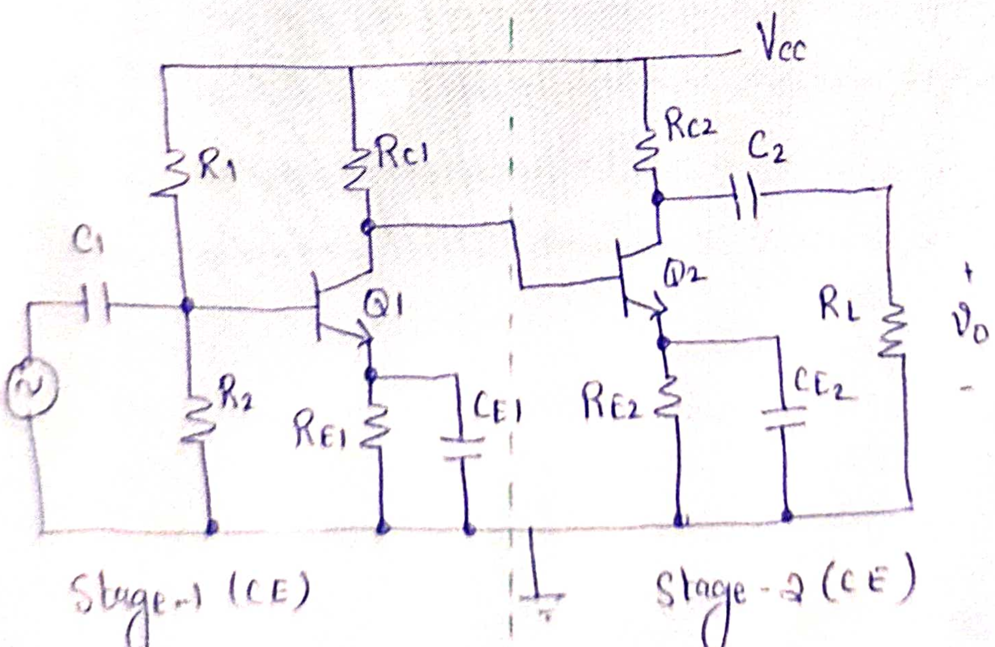
Current gain. A_i

$$A_i = A_V \times \frac{R_{in}}{R_{out}}$$

$$= \frac{g_m^2 \times (R_{C1} \| R_3 \| R_4 \| R_{ib2}) \cancel{(R_{C2} \| R_L)} \times (R_1 \| R_2 \| R_{ib1})}{\cancel{(R_{C2} \| R_L)}}$$

$$= g_m^2 \times (R_{C1} \| R_3 \| R_4 \| R_{ib2}) (R_1 \| R_2 \| R_{ib1})$$

2. Direct-Coupled Two-stage CE amplifier

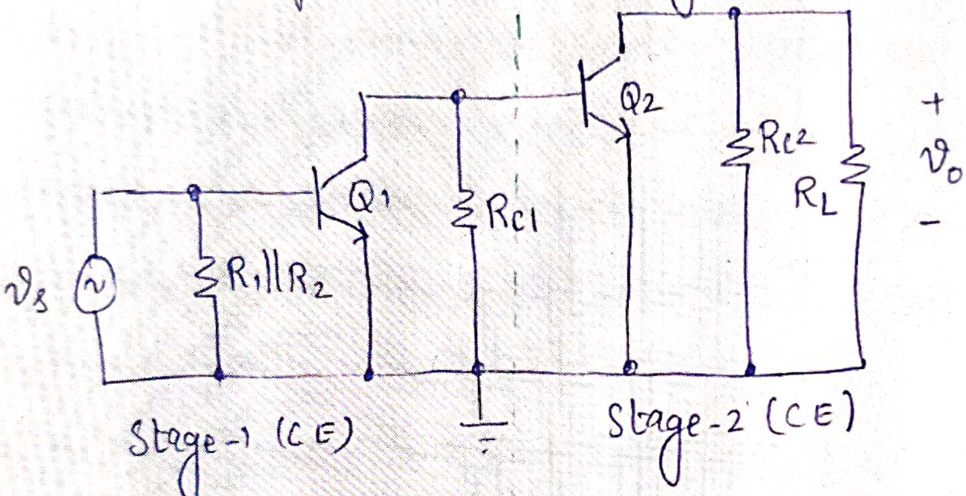


AVM

- Stage-1 o/p is directly connected to stage-2 i/p, thereby eliminating the need for an interstage coupling capacitor and two bias resistors.

- The no. of components used in this ckt. is kept to minimum, and hence economical.

The ac equi. ckt. for this multistage ampr. can be drawn as



Input Resistance, R_{in}

$R_{in1} = R_1 \| R_2 \| R_{ib1}$ where $R_{ib1} = r_\pi$

$R_{in2} = R_{C1} \| R_{ib2}$ where $R_{ib2} = r_\pi$

Output Resistance, R_{out}

$R_{out1} = R_{in2}$

$R_{out2} = R_{C2} \| R_L$

Voltage Gain, A_V

$A_{V1} = -g_m \times$ eff. resis @ collector of stage-1
$= -g_m \times (R_{C1} \| R_{ib2})$

$A_{V2} = -g_m \times$ eff. resis. @ collector of stage-2
$= -g_m \times (R_{C2} \| R_L)$

$\therefore$ The overall voltage gain of the multistage ampr is

$$A_V = A_{V1} \times A_{V2}$$
$$= -g_m (R_{C1} \| R_{ib2}) \times -g_m (R_{C2} \| R_L)$$
$$= +g_m^2 (R_{C1} \| R_{ib2}) (R_{C2} \| R_L)$$

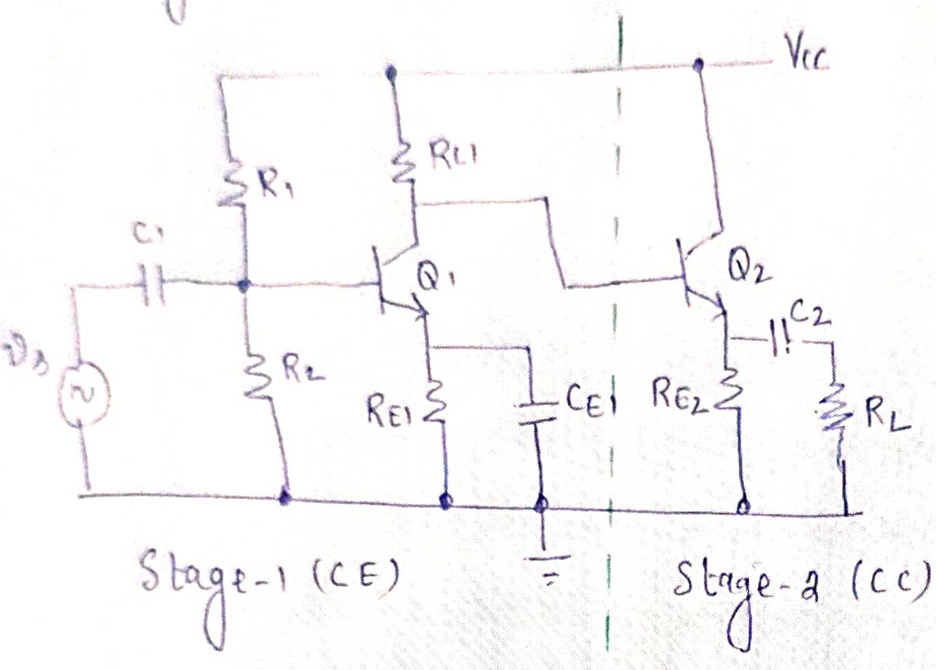
Current Gain, A_i

$$A_i = A_V \times \frac{R_{in}}{R_{out}} =$$

$$= \frac{+g_m^2 (R_{C1} \| R_{ib2}) \cancel{(R_{C2} \| R_L)} \times (R_1 \| R_2 \| R_{ib1})}{\cancel{(R_{C2} \| R_L)}}$$

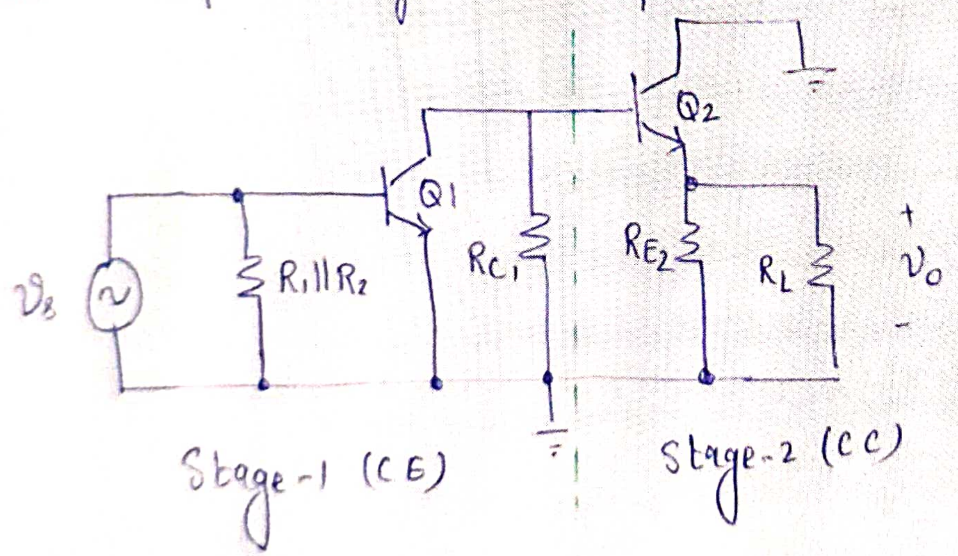
$$= +g_m^2 (R_{C1} \| R_{ib2}) (R_1 \| R_2 \| R_{ib1})$$

3. Two stage Circuit with Emitter Follower o/p (Direct-coupled)



- Stage-1 is CE circuit, and stage-2 is CC circuit.
- Stage-2 gives the circuit a very low o/p impedance, but has unity voltage gain.
- Stage-1 still has substantial voltage gain.

The ac equi. ckt. for this ampr can be drawn as



Input Resistance, Rin

$R_{in1} = R_1 \| R_2 \| R_{ib1}$ where $R_{ib1} = r_\pi$

$R_{in2} = R_{C1} \| R_{ib2}$ where $R_{ib2} = r_\pi (1 + g_m (R_E \| R_L))$

Output Resistance, Rout

$R_{out1} = R_{in2}$

$R_{out2} \simeq r_e$

Voltage Gain, Av

$A_{V1} = -g_m \times$ eff. resis. @ collector of stage-1

$= -g_m (R_{C1} \| R_{ib2})$

$A_{V2} \simeq 1$. (for CC ckt.)

∴ The overall voltage gain is given by

$A_V = A_{V1} \times A_{V2}$

$= -g_m (R_{C1} \| R_{ib2})$

Current Gain, Ai

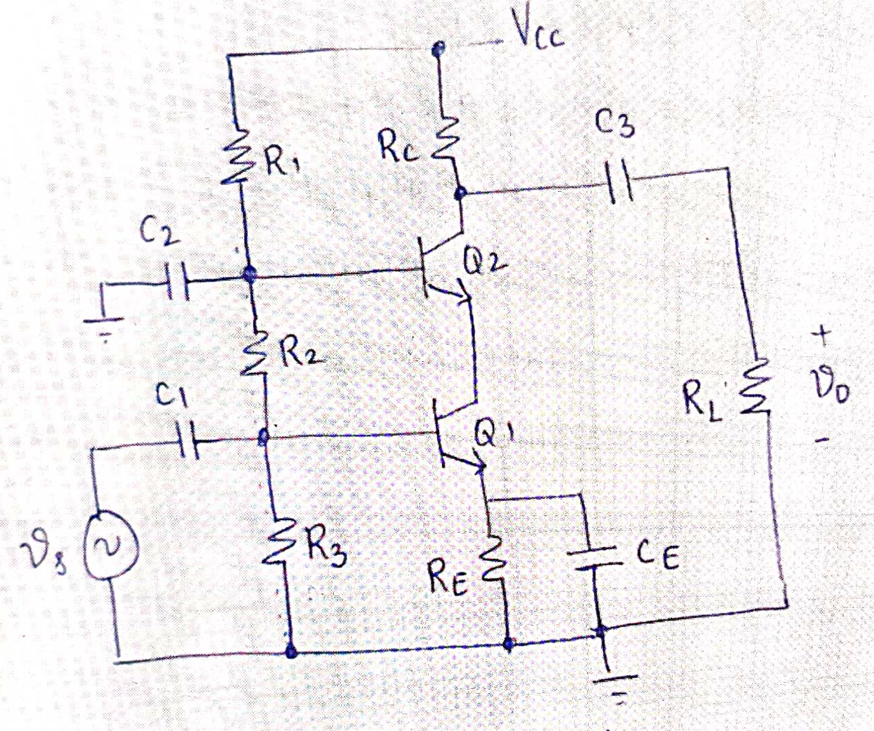
$$A_i = A_V \times \frac{R_{in}}{R_{out}} = \frac{-g_m (R_{C1} \| R_{ib2}) \times (R_1 \| R_2 \| R_{ib1})}{r_e}$$

$$= -g_m^2 (R_{C1} \| R_{ib2}) (R_1 \| R_2 \| R_{ib1})$$

since $r_e \simeq \frac{1}{g_m}$

1. Cascode amplifier (CE+CB stages)

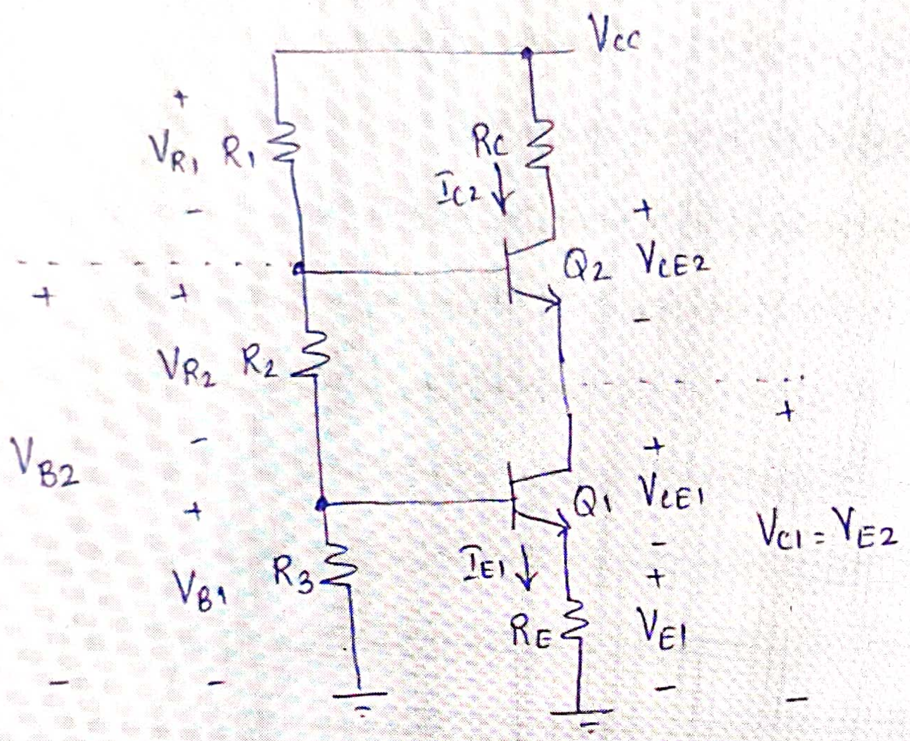
- The very low i/p impedance of a CB circuit (typically 25Ω) is a major disadvantage.
- To increase the circuit i/p impedance while retaining its high freq performance, the cascode amps can be used.
- It uses a CE stage driving a CB stage.



Transistor Q_1 and its associated components operates as a CE stage, while the circuit of Q_2 functions as a CB o/p stage.

Dc analysis

The Dc equi. ckt for the cascode amplifier can be obtained by (i) open circuiting all capacitors, and (ii) omitting signal source, ie, $V_s = 0$



The circuit analysis will yield the following results:

$$V_{B1} = V_{CC} \times \frac{R_3}{R_1 + R_2 + R_3}$$

also, $V_{B1} = V_{BE} + V_{E1}$ using which

$$V_{E1} = V_{B1} - V_{BE}$$

$$I_{E1} R_E = V_{B1} - V_{BE}$$

$$I_{E1} \simeq I_{C1} = I_{E2} \simeq I_{C2} = \frac{V_{B1} - V_{BE}}{R_E}$$

$$V_{B2} = V_{cc} \times \frac{R_2 + R_3}{R_1 + R_2 + R_3}$$

also, $V_{B2} = V_{BE} + V_{C1}$ where $V_{C1} = V_{CE1} + V_{E1}$

And, $V_{cc} = I_{C2} R_C + V_{CE2} + V_{CE1} + I_{E1} R_E$

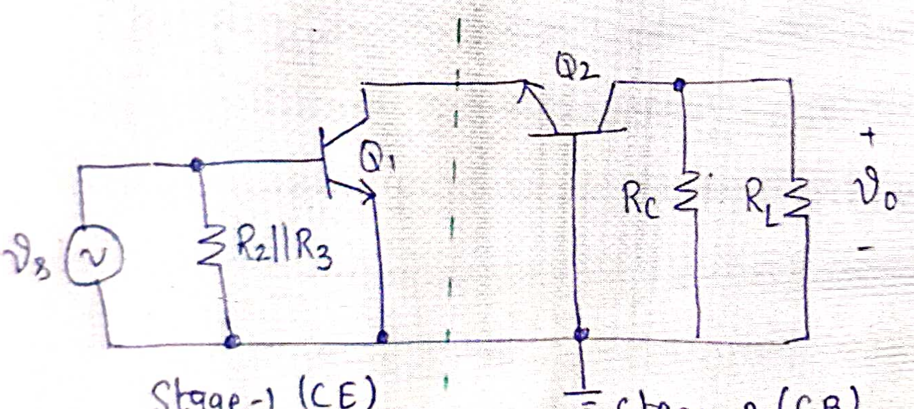
$= I_{C2} R_C + 2 V_{CE} + I_{C2} R_E$ $(\because V_{CE1} = V_{CE2} = V_{CE})$

$$\Rightarrow V_{CE} = \frac{V_{cc} - I_{C2}(R_C + R_E)}{2}$$

when the voltage and current levels are selected/determined, the resistor values are easily determined.

Ac analysis

The Ac equivalent ckt of the cascode amps. can be drawn a



Pls. note that R_1 has no significant effect in the performance of the amplifier circuit.

Input Resistance, Rin

$R_{in1} = R_2 || R_3 || R_{ib1}$ where $R_{ib1} = r_\pi$

$R_{in2} \simeq r_e$

Output Resistance, Rout

$R_{out1} = R_{in2}$

$R_{out2} = R_C \| R_L$

Voltage gain, Av

$A_{V1} = -g_m \times$ eff. resis. @ collector of stage-1

$= -g_m r_e \simeq 1$

$A_{V2} = g_m \times$ eff. resis. @ collector of stage-2

$= g_m (R_C \| R_L)$

∴ The overall voltage gain of the amp. is given by

$A_V = A_{V1} \times A_{V2}$

$= g_m (R_C \| R_L)$

Current Gain, Ai

$$A_i = A_V \times \frac{R_{in}}{R_{out}} = \frac{g_m \cancel{(R_C \| R_L)} \times (R_2 \| R_3 \| R_{ib1})}{\cancel{(R_C \| R_L)}}$$

$$= g_m (R_2 \| R_3 \| R_{ib1})$$