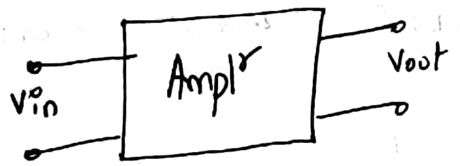
BJT amplifiers

Module 4.1:- Understanding concepts of amplification with reference to input/output characteristics

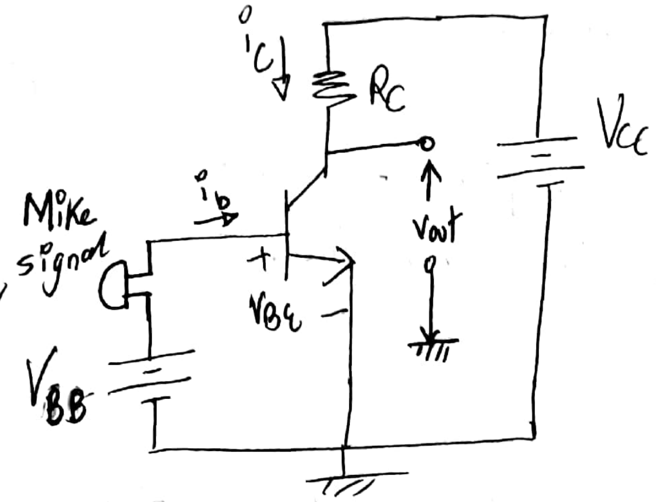
- Amplifier requirements:-



1) Gain should be high
   eg voltage gain of a voltage amplr → high
2) I/P impedance
3) O/P impedance
4) Linearity (O/P should be Linear w.r.t I/P)

- BJT as a device should amplify → small time-varying signals. → This condition must be satisfied for BJT amplifier to be $\boxed{\text{Linear}}$

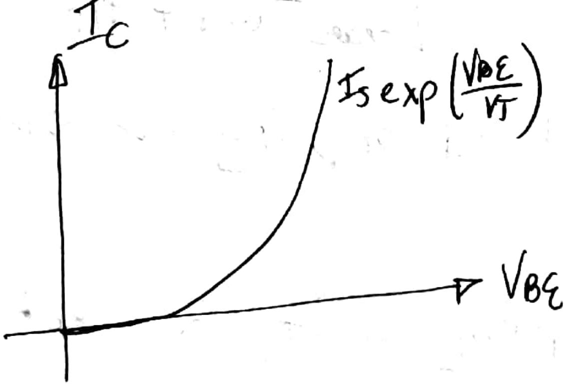
- Next, we need to superimpose small AC s/g with DC? Why DC biasing is required → so that BJT wakes up & works in proper mode ie active region → so that it is used as amplifier

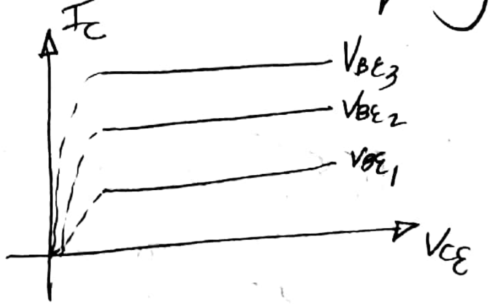


It acts a small-time varying I/P V_{in} ($V_{mike} = V_m \sin\omega t$)

→ BJT act as : <u>voltage-dependent current source</u>

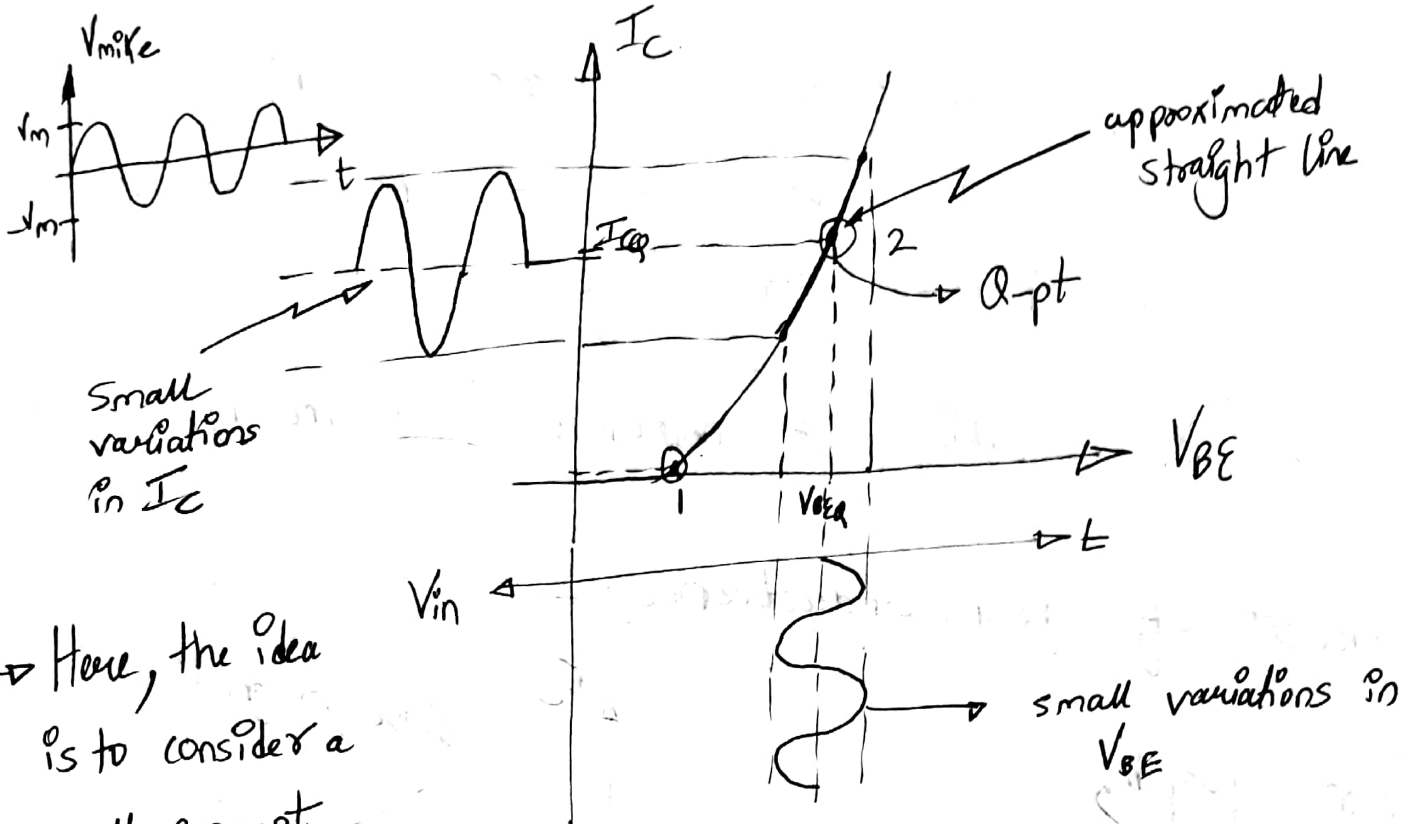
→ "converts" a voltage (V_{BE}) or V_{be} to a current (I_C) --- DC quantity, i_c --- AC quantity





<u>Biasing:</u> Provide proper voltage (V_{BE}) & current (I_C) so that the transistor can amplifies (in the absence of signals)

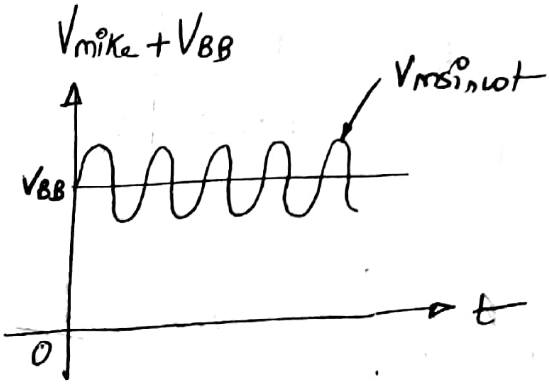
Operating point : The bias values chosen for V_{BE}, I_C, V_{CE} --- etc.



→ Here, the idea is to consider a small segment of exponential curve to be $\boxed{\text{Linear}}$ → straight line

→ So our I/p Limit should be within this Linear segment → Hence, called as Small-s/g

Combining transfer curve & time response



I_S - reverse satn current
eg 10^{-15}A

Observations:- 1) At point A, in absence of s/g, variations in collector current are very small ($\simeq I_S$) ie BJT is not biased & will not work in active region

2) At point B, BJT is biased in active region, since it has sufficient value of I_C & V_{BE}

3) A bjt can acts as voltage-dependent current source → since I_C changes in response to its base-emitter voltage.

4) The operating point determine how the bjt responds.

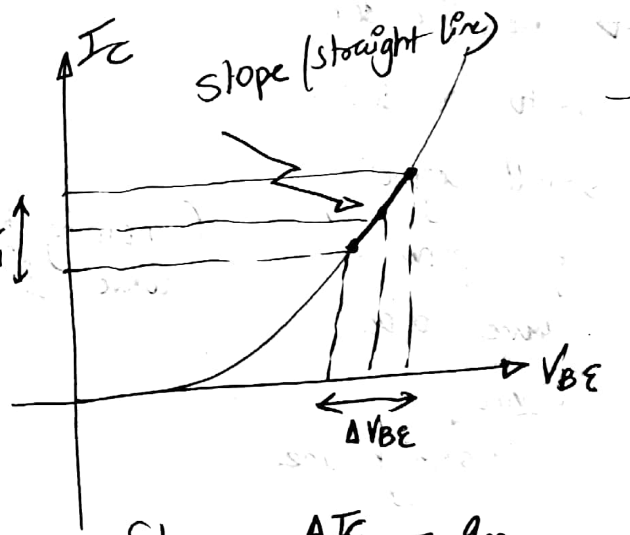
- Concept of transconductance :-

From graph,

$$\boxed{g_m = \left.\frac{dI_C}{dV_{BE}}\right|_{opt}}$$

slope of I_C vs V_{BE} characteristics

unit: $\frac{1}{\Omega}$ or $\frac{mA}{V}$



$$\text{Slope} = \frac{\Delta I_C}{\Delta V_{BE}} = g_m$$

$$\boxed{\Delta I_C = \Delta V_{BE}\, g_m}$$

ΔI_C: Small changes in I_C

ΔV_{BE}: small changes in V_{BE}

g_m: slope → a constant

It suggest that base-to emitter voltage controls the collector current in a BJT

$$g_m = \frac{dI_C}{dV_{BE}}$$

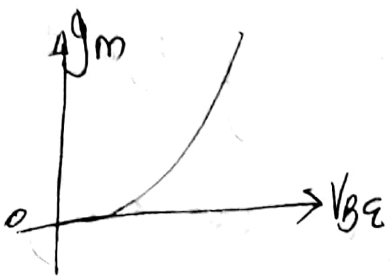
$$= \frac{d}{dV_{BE}}\left(I_S \exp\frac{V_{BE}}{V_T}\right)$$

$$= \frac{I_S}{V_T}\exp\frac{V_{BE}}{V_T}$$

$$\boxed{g_m = \frac{I_C}{V_T}}$$ ie $$\boxed{g_m = \frac{I_{CQ}}{V_T}}$$

($V_T = 26mV$ @ $27°C$)

$$\boxed{g_m = \frac{I_{CQ}}{V_T}}$$



1) With no bias $\Rightarrow I_C = 0 \Rightarrow g_m = 0$
$\downarrow$
No amplificatn

2) For amplification, we need a certain $g_m \Rightarrow$ certain $I_{CQ} \rightarrow$ certain V_{BE}

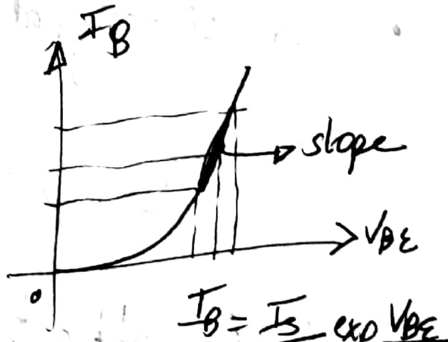
$\rightarrow$ Small ~~-signal operation:-~~

$\hookrightarrow$ The signal coming into the ckt is "Small"
$\hookrightarrow$ comparable to V_T value.

$\rightarrow$ The signal perturbs the bias (operating) point by only a small amount.

- Small-sig parameter (r_π) :-

Consider I/P characteristics of bjt



$$I_B = \frac{I_S}{\beta} \exp \frac{V_{BE}}{V_T}$$

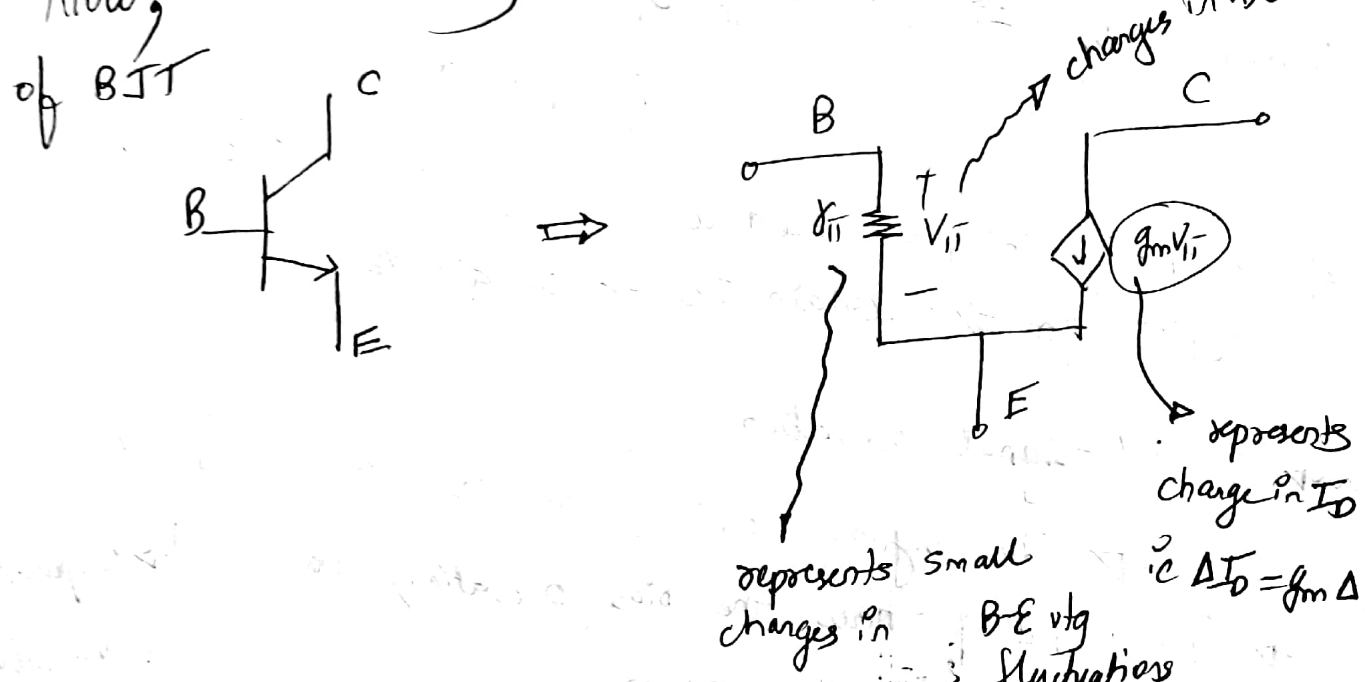
$$r_\pi = \frac{1}{\text{Slope}} = \frac{\Delta I_B}{\Delta V_{BE}} \Bigg|_{V_{BC} = \text{constant}}$$

ie $$\frac{dI_B}{\Delta V_{BE}} = \frac{d}{dV_{BE}}\left(\frac{I_S}{\beta} \exp \frac{V_{BE}}{V_T}\right) = \frac{I_S}{\beta \times V_T} \exp\left(\frac{V_{BE}}{V_T}\right)$$

ie $$\frac{dI_B}{dV_{BE}} = \frac{I_B}{V_T} \therefore$$ ie $$\boxed{\frac{dV_{BE}}{dI_B} = r_\pi = \frac{I_{BQ}}{V_T}}$$

• <u>Small-slg hybrid-π model of bjt</u> :-

Now, we are ready to draw small-signal model of BJT

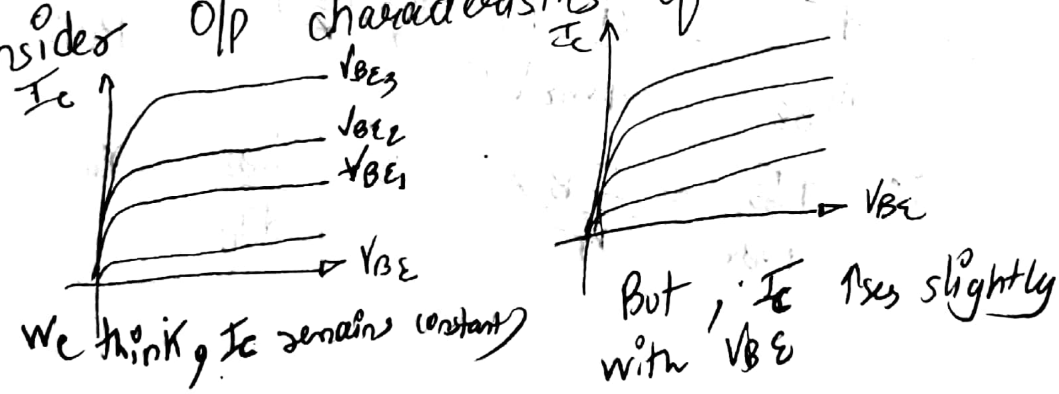


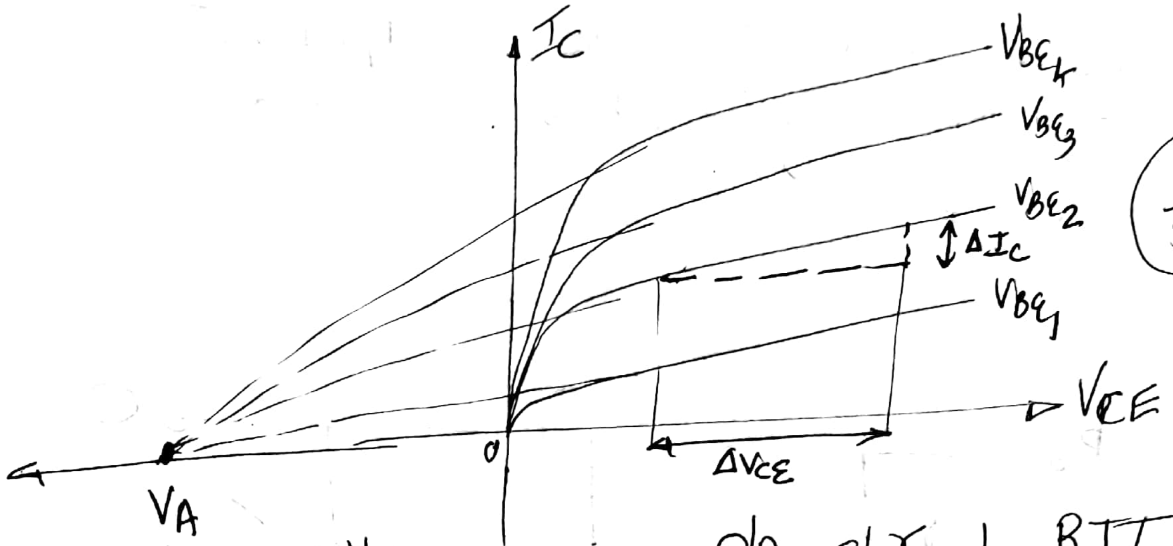
• <u>Small-signal model</u> → (represents only time-varying quantities)

↳ represent only changes in parameters.

• <u>Early effect</u> (Small-slg o/p resistance/impedance) (r_o OR r_d)

let's consider o/p characteristics of BJT





$\frac{1}{slope} = r_0$ or r_d

O/p ch^r of BJT

- In above graph, if we extrapolate I_C curve to -ve axis of V_{CE}, these family of curves meet at a point called "Early voltage" V_A.

- In reality, I_C ↑ses slightly with V_{CE} due to early effect.

$$I_C = \left(I_S \exp \frac{V_{BE}}{V_T}\right)\left(1 + \frac{V_{CE}}{V_A}\right)$$

V_A : Early voltage

$$Slope = \frac{dI_C}{dV_{CE}} = \left(\frac{I_S}{V_A} \exp \frac{V_{BE}}{V_T}\right)\left(1 + \frac{V_{CE}}{V_A}\right)$$

ie $\frac{dI_c}{dV_{CE}} = \frac{I_{CQ}}{V_A}$

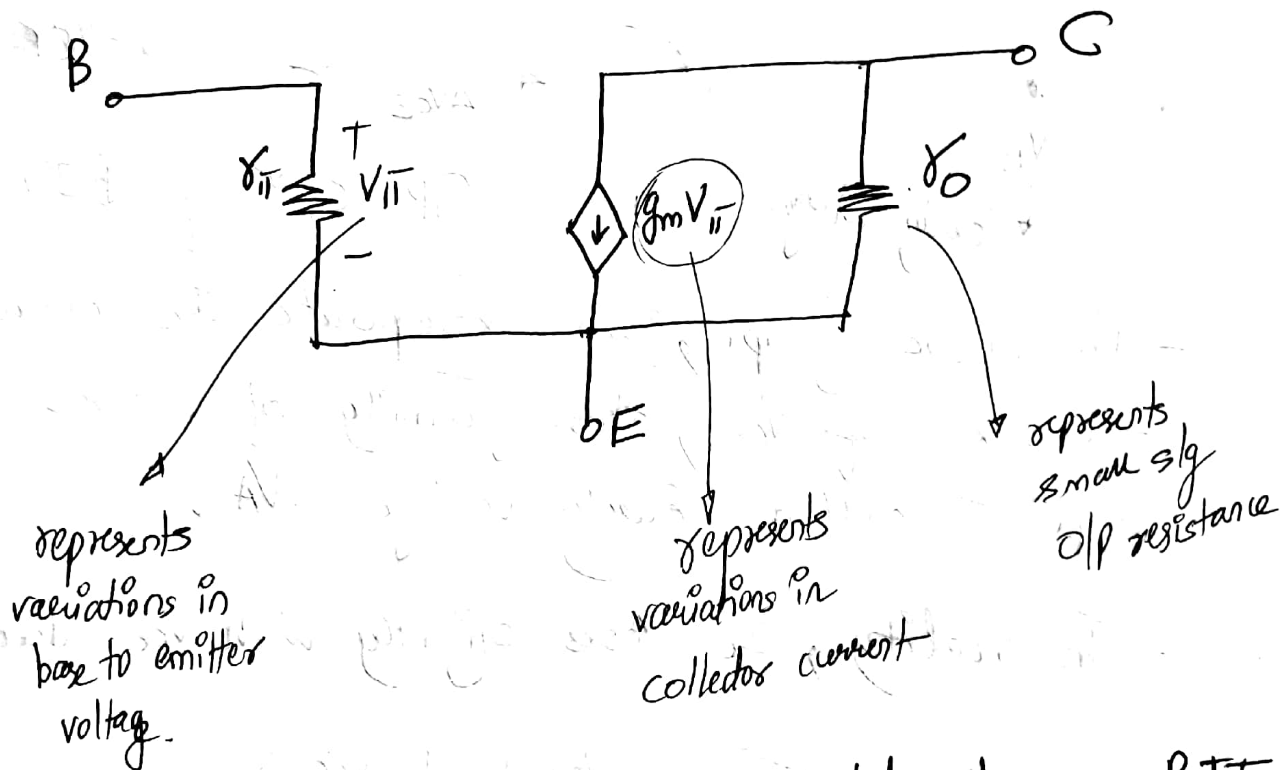
ie $r_o = r_d = \frac{dV_{CE}}{dI_c} = \frac{V_A}{I_{CQ}}$

$$\boxed{\text{ie } r_o = r_d = \frac{V_A}{I_{CQ}}}$$

- We need to include r_o, in small-slg model.

small-slg o/p resistance of a bjt biased in forward active region.

Complete small-s/g model of npn BJT including early effect is given below



Small-signal hybrid-π model of npn BJT

→ Small-signal parameters :-

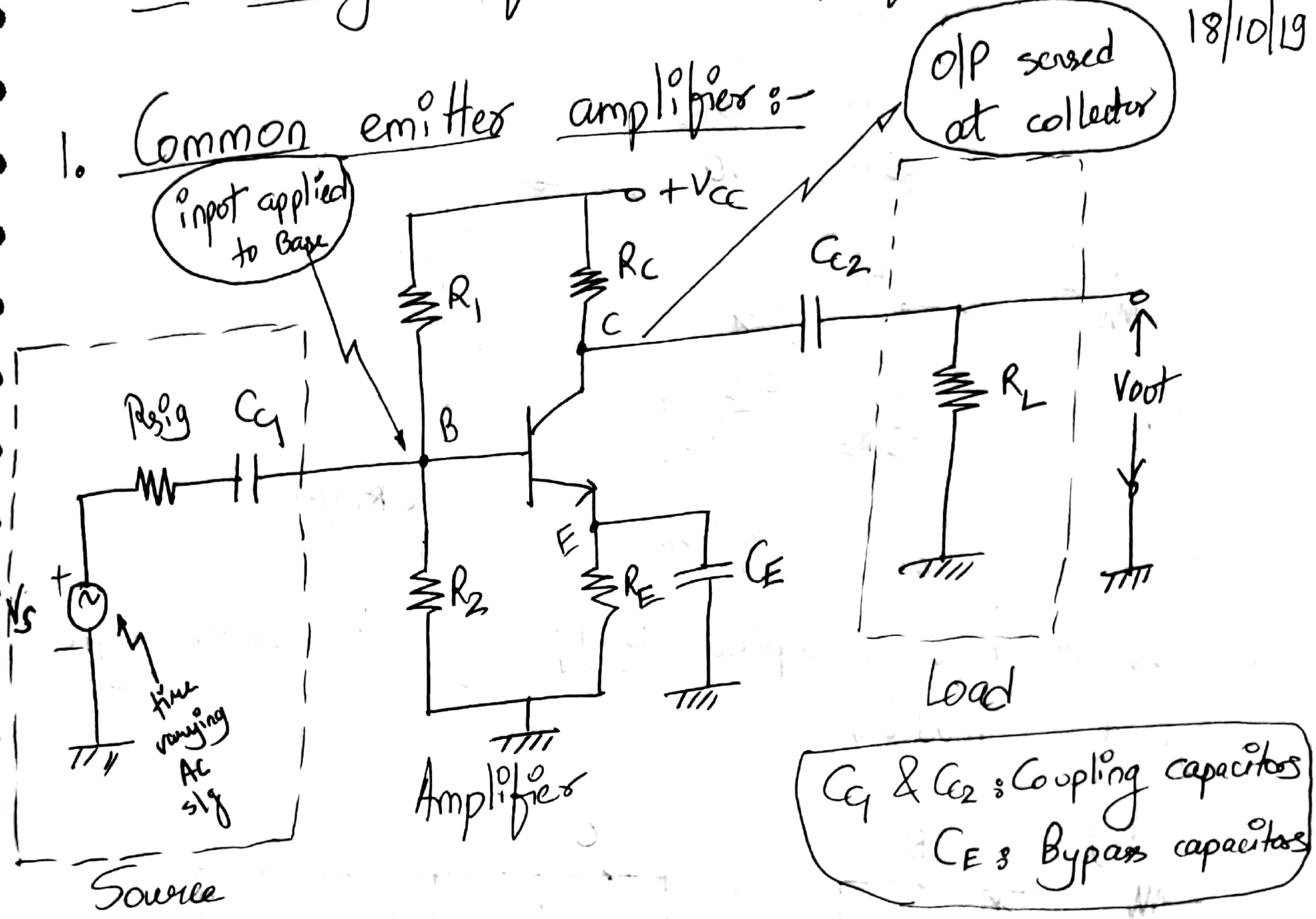
1. $\boxed{r_\pi = \frac{I_{BQ}}{V_T}}$

2. $\boxed{g_m = \frac{I_{CQ}}{V_T}}$

3. $\boxed{r_o = \frac{V_A}{I_{CQ}}}$

AC Analysis of BJT amplifier :-

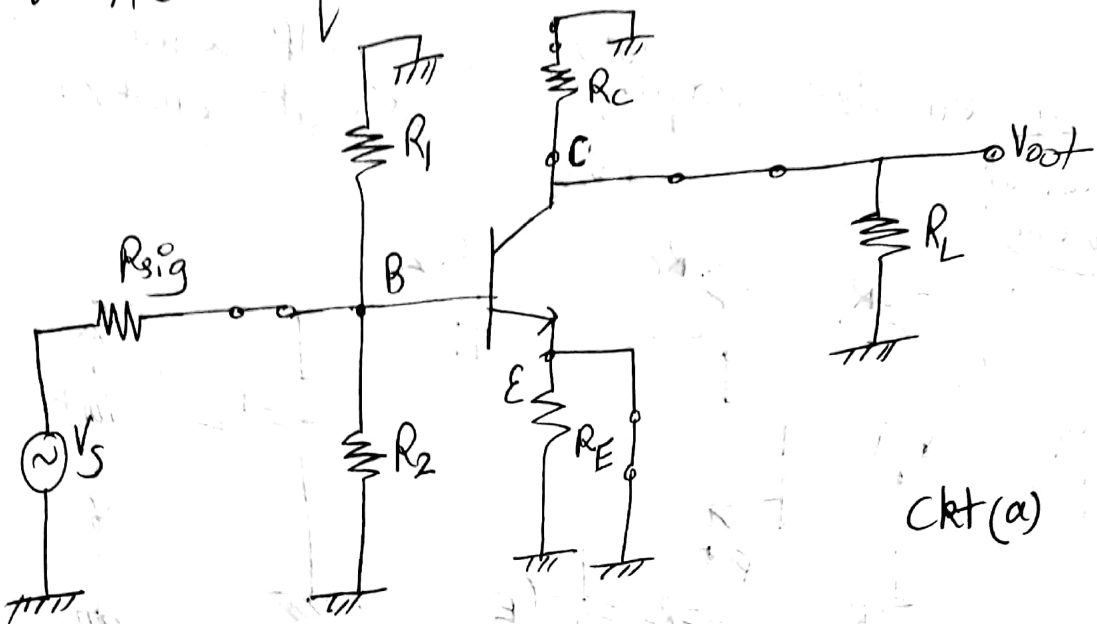
1. Common emitter amplifier :-



Observations:

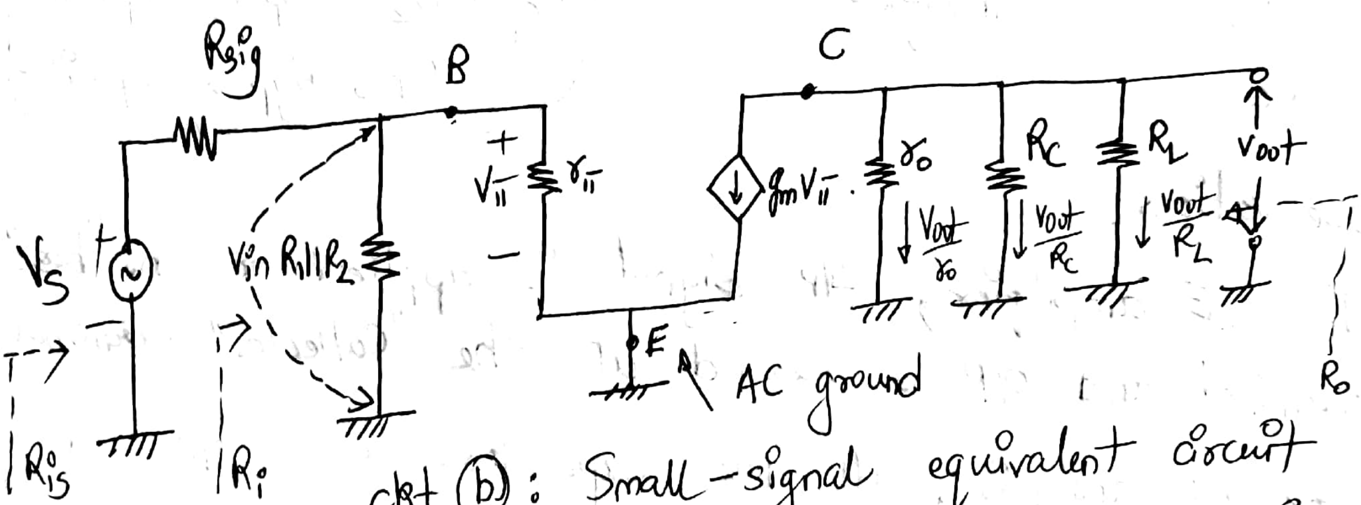
1. In CE amplifier, i/p signal is applied to the "base" terminal and o/p is sensed at the "Collector" terminal.
2. For AC analysis, all the capacitors are replaced by a short circuit → as the capacitive impedances ($X_C = \frac{1}{2\pi f C}$) are very low at mid-frequencies
3. DC supply is also replaced by a short circuit for small signal (AC) analysis.

→ AC equivalent circuit is,



ckt (a)

→ Now, we have to replace $\boxed{BJT}$ by its small-signal hybrid-π model,



ckt (b) : Small-signal equivalent circuit

<u>Analysis:</u> 1) To find A_v : voltage gain expression

· From ckt b, $V_{in} = V_{\pi}$

KCL at Collector terminal,

$$g_m V_\pi + \frac{V_{out}}{r_o} + \frac{V_{out}}{R_C} + \frac{V_{out}}{R_L} = 0$$

$$g_m V_{in} = -V_{out}\left(\frac{1}{r_o} + \frac{1}{R_C} + \frac{1}{R_L}\right)$$

$$\rightarrow \boxed{A_V = \frac{V_{out}}{V_{in}} = -g_m\,(r_o \,||\, R_C \,||\, R_L)}$$

small-slg voltage gain of amplifier

-ve sign indicates that I/P & o/p are out-of phase

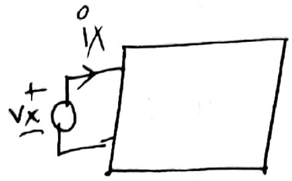
Now, $A_{VS} = \frac{V_{out}}{V_S} = \frac{V_{out}}{V_{in}} \times \frac{V_{in}}{V_S} = A_V \times \frac{V_{in}}{V_S}$

From ckt (b), $A_{VS} = A_V \frac{V_{in}}{V_S}$

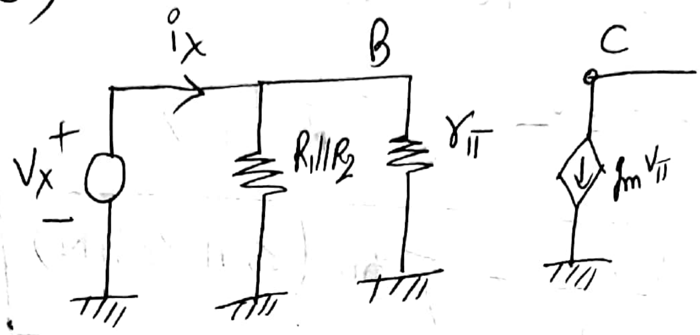
$$\rightarrow \frac{V_{in}}{V_S} = \frac{R_1 || R_2}{R_1 || R_2 + R_{sig}}$$ --- by V.D.R

ie $$\boxed{A_{VS} = A_V \times \frac{R_1 || R_2}{R_1 || R_2 + R_{sig}}}$$

2) Input impedance/resistance (Z_i/R_i):



From ckt ⓑ,



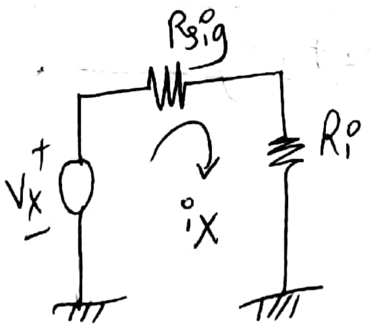
Since, B–C junction is reverse-biased & open-ckt, no current flows from B to C in ckt above,

$\therefore$ Current i_x flows into $(R_1 \| R_2)$ branch & r_π branch

$$\therefore \frac{V_x}{i_x} = R_1 \| R_2 \| r_\pi$$

ie $$\boxed{R_i = R_1 \| R_2 \| r_\pi}$$

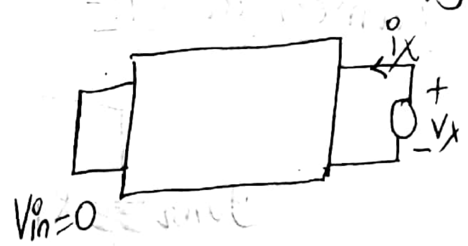
Now, if we include source resistance R_{sig}, we have



$$R_{is} = \frac{V_x}{i_x} = R_{sig} + R_i$$

ie $$\boxed{R_{is} = R_{sig} + R_1 \| R_2 \| r_\pi}$$

3. O/P impedance/resistance : (Z_o/R_o)



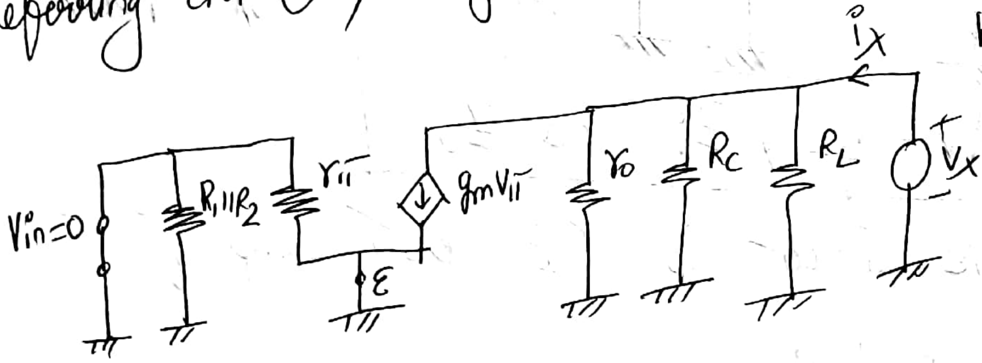
For o/p resistance calculation, we short-ckt i/p source.

ie $V_{in} = 0$ ie $V_s = 0$

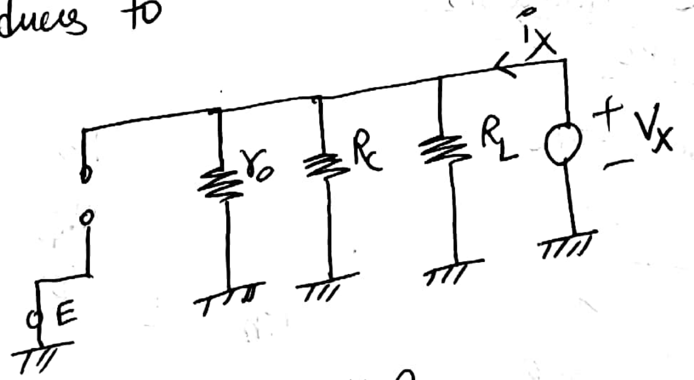
ie Since $V_{in} = V_\pi \Rightarrow V_\pi = 0$; $g_m V_\pi = 0$

It means that a current source being zero it is replaced by open-ckt

Referring ckt (b), we get



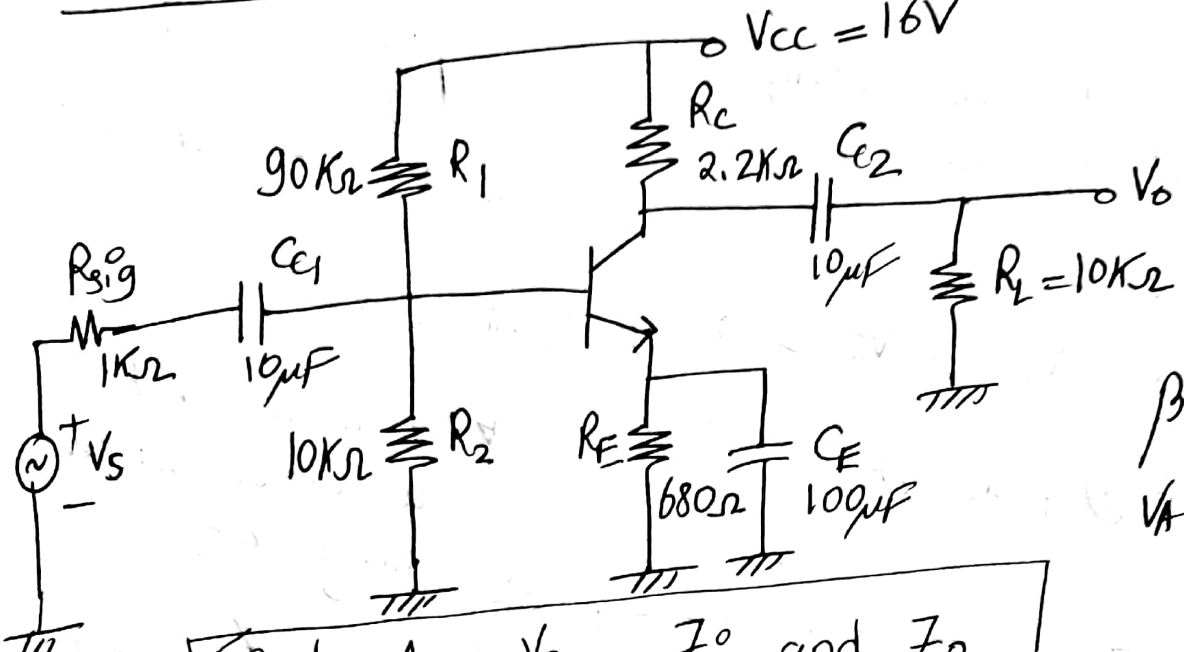
Above ckt reduces to



ie $\dfrac{V_x}{i_x} = r_o \| R_c \| R_L$

ie $\boxed{R_o = r_o \| R_c \| R_L}$

Numerical 01:-



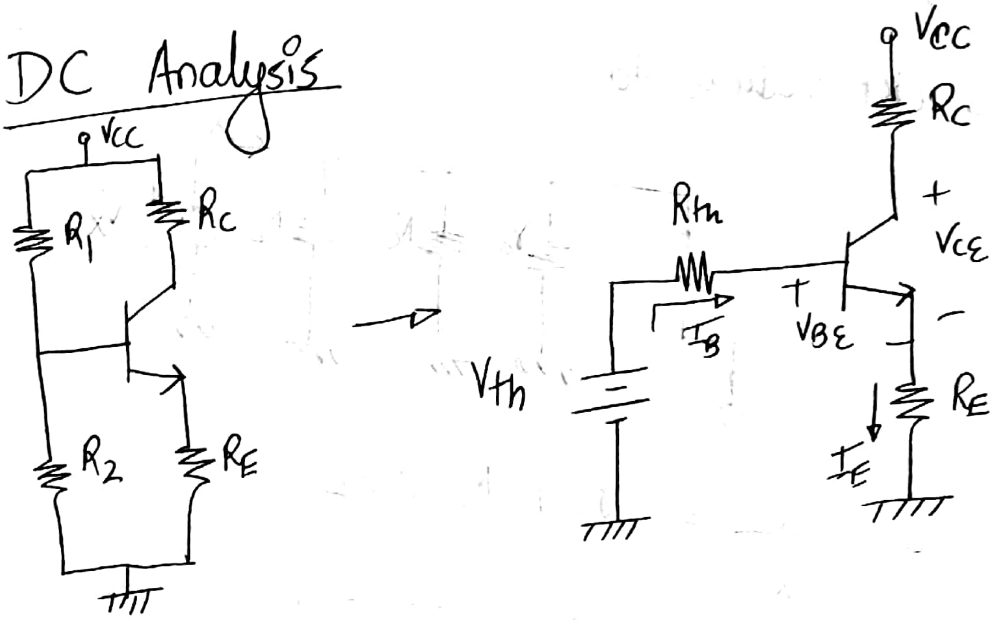
$\beta = 210$

$V_A = 100V.$

Find $A_v = \frac{V_o}{V_s}$, Z_i and Z_o

Sol^n: 1] Above circuit is CE BJT amplifier

2] DC Analysis



• $V_{th} = \frac{R_2}{R_1+R_2} \times V_{cc} = \frac{10K}{10K+90K} \times 16 = \underline{1.6V}$

• $R_{th} = R_1 \parallel R_2 = 10K \parallel 90K = 9K\Omega$

Scanned by CamScanner

KVL to B-E loop gives,

$$V_{th} - I_B R_{th} - V_{BE(ON)} - I_E R_E = 0$$

$$I_E = (1+\beta) I_B$$

$$\rightarrow V_{th} - I_B R_{th} - V_{BE(on)} - (1+\beta) I_B R_E = 0$$

$$\rightarrow I_B = \frac{V_{th} - V_{BE(ON)}}{R_{th} + (1+\beta) R_E}$$

Assume $V_{BE(ON)} = 0.7V$

$$I_B = \frac{1.6 - 0.7}{9K + 211 \times 680} = \underline{5.9 \mu A}$$

$$\rightarrow I_{CQ} = \beta I_B = \underline{1.2395 \text{ mA}}$$

$$\rightarrow I_{EQ} = I_{CQ} + I_B = \underline{1.2454 \text{ mA}}$$

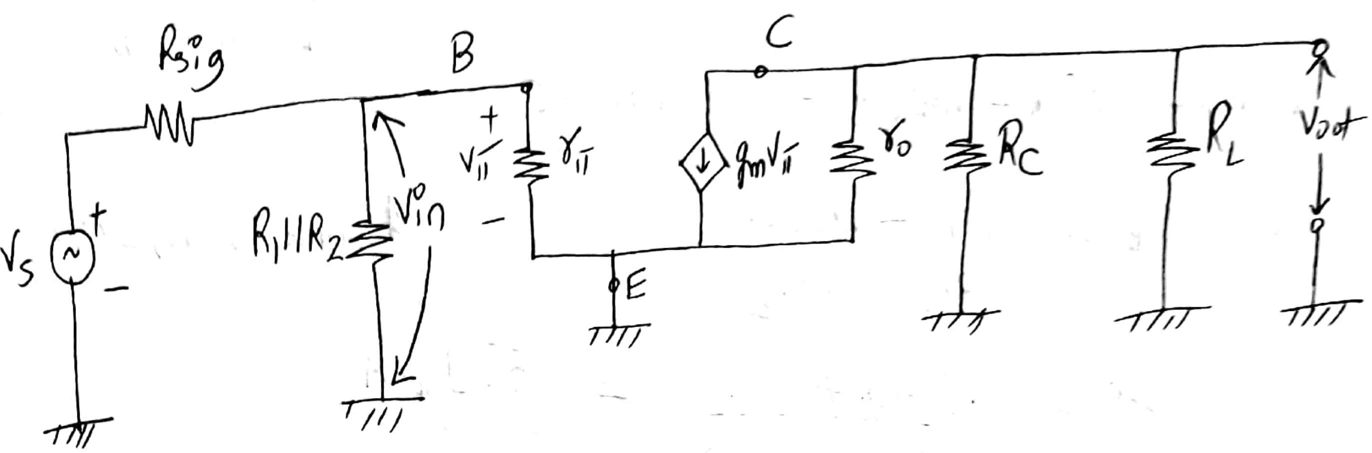
3] <u>Small-signal parameters:-</u>

$$g_m = \frac{I_{CQ}}{V_T} = \frac{1.2395 \text{mA}}{26 \text{ mV}} = 47.67 \frac{\text{mA}}{\text{V}}$$

$$r_o = \frac{V_A}{I_{CQ}} = \frac{100}{1.2395 \text{mA}} = 80.68 K\Omega$$

$$r_\pi = \frac{V_T}{I_{BQ}} = \frac{26 \text{mV}}{5.9 \mu A} = 4.4 K\Omega$$

4] Small-sig equivalent circuit :-



→ I/p impedance $Z_i = R_1 \| R_2 = 90K \| 10K\Omega$

$$\boxed{Z_i = 9K\Omega}$$

$$Z_{is \text{ with } R_{sig}} = R_{sig} + Z_i = 1K\Omega + 9K\Omega = \underline{10K\Omega}$$

→ o/p impedance $Z_o = r_o \| R_C \| R_L$

$$= 80.68K \| \underbrace{2.2K\Omega \| 10K\Omega}$$

$$= 80.68K \| 1.8K\Omega$$

$$\boxed{Z_o = 1.76K\Omega}$$

→ Voltage gain $A_v = \frac{V_o}{V_{in}}$

$$A_{vs} = \frac{V_o}{V_s} = \frac{V_o}{V_{in}} \times \frac{V_{in}}{V_s} = A_v \times \frac{V_{in}}{V_s}$$

$$A_v = \frac{V_o}{V_{in}}$$

$$= -g_m (r_o \| R_L \| R_C)$$

$$= -47.67 \times 10^{-3} \times 1.76 K\Omega$$

$$\boxed{A_v = -83.89}$$

$$A_{vs} = A_v \times \frac{V_{in}}{V_s}$$

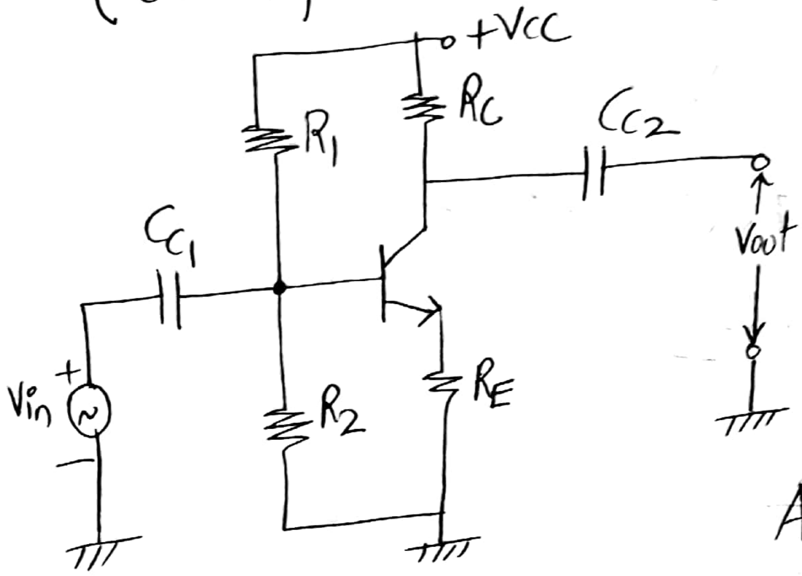
$$\frac{V_{in}}{V_s} = \frac{R_1 \| R_2}{R_1 \| R_2 + R_{sig}} = \frac{9K}{9K + 1K} = \underline{0.9}$$

$$A_{vs} = \frac{V_o}{V_s} = A_v \times 0.9 = -83.89 \times 0.9$$

$\boxed{A_{vs} = -75.5}$ ---- voltage gain of given CE amplifier

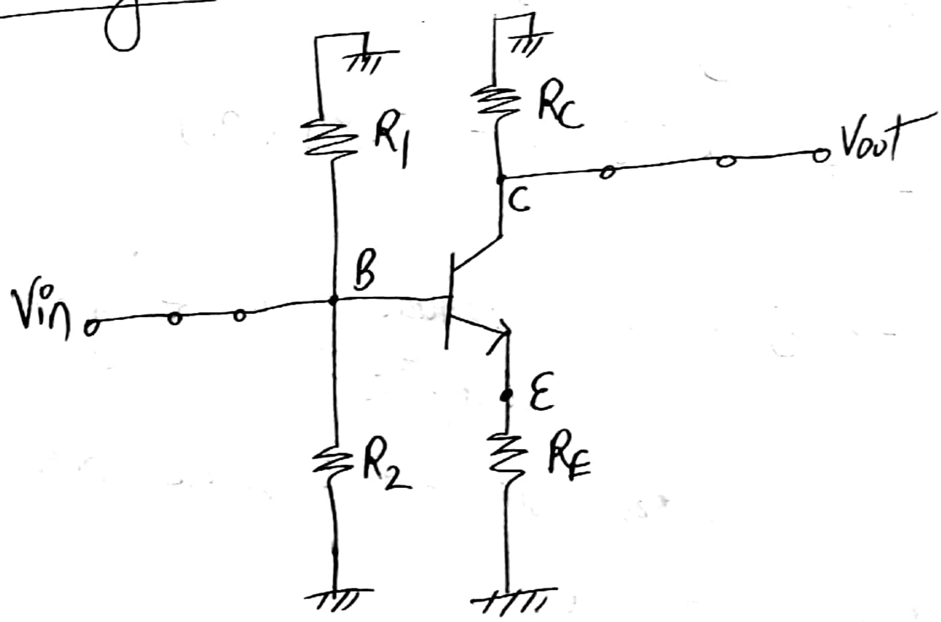
→ -ve sign indicates 180° out of phase between I/p and o/p signals.

2. Degenerated Common-emitter amplifier:
(CE amplr with R_E unbypassed)



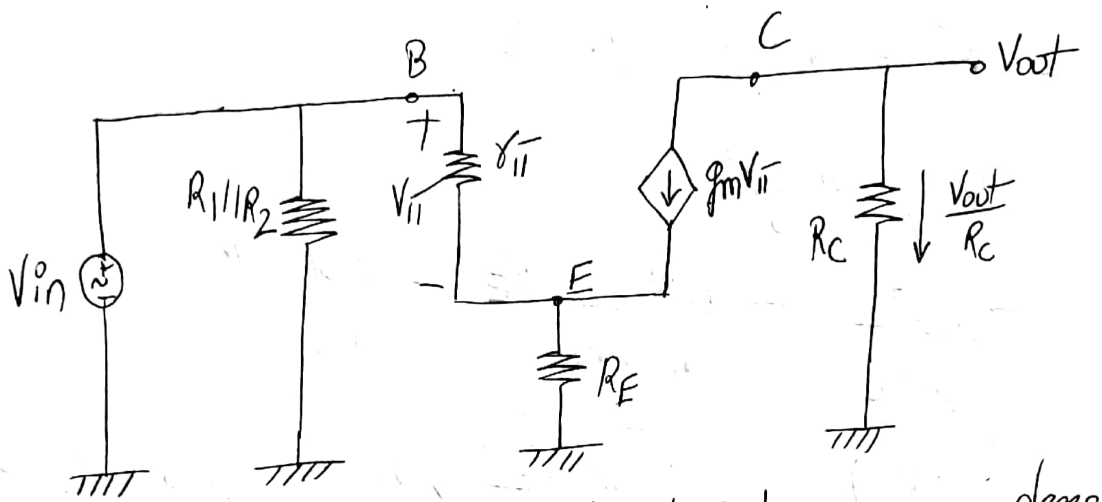
Assume $\boxed{r_0 = \infty}$ for analysis

AC analysis:-



Next, we replace BJT by its small-sig hybrid-π model

Small-signal Voltage gain : $A_v = \frac{V_{out}}{V_{in}}$



ckt a) Small-sig equivalent ckt of a degenerated CS stage

KCL at 'C' node, $g_m V_\pi + \frac{V_{out}}{R_C} = 0$

ie $V_\pi = \frac{-V_{out}}{g_m R_C}$ — (1)

KCL at 'E' node,

$$\underbrace{\left(\frac{V_\pi}{r_\pi} + g_m V_\pi\right)}_{\text{current through } R_E} R_E = \text{voltage drop on } R_E$$

ie $\left[\frac{-V_{out}}{g_m R_C} \times \frac{1}{r_\pi} + \cancel{g_m}\left(\frac{-V_{out}}{\cancel{g_m} R_C}\right)\right] R_E = \text{voltage drop on } R_E$ — (2)

KVL in B-E loop, gives

$$V_{in} = V_{\pi} + \text{voltage drop on } R_E$$

From (1) & (2), we get

$$V_{in} = -\frac{V_{out}}{g_m R_C} - \frac{V_{out}}{g_m r_{\pi} R_C} R_E - \frac{V_{out}}{R_C} R_E$$

$$\boxed{g_m r_{\pi} = \beta} \; ? \longrightarrow \boxed{g_m = \frac{I_C}{V_T} \; ; \; r_{\pi} = \frac{V_T}{I_B} \quad g_m r_{\pi} = \frac{I_C}{I_B} = \beta}$$

$$V_{in} = -\frac{V_{out}}{g_m R_C} - \frac{V_{out}}{\beta R_C} R_E - \frac{V_{out}}{R_C} R_E$$

$$V_{in} = -\frac{\beta V_{out} + g_m R_E V_{out} + \beta g_m R_E V_{out}}{\beta g_m R_C}$$

$$\boxed{\frac{V_{out}}{V_{in}} = \frac{-\beta g_m R_C}{\beta + (1+\beta) g_m R_E}}$$

Let's, simplify it further

Multiply & divide by βg_m

$$\frac{V_{out}}{V_{in}} = -\frac{R_C}{\frac{1}{g_m} + \frac{(1+\beta)}{\beta} R_E}$$

But $\frac{1+\beta}{\beta} \approx 1$

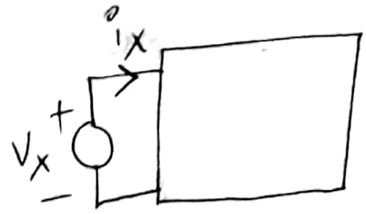
ie $$\boxed{A_v = \frac{V_{out}}{V_{in}} \simeq -\frac{R_C}{\frac{1}{g_m} + R_E}}$$ ---- small-slg voltage gain of degenerated CS amplr

→ The voltage gain of degenerated CS amplr has certainly reduced, but it is more stable

→ let's verbalize the above result,

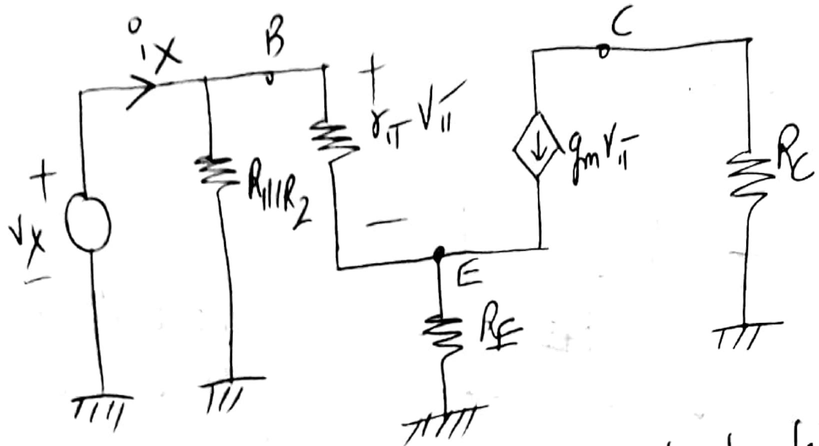
$$\boxed{A_v = -\frac{\text{resistance tied between Collector \& gnd}}{\frac{1}{g_m} + \text{resistance tied betn emitter \& gnd.}}}$$

I/p impedance:

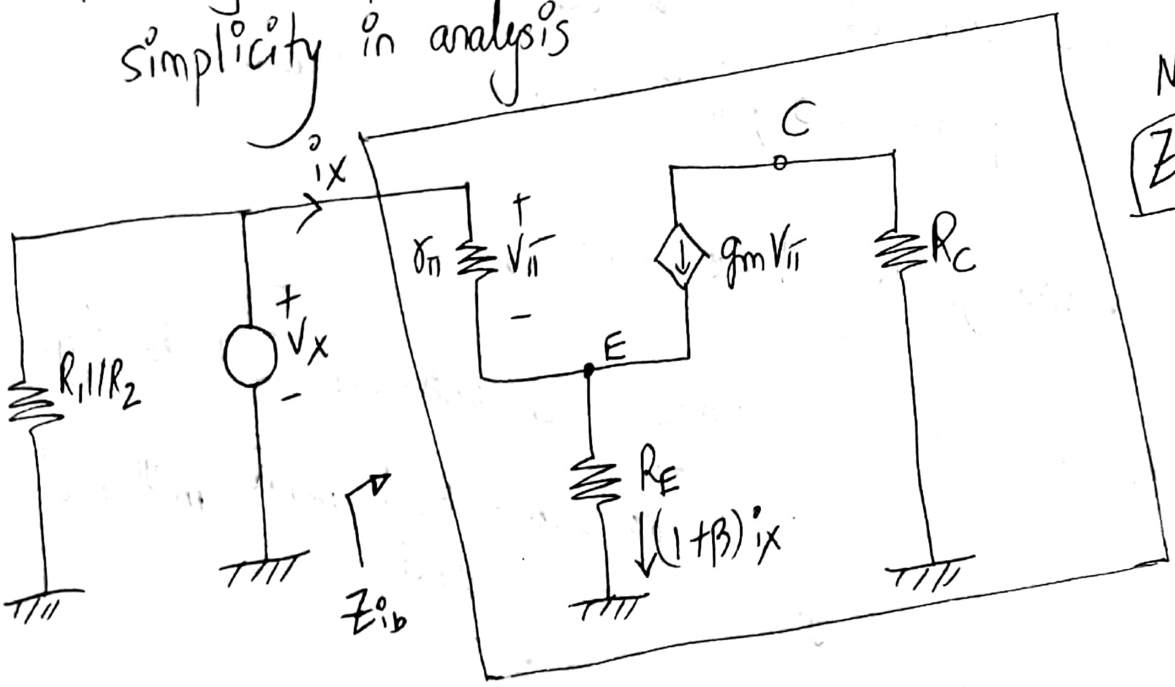


$$Z_i = \frac{V_x}{i_x}$$

let's draw ckt(a),



let's just push $(R_1 \| R_2)$ branch to left of source V_x for simplicity in analysis



Now,

$$\boxed{Z_i = Z_{ib} \| R_1 \| R_2}$$

From ckt, $V_\pi = i_x r_\pi$

$\rightarrow g_m V_\pi = g_m i_x r_\pi = \beta i_x = i_c$

current through $R_E = i_E = (1+\beta) i_x$

KVL to B-E loop gives,

$$V_X = V_\pi + V_{RE}$$

$$V_{RE} = i_E R_E = (1+\beta) i_x R_E$$

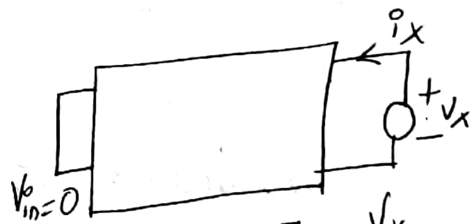
$$V_X = i_x r_\pi + (1+\beta) i_x R_E$$

$$V_X = i_x \left[r_\pi + (1+\beta) R_E \right] \rightarrow \frac{V_X}{i_X} = r_\pi + (1+\beta) R_E$$

$$Z_{i_B} = \frac{V_x}{i_x} = r_\pi + (1+\beta) R_E$$

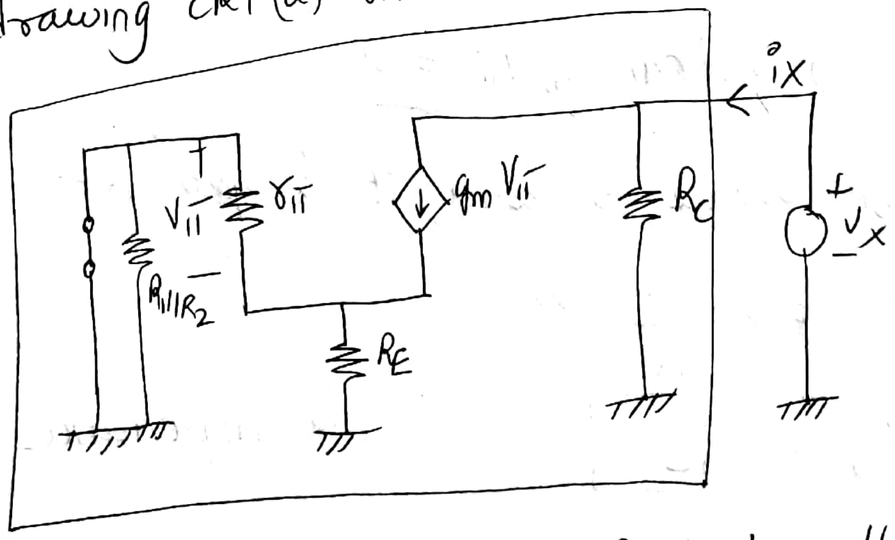
ie $\boxed{Z_i = R_1 || R_2 || \left[r_\pi + (1+\beta) R_E \right]}$ ---- high I/P impedance

* Output impedance Z_o :

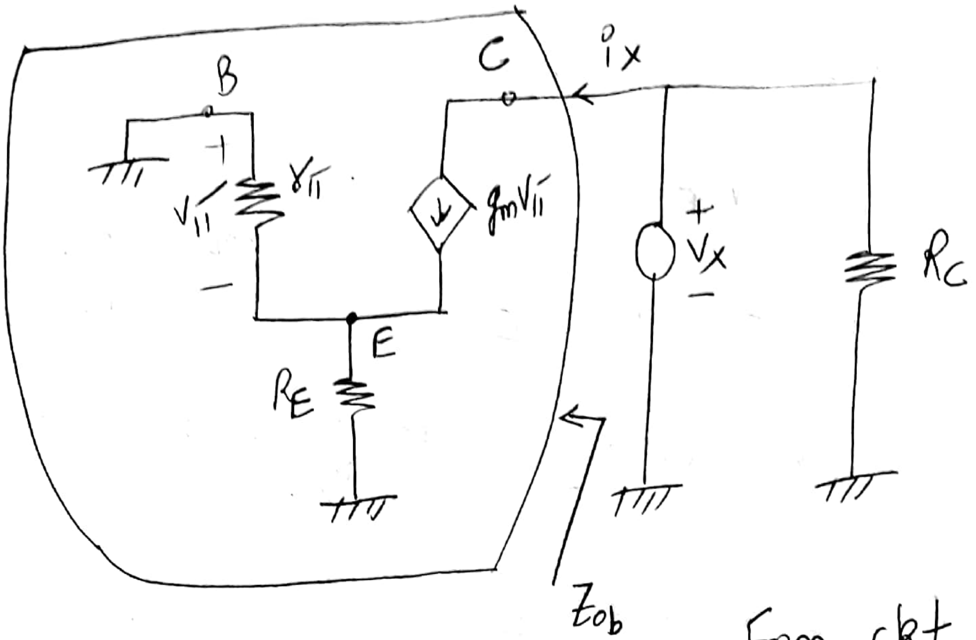


$$Z_o = \frac{V_x}{i_x}$$

Redrawing ckt (a) with $V_{in} = 0$



Next we push R_c to the right of voltage source V_x for simplicity,



$Z_o = Z_{ob} \| R_C$

From ckt $\underline{V_{R_E} = -V_\pi}$

KCL at 'E' node gives,

$$\frac{V_\pi}{r_\pi} + g_m V_\pi = \frac{-V_\pi}{R_E}$$

This implies $\underline{V_\pi = 0}$

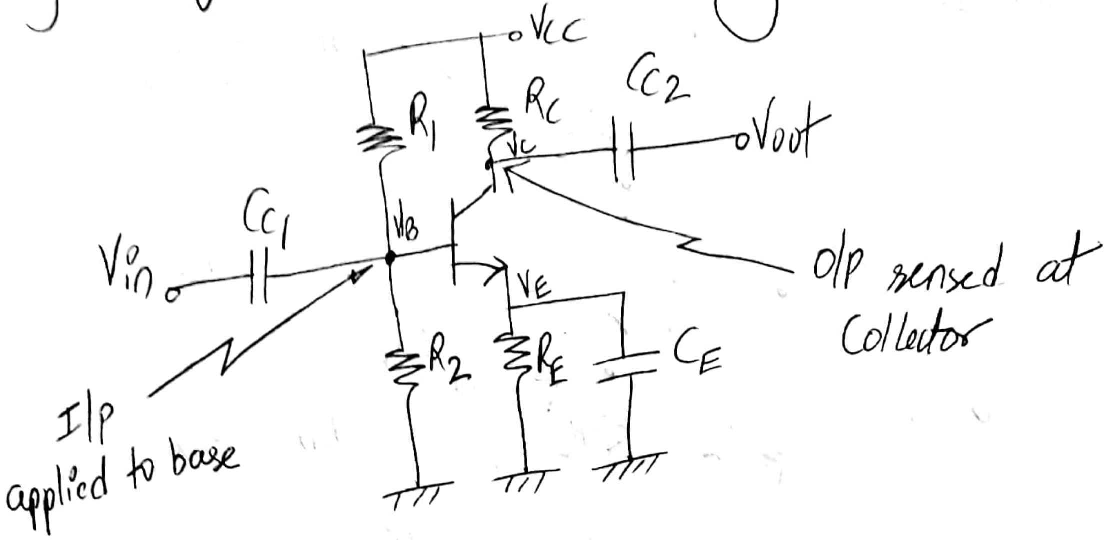
If $V_\pi = 0$; then $\underline{g_m V_\pi = 0}$

ie current source is zero, it is open ckt

ie $Z_{ob} = \dfrac{V_x}{i_x} = \infty$

$\therefore$ $\boxed{Z_o = R_C}$ ---- o/p impedance

Why gain of CE amplifier is negative?



let say's V_{in} (ac) ↑ses, then V_B ↑ses (as $V_B + V_{in}$ is at B)
(DC) (AC)

Now, V_E (DC) is a constant, since capacitor C_E blocks DC values

ie $V_{BE} = (V_B - V_E)$ ↑ses $\xrightarrow[\text{means}]{\text{which}}$ I_B ↑ses

Now, $I_C = \beta I_B$; if I_B ↑ses → I_C ↑ses

Also, $V_C = V_{CC} - I_C R_C$; if I_C ↑ses then V_C ↓ses
ie V_{out} ↓ses

In summary in CE amplr:

If V_{in} ↑ses → V_B ↑ses → V_E constant → V_{BE} ↑ses → I_B ↑ses → ↑ses $I_C = \beta I_B$ → V_C ↓ses → ie V_{out} ↓ses

ie I/p and o/p signals are out of phase with each other, hence voltage gain is -ve in CE amplr.

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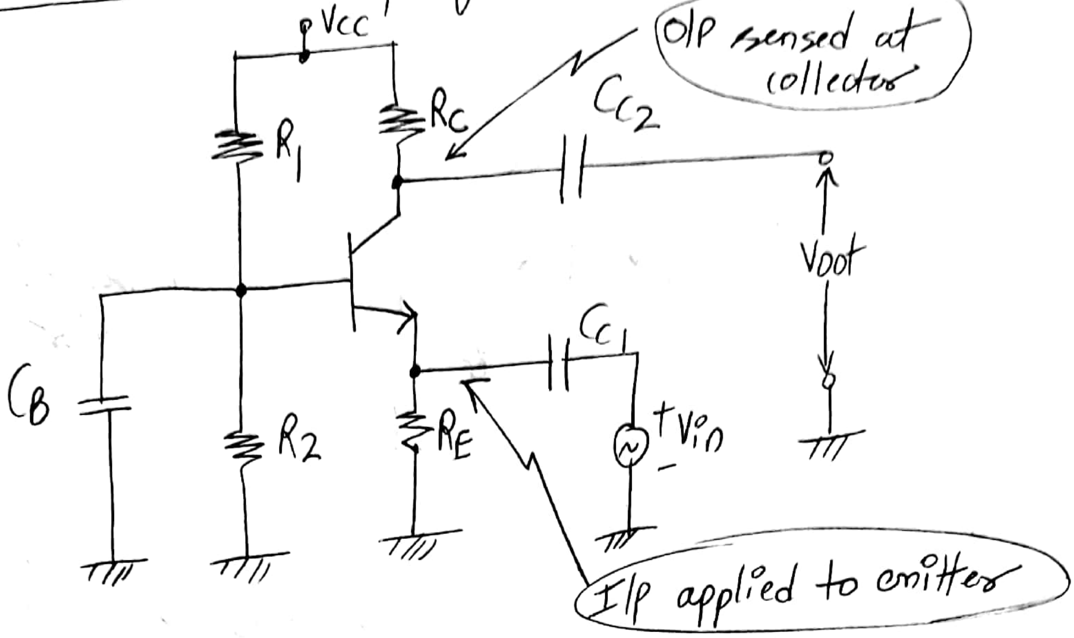
3] Common Base amplifier (npn BJT) :-



let say's, $V_{in}\uparrow$ses ie $V_E\uparrow$ses (as $\underset{(DC)}{V_E} + \underset{(AC)}{V_{in}}$ is at E terminal)

$\underset{(DC)}{V_B}$ is a constant, as C_B blocks DC value

ie $V_{BE} = (V_B - V_E)\downarrow$ses $\rightarrow I_B\downarrow$ses

$I_C = \beta I_B$; if $I_B\downarrow$ses $\rightarrow I_C\downarrow$ses

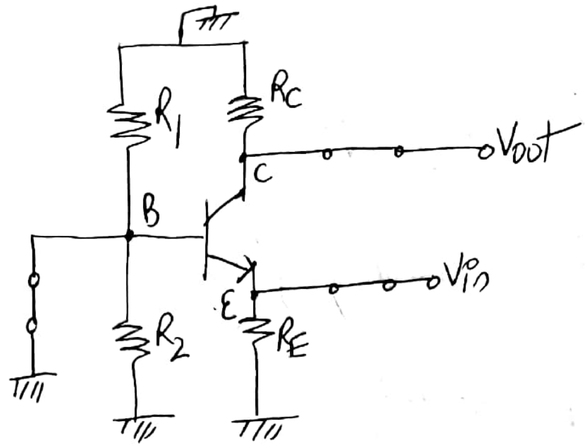
Also, $V_C = V_{CC} - I_C R_C$ ie If $I_C\downarrow$ses $\rightarrow V_C\downarrow$ses

ie $V_{out}\downarrow$ses

In summary, As $V_{in}\uparrow$ses $\rightarrow V_E\uparrow$ses $\rightarrow V_B$ constant $\rightarrow V_{BE}\downarrow$ses $\rightarrow I_B\downarrow$ses $\rightarrow I_C\downarrow$ses $\rightarrow V_C\uparrow$ses $\rightarrow$ ie $V_{out}\uparrow$ses

ie I/P & O/P signal in a CB amplifier are in phase with each other.

AC Analysis:-

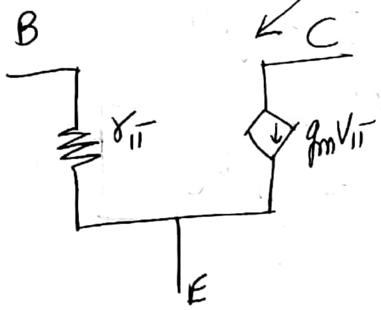


Assume

$V_A = \infty$

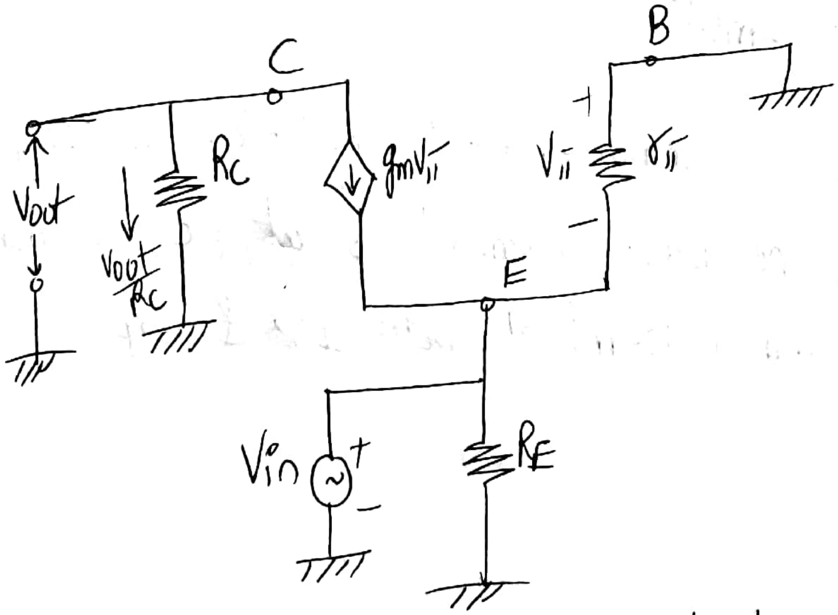
ie $r_o = \infty$

Next, we replace BJT by its small-signal hybrid model,



Small-signal voltage gain: $A_v = \dfrac{V_{out}}{V_{in}}$

we interchange B & C terminals for simplicity



ckt (b) : Small-sig equivalent ckt of CB amplifier

From ckt(b), $V_\pi = -V_{in}$

KCL at 'c' node, gives

$$g_m V_\pi + \frac{V_{out}}{R_C} = 0$$

$$\text{ie} - g_m V_{in} = \frac{-V_{out}}{R_C}$$

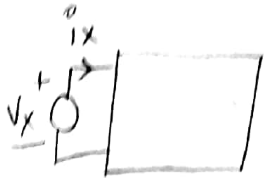
$$\text{ie } \frac{V_{out}}{V_{in}} = g_m R_C$$

$$\text{ie } \boxed{A_V = +g_m R_C}$$ ---- Small-slg voltage gain

→ The +ve sign in gain formula indicates no phase difference betn the input and o/p signals. in a Common Base ampl^r

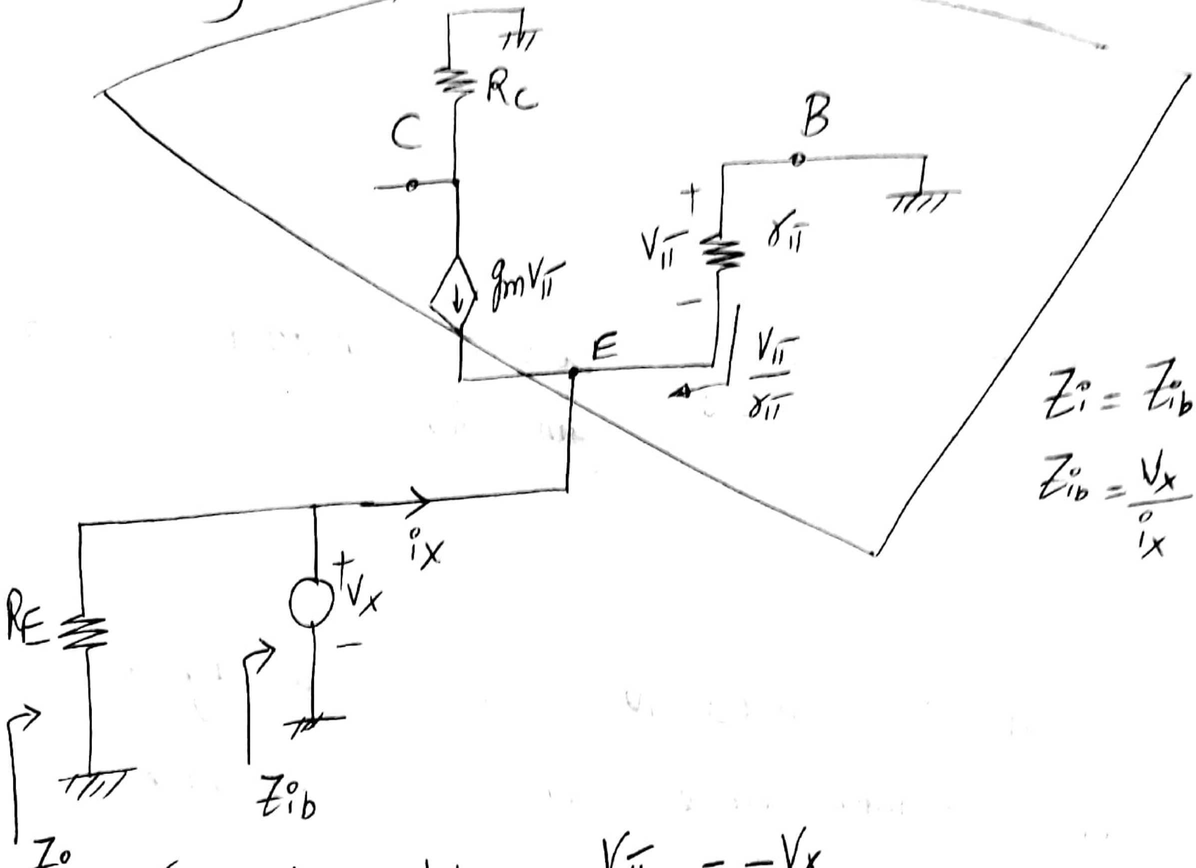
→ It is called "Common-base" amplifier since, in AC analysis, the base terminal is at ac ground & act as common terminal betn I/P & o/p.

Input impedance: Z_i



$Z_i = \frac{V_x}{i_x}$

Redrawing ckt(b),



$Z_i = Z_{ib} \,\|\, R_E$

$Z_{ib} = \frac{V_x}{i_x}$

From above ckt, $\underline{V_\pi = -V_x}$

KCL at 'E' node, gives

$$i_x + g_m V_\pi + \frac{V_\pi}{r_\pi} = 0$$

$$i_x = -V_\pi \left(g_m + \frac{1}{r_\pi} \right)$$

$$i_x = V_x \left(\frac{1 + g_m r_\pi}{r_\pi} \right)$$

$g_m r_\pi = \beta$

$$i_x = V_x \left(\frac{1+\beta}{r_\pi} \right)$$

$1+\beta = \beta$

$$i_x = V_x\left(\frac{\beta}{r_\pi}\right)$$

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

$$i_x = V_x g_m$$

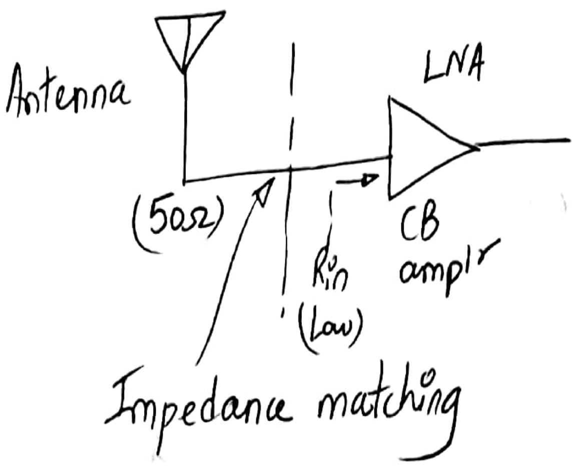
$$\boxed{\frac{V_x}{i_x} = \frac{1}{g_m}}$$

Now, $\boxed{Z_i = \frac{1}{g_m} \parallel R_E}$ Low I/p impedance in CB amplifier

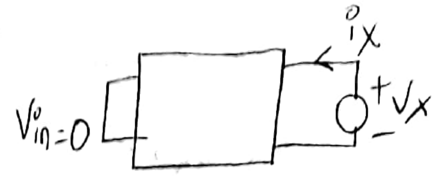
Application :

↳ CB ampl^r is used to be driven by a low impedance source such as an antenna.

which is also of low impedance of around 50Ω

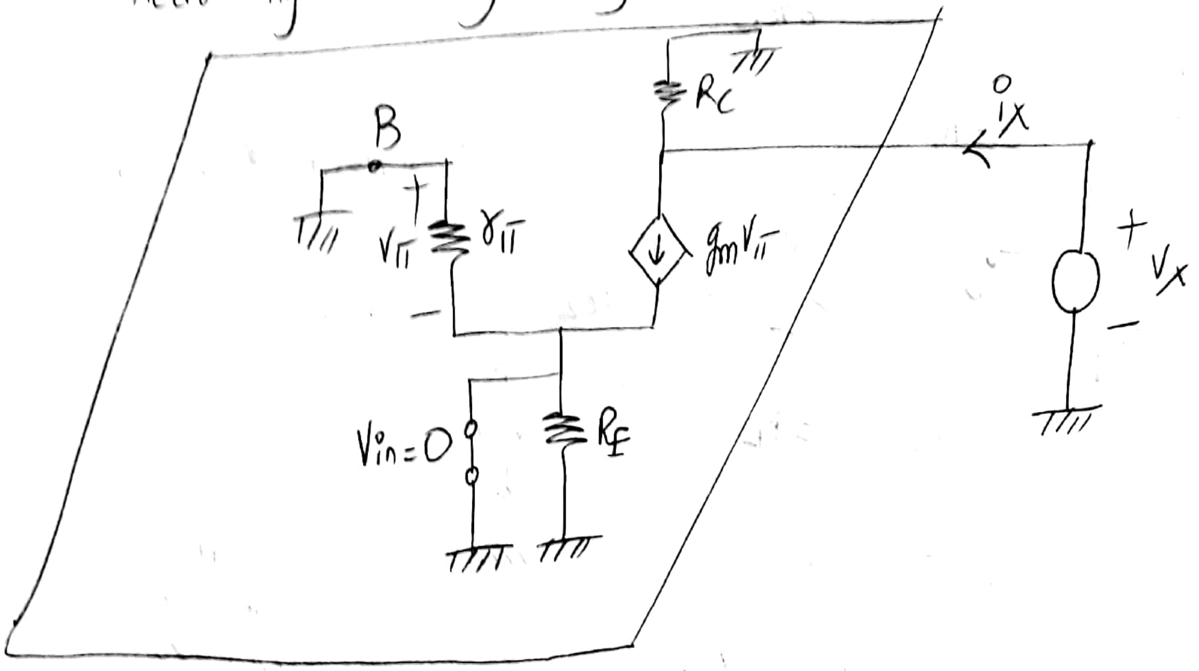


O/P impedance: Z_o



$$Z_o = \frac{V_x}{i_x}$$

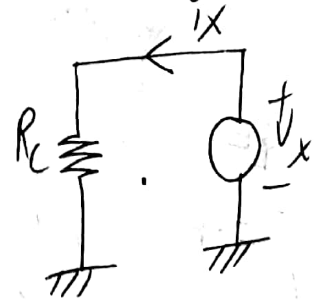
Redrawing ckt (b) by making $V_{in}=0$



Since, $V_{in}=0$ & $V_\pi = -V_{in} = 0$

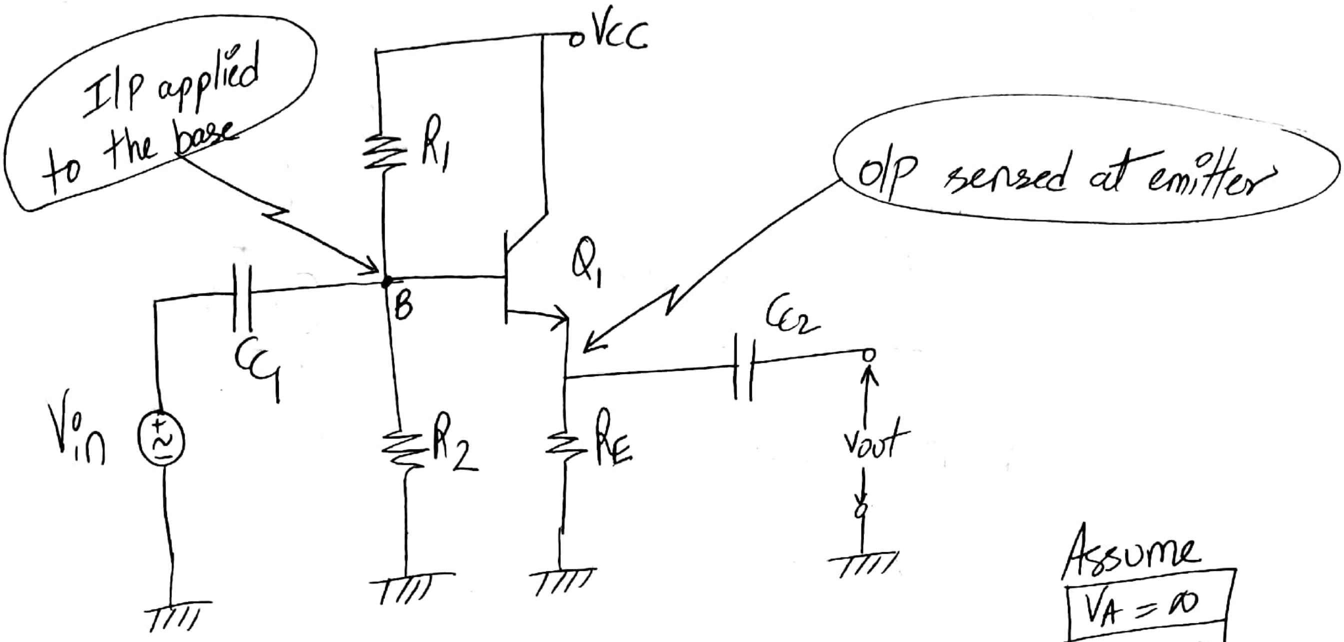
ie $g_m V_\pi = 0$ ie current source ($g_m V_\pi$) is open-circuited

ckt reduces to



$$\boxed{Z_o = \frac{V_x}{i_x} = R_C}$$ --- O/P impedance

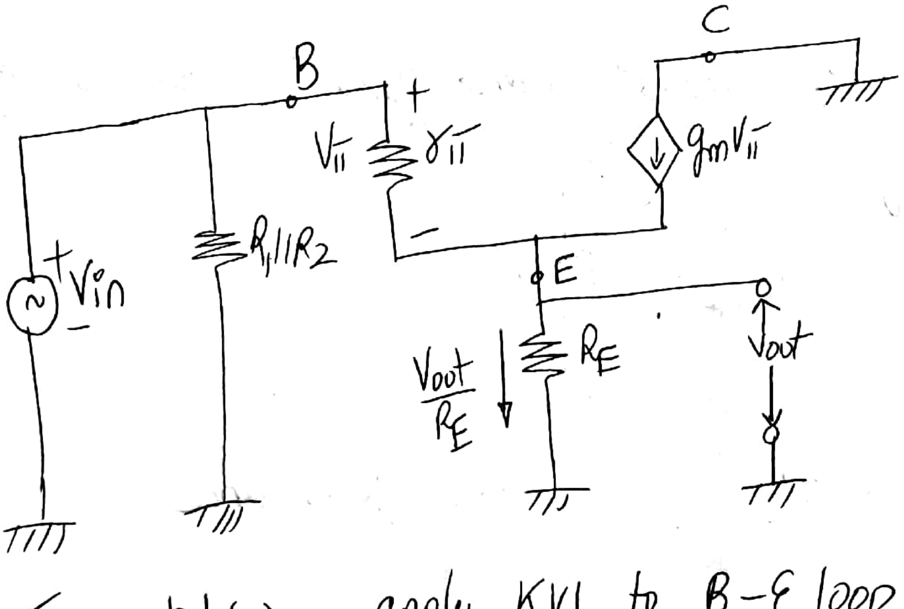
* Common-collector amplifier (npn BJT) (Emitter follower)



Assume

$V_A = \infty$
ie $r_o = \infty$

Small-signal voltage gain: A_v



ckt(c): Small-signal equivalent ckt of CC ampl^r

From ckt(c), apply KVL to B−E loop,

$V_{in} = V_\pi + V_{out}$ ie $\boxed{V_\pi = V_{in} - V_{out}}$ — (1)

KCL at 'E' node, gives

$$\frac{V_\pi}{r_\pi} + g_m V_\pi = \frac{V_{out}}{R_E}$$

$$\frac{V_{in} - V_{out}}{r_\pi} + g_m (V_{in} - V_{out}) = \frac{V_{out}}{R_E} \qquad \text{(From (1))}$$

$$\frac{V_{in}}{r_\pi} + g_m V_{in} = \frac{V_{out}}{R_E} + g_m V_{out} + \frac{V_{out}}{r_\pi}$$

$$V_{in}\left(\frac{1}{r_\pi} + g_m\right) = V_{out}\left[\frac{r_\pi + g_m r_\pi R_E + R_E}{r_\pi R_E}\right]$$

$$V_{in}\left(\frac{1 + g_m r_\pi}{\cancel{r_\pi}}\right) = V_{out}\left[\frac{r_\pi + g_m r_\pi R_E + R_E}{\cancel{r_\pi} R_E}\right]$$

But, $g_m r_\pi = \beta$

$$V_{in}(1+\beta) = V_{out}\left[\frac{r_\pi + (1+\beta)R_E}{R_E}\right]$$

$$\frac{V_{out}}{V_{in}} = \frac{R_E(1+\beta)}{r_\pi + (1+\beta)R_E}$$

$\div$ & $\times$ N^r & D^r by $(1+\beta)$

$$\frac{r_\pi}{1+\beta} \simeq \frac{r_\pi}{\beta} = \frac{1}{g_m}$$

$$\frac{V_{out}}{V_{in}} = \frac{R_E}{\frac{r_\pi}{(1+\beta)} + R_E}$$

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ie $\dfrac{V_{out}}{V_{in}} \simeq \boxed{\dfrac{R_E}{\frac{1}{g_m} + R_E} = A_v}$

let's verbalize the gain formula,

$$\boxed{A_v = \frac{\text{Resistance tied betn Emitter \& ac ground}}{\frac{1}{g_m} + \text{resistance tied betn Emitter \& ac gnd}}}$$

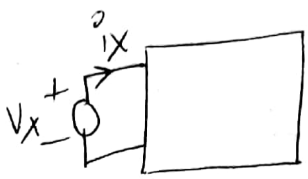
$A_v = \dfrac{g_m R_E}{1 + g_m R_E}$ is always very close to 1, but always less than unity

ie $\boxed{A_v \leq 1}$ for a CC amplifier or emitter follower

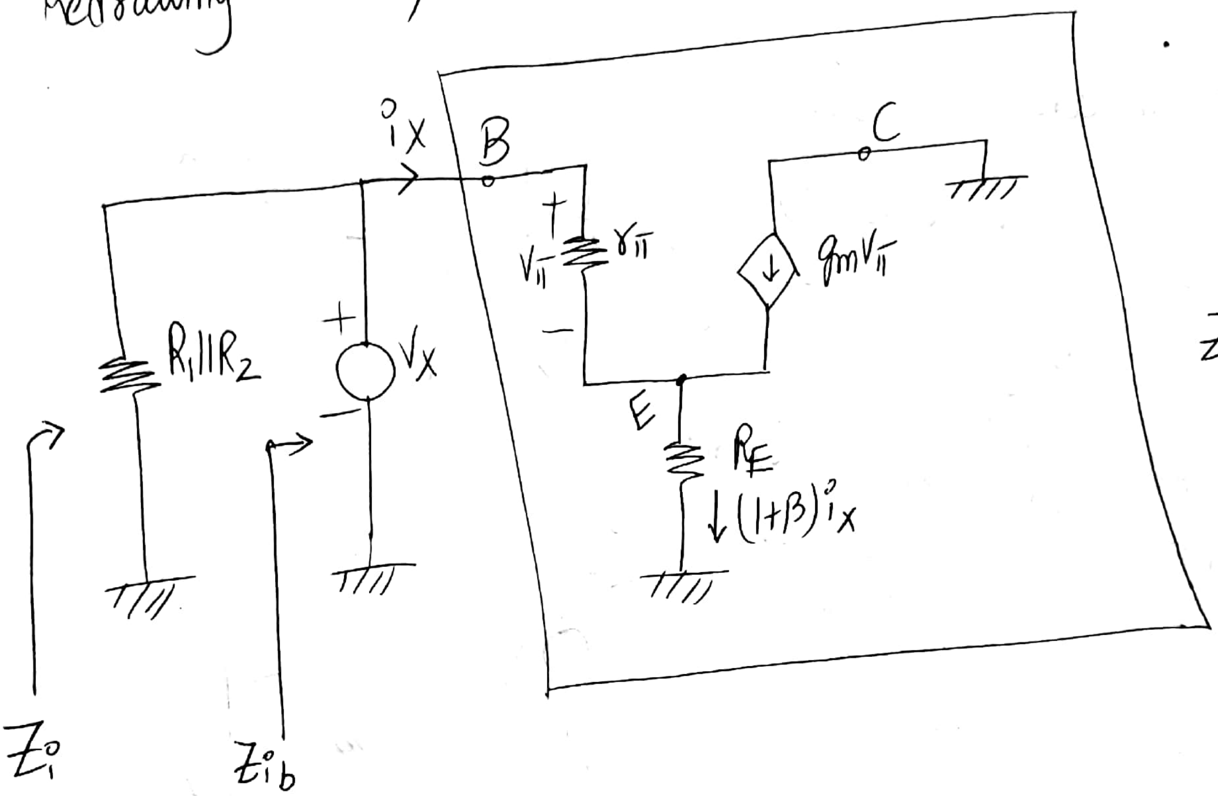
→ There is no phase difference betn the I/p & o/p signals in an emitter follower.

→ In this amplifier, i/p signal changes in the base follows the changes in the emitter. Hence, the name of circuit is "emitter follower".

I/P impedance : Z_i



Redrawing ckt (c),



$$Z_{ib} = \frac{V_x}{i_x}$$

From ckt, $\underline{V_\pi = i_x r_\pi}$

ie $g_m V_\pi = g_m i_x r_\pi$

Current through 'B' is i_x

Current through 'E' is $(1+\beta) i_x$

KVL at B-E loop, gives

$V_x = V_\pi +$ voltage drop across R_E

$$V_x = i_x r_\pi + (1+\beta) i_x R_E$$

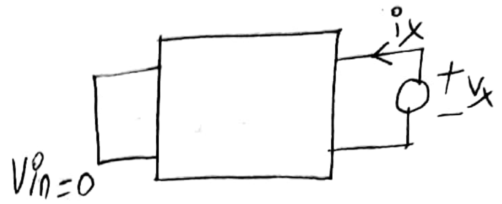
$$Z_{ib} = \frac{V_x}{i_x} = r_\pi + (1+\beta) R_E$$

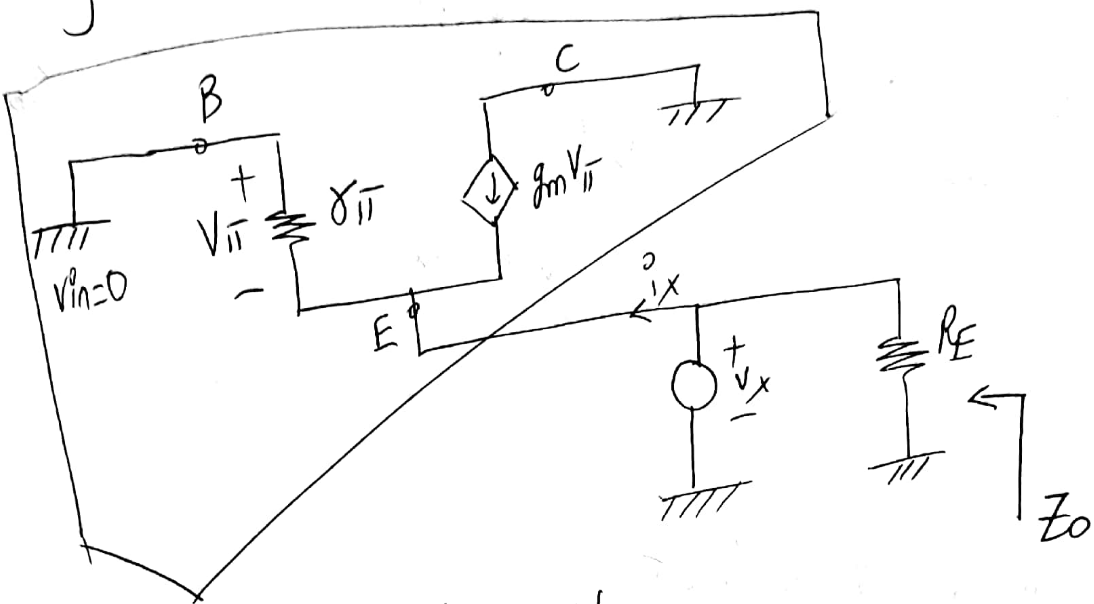
$$\boxed{Z_i = R_1 \| R_2 \| [r_\pi + (1+\beta)R_E]}$$

high i/p impedance in CC ampl^r

* <u>Output impedance</u> : Z_o

Redrawing ckt(c) with $V_{in}=0$





From above ckt, $\quad V_\pi = -V_x$

KCL at 'E' node gives,

$$\frac{V_\pi}{r_\pi} + g_m V_\pi + i_x = 0$$

$$-\frac{V_x}{r_\pi} - g_m V_x = -i_x$$

$$V_x\left(\frac{1}{r_\pi} + g_m\right) = i_x$$

$$i_x = V_x \left(\frac{g_m r_\pi + 1}{r_\pi} \right) \qquad g_m r_\pi = \beta$$

$$i_x = V_x \left(\frac{1+\beta}{r_\pi} \right) \qquad 1+\beta \simeq \beta$$

$$i_x = V_x \left(\frac{\beta}{r_\pi} \right) \qquad \frac{\beta}{r_\pi} = g_m$$

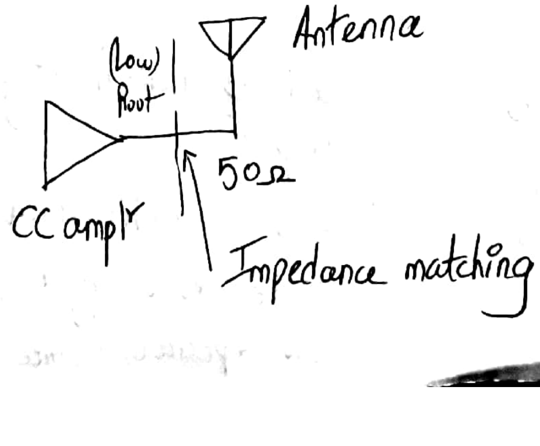
$$i_x = V_x \, g_m$$

$$\boxed{\frac{V_x}{i_x} = \frac{1}{g_m}}$$

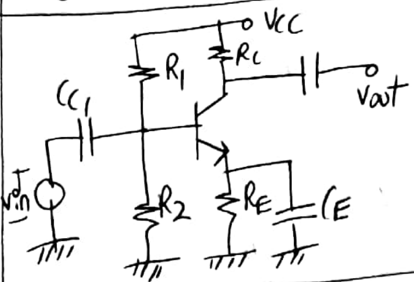
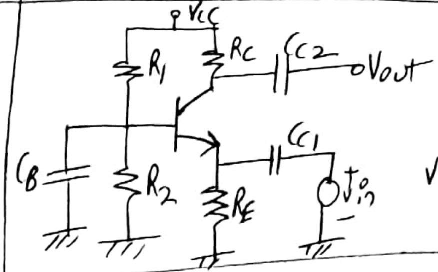
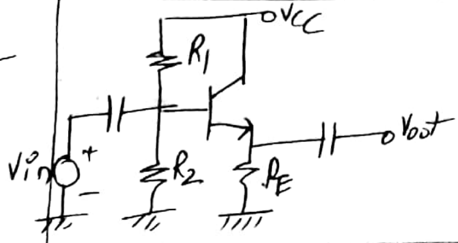
$$\therefore \boxed{Z_o = R_E \parallel \frac{1}{g_m}}$$ Low output impedance

Application of CC amplifier :-

- It is used as a buffer betn ampl^r and o/p stage
- It is used to drive a low impedance antenna or speaker



- Comparison of CE, CB and CC amplifiers

	Common-emitter	Common-base	Common-collector
1. Circuit			
2. I/p applied to	Base terminal	Emitter terminal	Base terminal
3. o/p sensed at	Collector terminal	Collector terminal	Emitter terminal
4. Voltage gain	$A_v = -g_m R_C$ $\boxed{\text{high}}$	$A_v = g_m R_C$ $\boxed{\text{high}}$	$A_v = \frac{g_m R_E}{1+g_m R_E} \approx 1$ $\boxed{\text{low}}$
5. I/p impedance	$Z_i = R_1 \| R_2 \| r_\pi$ $\boxed{\text{medium}}$	$Z_i = \frac{1}{g_m} \| R_E$ $\boxed{\text{low}}$	$Z_i = R_1 \| R_2 \| [r_\pi + (1+\beta)R_E]$ $\boxed{\text{v.high}}$
6. o/p impedance	$Z_o = R_C$ $\boxed{\text{medium}}$	$Z_o = R_C$ $\boxed{\text{medium}}$	$Z_o = \frac{1}{g_m} \| R_E$ $\boxed{\text{low}}$
7. Phase of o/p signal	Out of Phase with i/p signal	In phase with i/p signal	In phase with i/p signal
8. Application	1) Common used as inverting voltage amplifiers	1) used as non-inverting amplr 2) used as a ckt which can be driven by a low impedance source	1) used as a voltage buffer 2) used to drive a low impedance load (eg antenna or speaker)

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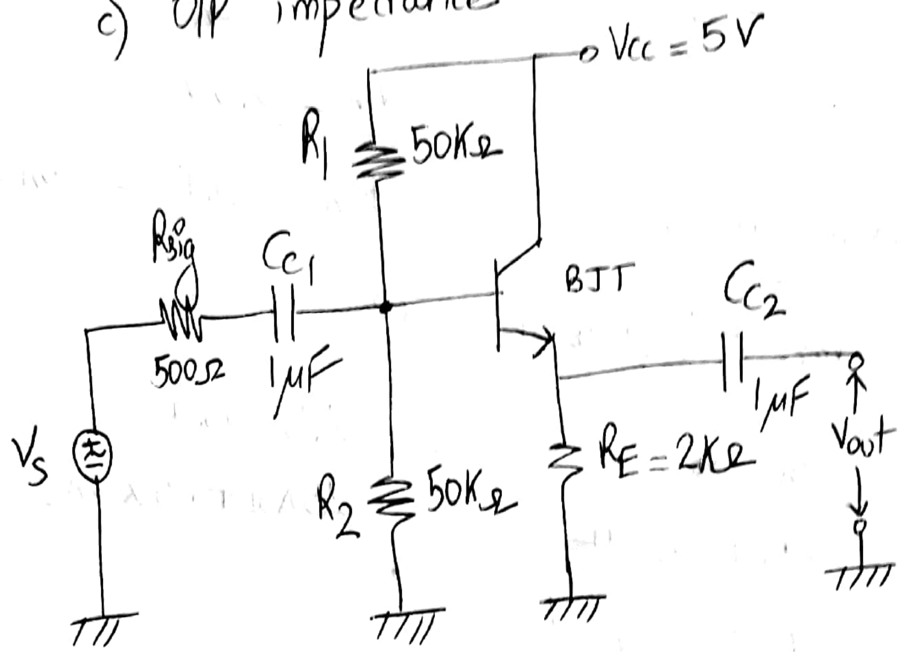
Numerical 02

Determine the following for circuit shown below

a) Small-slg voltage gain

b) I/P impedance

c) O/P impedance



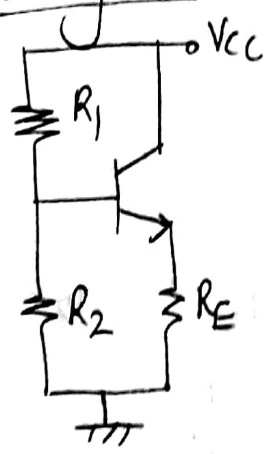
$\beta = 100$

$V_{BE(on)} = 0.7V$

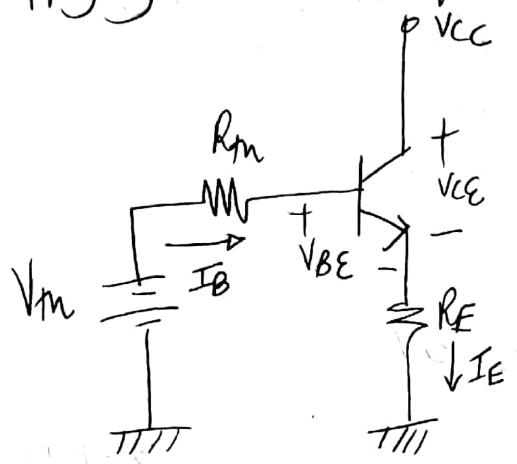
$V_A = 80V$

Soln:- 1] Above circuit is common collector amplifier using npn BJT

2] DC analysis:-



Applying thevenin's equivalent at base,



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

$$= \frac{50K}{100K} \times 5$$

$$V_{th} = 2.5V$$

$$R_{th} = R_1 \parallel R_2 = 25K\Omega$$

KVL to B-E loop gives,

$$V_{th} - I_B R_{th} - V_{BE} - (1+\beta) I_B R_E = 0$$

$$I_B = \frac{V_{th} - V_{BE}}{R_{th} + (1+\beta) R_E} = \frac{2.5 - 0.7}{25K\Omega + 101 \times 2K\Omega}$$

$$\boxed{I_{BQ} = 7.93 \ \mu A}$$

ie $I_{CQ} = \beta . I_{BQ} = 100 \times 7.93 \times 10^{-6}$

$$\boxed{I_{CQ} = 0.793 \ mA}$$

$$I_E = I_B + I_C = 0.8 \ mA$$

KVL to C-E loop gives,

$$V_{CC} - V_{CE} - I_E R_E = 0$$

$$V_{CEQ} = V_{CC} - I_E R_E = 5 - 0.8 \times 10^{-3} \times 2K\Omega$$

$$\boxed{V_{CEQ} = 3.398 \ V}$$

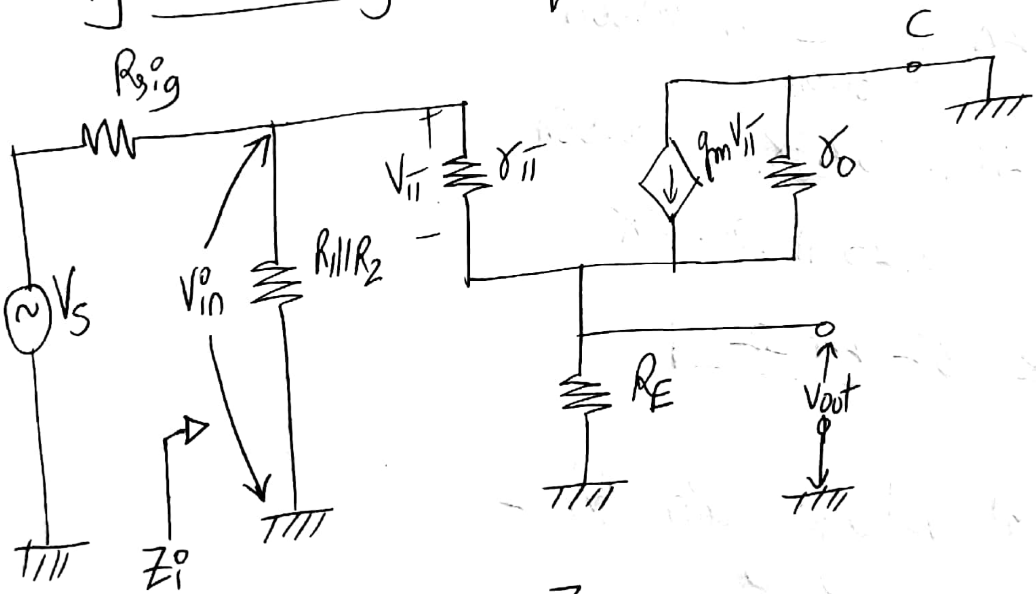
3] Small-signal model parameters:-

a) $r_\pi = \frac{\beta V_T}{I_{CQ}} = \frac{V_T}{I_{BQ}} = \frac{26mV}{7.93\mu A} = \underline{3.279\,K\Omega}$

b) $g_m = \frac{I_{CQ}}{V_T} = \frac{0.793\,mA}{26\,mV} = \underline{30.5\,\frac{mA}{V}}$

c) $r_o = \frac{V_A}{I_{CQ}} = \frac{80}{0.793\,mA} = \underline{100.88\,K\Omega}$

4] Small-signal equivalent circuit:-



a) I/P impedance: Z_i

$$Z_i = R_1 || R_2 || [r_\pi + (1+\beta)(R_E || r_o)]$$

$$r_o || R_E = 100.88K || 2K\Omega = 1.96K\Omega$$

$$r_\pi + (1+\beta)(r_o || R_E) = 201.24\,K\Omega$$

$$Z_i = R_1 || R_2 || 201.24K$$
$$= 50K || 50K || 201.24K$$
$$= 25K || 201.24K\Omega$$
$$\boxed{Z_i = 22.24\,K\Omega}$$

b) Output resistance: Z_o

$$Z_o \simeq R_E || \frac{1}{g_m} || r_o$$
$$= 2K || \frac{1}{30.5m} || 100.88K$$
$$= \underbrace{2K || 32.78} || 100.88K$$
$$= 32.25 || 100.88K$$
$$\boxed{Z_o \simeq 32.24\,\Omega}$$

c) Small-signal voltage gain (A_v) :-

$$A_{vs} = \frac{V_o}{V_s} = \frac{V_o}{V_{in}} \frac{V_{in}}{V_s} = A_v \times \frac{V_{in}}{V_s}$$

$$A_v = \frac{R_E || r_o}{\frac{1}{g_m} + (R_E || r_o)}$$

$$A_v = \frac{R_E \| r_o}{\frac{1}{g_m} + R_E \| r_o}$$

$$R_E \| r_o = 2K \| 100.88K = 1.96K\Omega$$

$$\frac{1}{g_m} = \frac{1}{30.5 \frac{mA}{V}} = 32.78$$

$$\therefore A_v = \frac{1.96K\Omega}{32.78 + 1.96K\Omega} \approx \underline{0.9835}$$

$$A_{vs} = A_v \times \frac{V_{in}}{V_s}$$

$$\frac{V_{in}}{V_s} = \frac{Z_i}{Z_i + R_{sig}} = \frac{22.24K\Omega}{22.24K + 500} = 0.978$$

$$\therefore A_{vs} = \frac{V_o}{V_s}$$

$$= 0.9835 \times 0.978$$

$$\boxed{A_{vs} = +0.962}$$ ---- Small-signal voltage gain of CC ampl^r

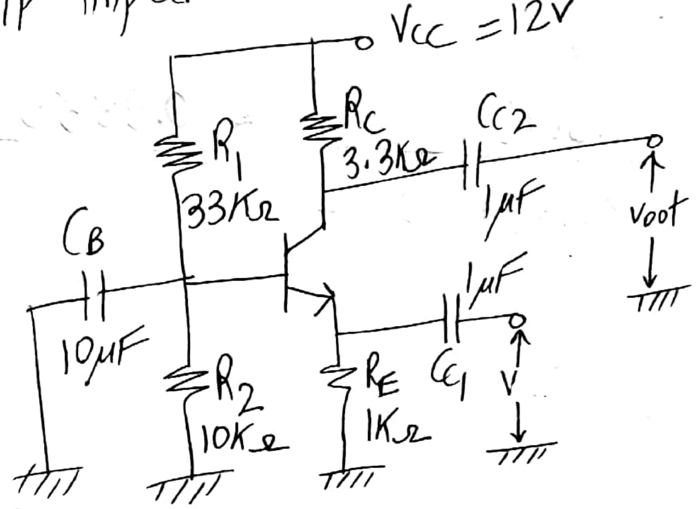
Numerical 03:

Determine the following for circuit below:-

a) Small-signal voltage gain

b) I/P impedance

c) O/P impedance



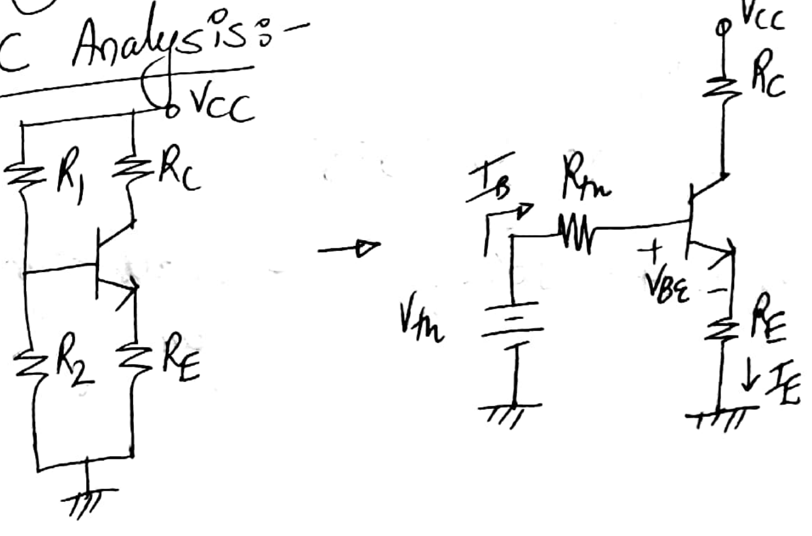
$\beta = 99$

$V_{BE(on)} = 0.7V$

$V_A = \infty$

Soln:- 1] Above circuit is common base amplifier using npn BJT

2] DC Analysis:-



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

$= \underline{2.79}\ V$

$R_{th} = R_1 \| R_2$

$= \underline{7.67}\ K\Omega$

KVL to B-E loop gives,

$$V_{th} - I_B R_{th} - V_{BE} - I_B(1+\beta)R_E = 0$$

$$I_B = \frac{V_{th} - V_{BE(on)}}{R_{th} + (1+\beta)R_E} = \frac{2.79 - 0.7}{7.67K\Omega + 100 \times 1K\Omega}$$

$$\boxed{I_{BQ} = 19.41\ \mu A}$$

$$I_{CQ} = \beta I_{BQ} = 99 \times 19.41\ \mu A$$

$$\boxed{I_{CQ} = 1.92\ mA}$$

$$I_E = I_C + I_B = \underline{1.94\ mA}$$

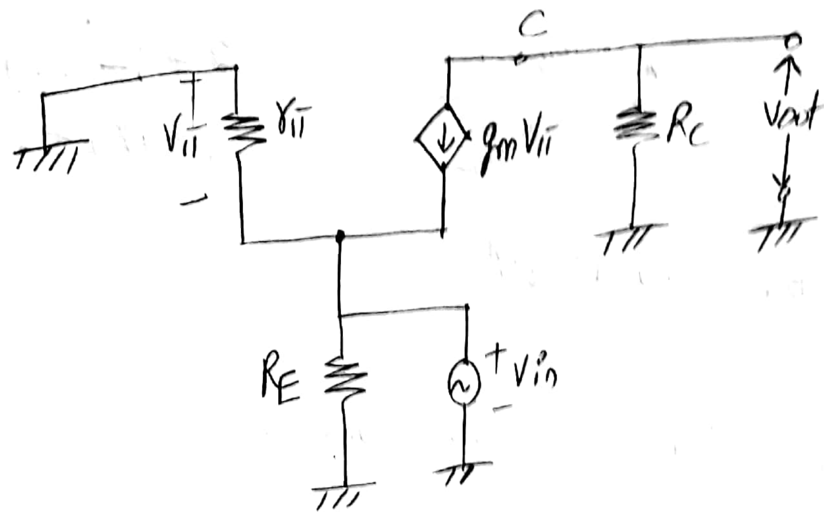
3] <u>Small-signal parameters:-</u>

a) $r_\pi = \frac{V_T}{I_{BQ}} = \frac{26mV}{19.41\mu A} = \underline{1.34K\Omega}$

b) $g_m = \frac{I_{CQ}}{V_T} = \frac{1.92\ mA}{26mV} = \underline{73.85\ \frac{mA}{V}}$

c) $r_o = \frac{V_A}{I_{CQ}} = \infty$

4] Small-signal equivalent circuit :-



a) Small-signal voltage gain : A_V

$$A_V = \frac{V_o}{V_{in}} = g_m R_C$$

$$A_V = 73.85 \times 10^{-3} \times 3.3\,K\Omega$$

$$\boxed{A_V = 243.69}$$

b) Input impedance : Z_i

$$Z_i = \frac{1}{g_m} \parallel R_E = \frac{1}{73.85 \times 10^{-3}} \parallel 1K\Omega = 13.54 \parallel 1K\Omega$$

$$\boxed{Z_i = 13.36\,\Omega}$$

c) Output impedance : Z_o

$\boxed{Z_o = R_C \Rightarrow}$ ie $\boxed{Z_o = 3.3K\Omega}$