BJT Amplifiers.

Overview of DC analysis of BJT circuits & Models.

Introduction to BJT circuits & models.

\# Transistors are 3 terminal device, namely

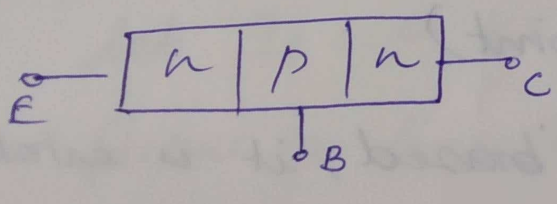
1. Emitter - heavily doped
2. Base - thin & lightly doped
3. collector. - large & moderately doped.

\# Two types

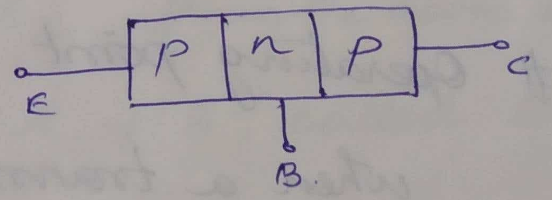
1. unipolar - 'I' conduction - one type of charge
2. Bipolar - 'I' " - both the charge carriers

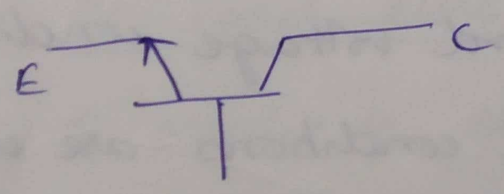
\# BJT -

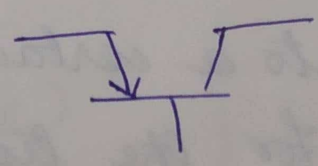
n - p - n



p - n - p



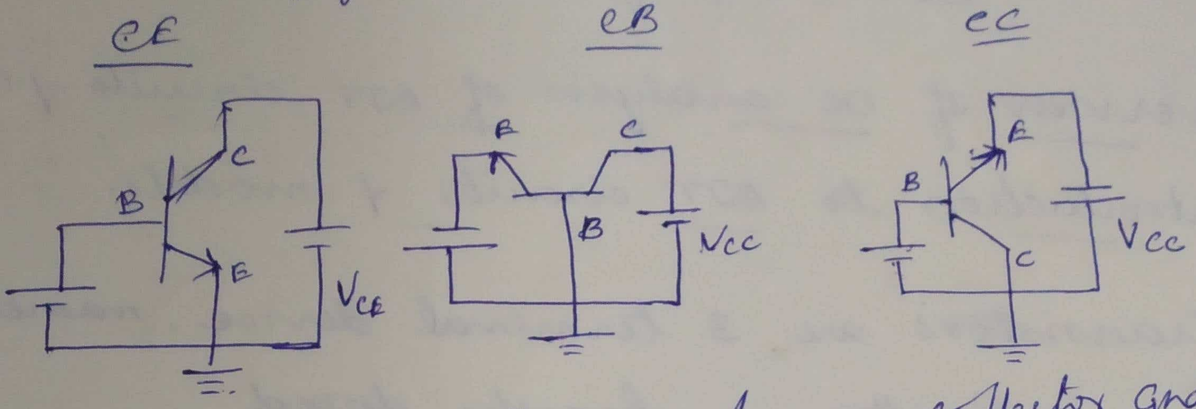




$$\boxed{\begin{aligned} I_E &= (1+\beta) I_B \\ I_C &= \beta I_B \\ I_E &\simeq I_C \end{aligned}}$$

→ magnitude of collector current

BJT configurations.



Emitter grounded   Base gnd   collector gnd.

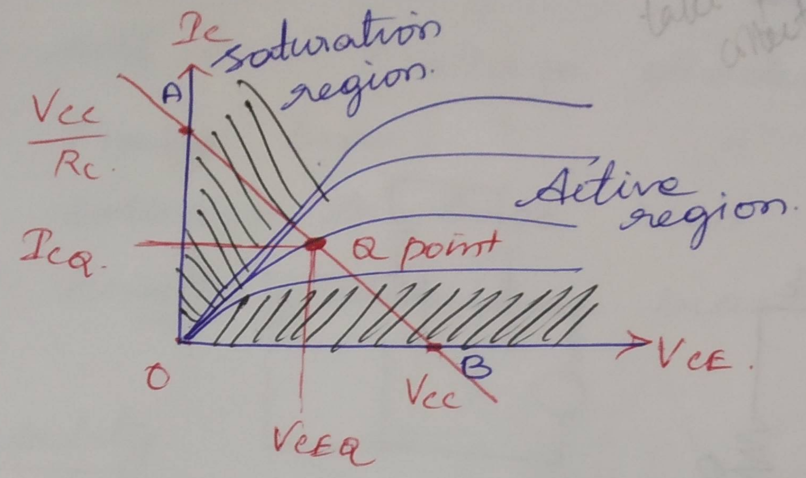
CE is the most popular configuration, because of its high voltage and current gain

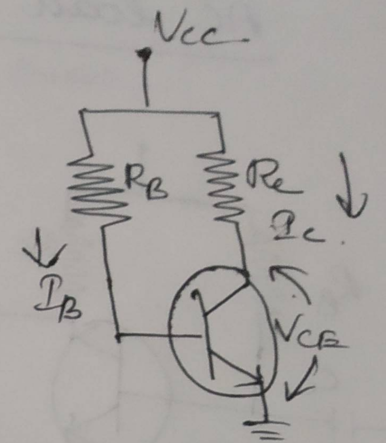
Need for biasing.
- to establish a fixed level of current and voltages.

Operating point (Q - point)
when a transistor is biased, it is established to a certain current and voltage condition for the transistor. These conditions are called dc operating point.

DC load line :-

load we'll take from collector side





$V_{cc} - I_c R_c - V_{CE} = 0.$

To find A + B from the above (dgm) + (eqn)

$V_{cc} - I_c R_c = V_{CE}$. $y = mx + c$

$\therefore$ to determine ↓ V_{CE} ↓ $I_c R_c$ ↓ V_{cc}

one component, the other is kept zero.

$\therefore$ let $V_{CE} = 0$; $V_{cc} = I_c R_c$

$\therefore I_c = V_{cc}/R_c$.

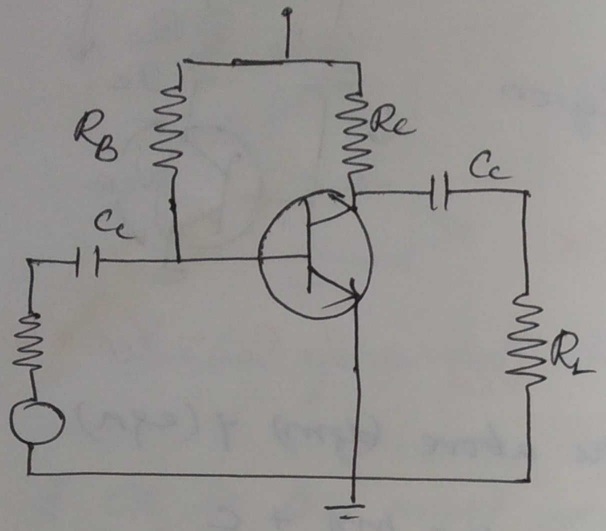
let $I_c = 0$; $V_{cc} = V_{CE}$. from the above e

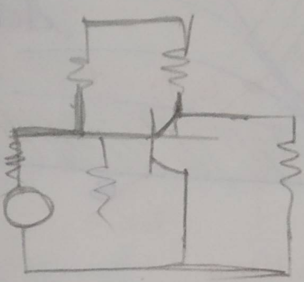
Draw a line between A + B, called th

DC load line,

Q point is at (V_{CEQ}, I_{CQ})

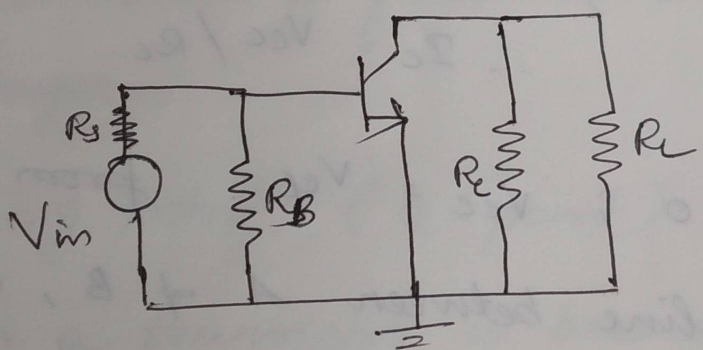
AC load line





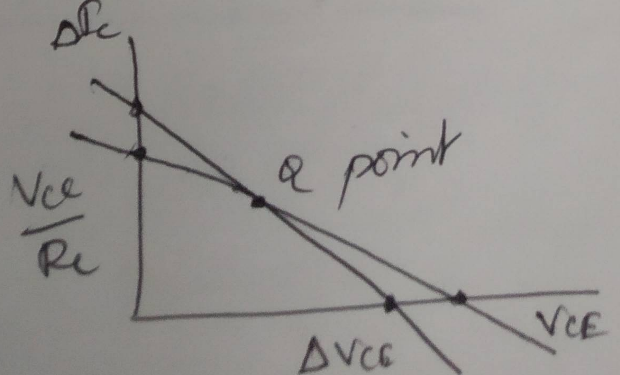
\# for AC analysis coupling and bypass capacitor acts as short circuit.

\# DC supply also replaced by short circuit



$$\therefore \quad V_{CE\,max} = V_{CEQ} + I_{CQ} \cdot R_{ac}$$

$$I_{C\,max} = \frac{V_{CEQ}}{R_{ac}} + I_{CQ}$$



Types of biasing.

1. self bias / voltage divider bias.
2. Fixed bias.
3. collector to base bias.
4. Emitter stabilized bias.

Stability

- measure of sensitivity of a network to variations in its parameters.

I_C is sensitive.

(i) β ; $S(\beta) = \frac{\Delta I_C}{\Delta \beta}$

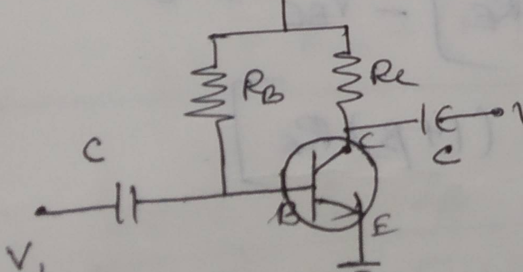
phase constant

(ii) V_{BE} ; $S(V_{BE}) = \frac{\Delta I_C}{\Delta V_{BE}}$

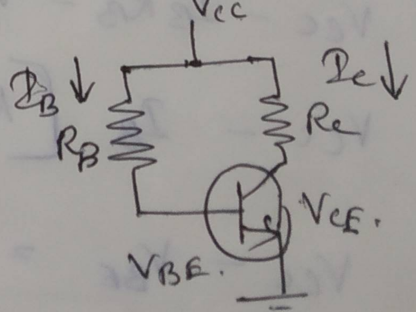
(iii) I_{CO} ; $S(I_{CO}) = \frac{\Delta I_C}{\Delta I_{CO}}$

saturation collector current

Fixed Bias



$\Rightarrow$



To find Q point.

$V_{CC} - I_C R_C - V_{CE} = 0$

$\Rightarrow V_{CE} = V_{CC} - I_C R_C$.

$V_{CC} - I_B R_B - V_{BE} = 0$

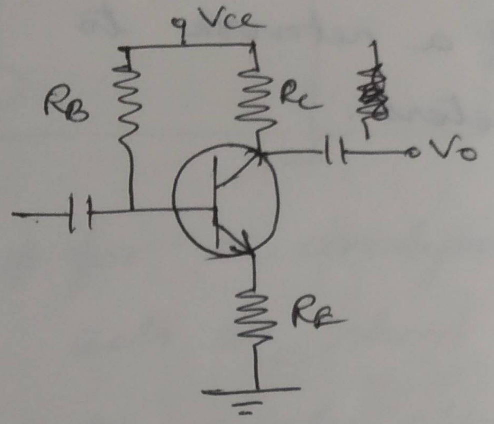
$\Rightarrow I_B = \frac{V_{CC} - V_{BE}}{R_B}$.

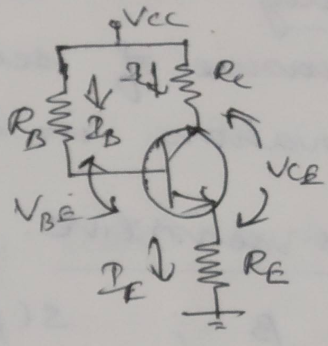
$$\Rightarrow I_c = \beta I_B.$$

$$= \beta \left[\frac{V_{CC} - V_{BE}}{R_B} \right]$$

$$S(I_{CO}) = \beta + 1$$

Emitter Bias Configurations.





Q point

$$V_{CC} - I_B R_B - V_{BE} - I_E R_E = 0.$$

$$= V_{CC} - I_B R_B - V_{BE} - (1+\beta) I_B \cdot R_E = 0$$

$$= V_{CC} - I_B R_B - V_{BE} - (I_B + \beta I_B) \cdot R_E$$

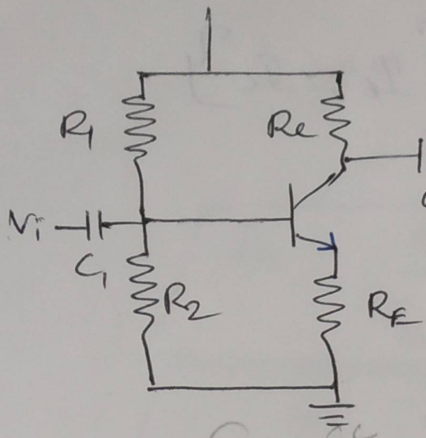
$$= V_{CC} - I_B \left[R_B + (1+\beta) R_E \right] - V_{BE} = 0$$

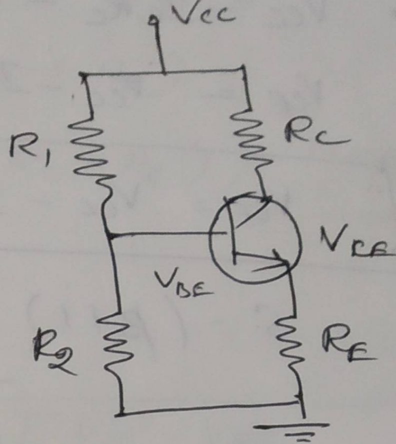
$$= V_{CC} - V_{BE} = I_B \left[R_B + (1+\beta) \cdot R_E \right]$$

$$\therefore \boxed{I_B = \frac{V_{CC} - V_{BE}}{R_B + (1+\beta) R_E}} \quad 1$$

$$\boxed{I_C = \beta \cdot I_B = \beta \cdot \frac{V_{CC} - V_{BE}}{R_B + (1+\beta) R_E}} \quad 1$$

Voltage divider Bias





$R_{Th} = R_1 \parallel R_2$

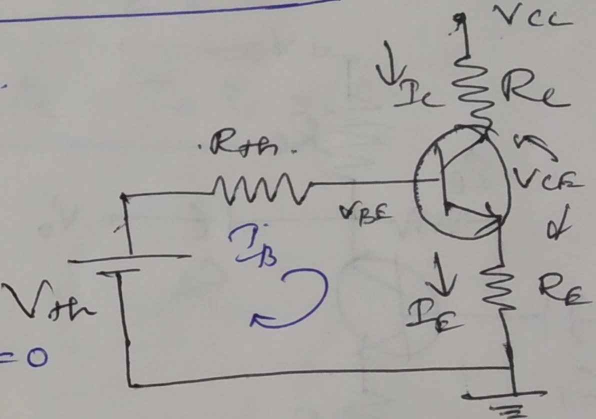
$$\boxed{R_{TH} = \frac{R_1 R_2}{R_1 + R_2}}$$

R_{Th} { V - SC, I - OC, R_L - remove

$$\boxed{V_{Th} = V_B = \frac{V_{CC} \times R_2}{R_1 + R_2}}$$

{ R_L - remove, find O.C. voltage

To find Q point.



$V_{Th} - I_B R_{Th} - V_{BE} - I_E R_E = 0$

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

$\Rightarrow I_B \left(R_{Th} + (1+\beta) R_E \right) = V_{Th} - V_{BE}$

$$\therefore \boxed{I_B = \frac{V_{Th} - V_{BE}}{R_{Th} + (1+\beta) R_E}}$$

$\therefore I_C = \beta \cdot I_B$

$$\boxed{I_C = \beta \cdot \left[\frac{V_{Th} - V_{BE}}{R_{Th} + (1+\beta) R_E} \right]}$$

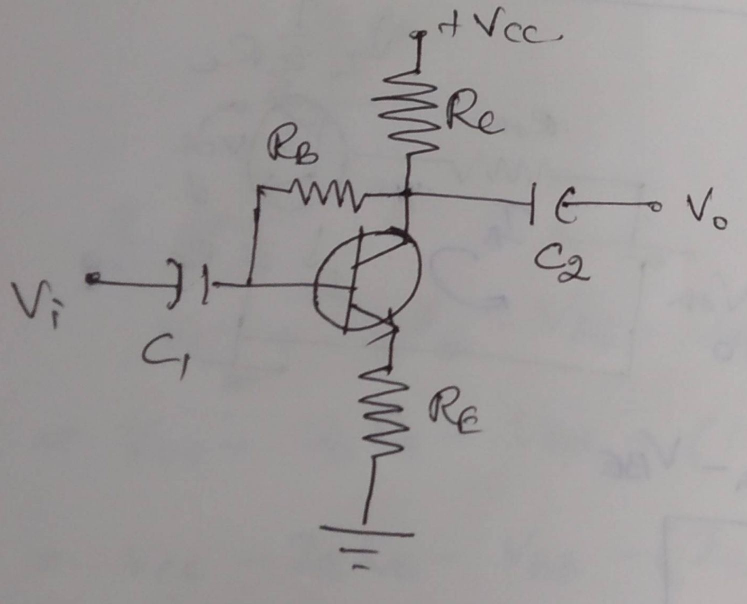
$$\Rightarrow V_{CC} - I_C R_C - V_{CE} - I_E R_E = 0.$$

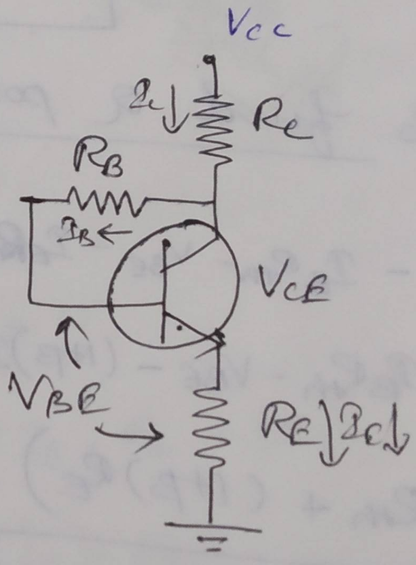
$$V_{CE} = V_{CC} - I_C R_C - I_E R_E . \quad \{ I_E \simeq I_C \}$$

$$\boxed{\therefore V_{CE} = V_{CC} - I_C \left[R_C + R_E \right]}$$

$$S = (\beta + 1) \frac{1 + R_{th}/R_E}{(1+\beta) + R_{th}/R_E} .$$

Collector feedback Bias.





Q point :-

$$\Rightarrow V_{CC} - I_C R_C - I_B R_B - V_{BE} - I_E R_E = 0 .$$

$$\because I_E \simeq I_C \quad +$$

$$I_C = \beta I_B .$$

$$\Rightarrow V_{CC} - \beta I_B R_C - I_B R_B - V_{BE} - \overset{\beta I_B}{\cancel{I_C}} R_E = 0$$

$$\Rightarrow V_{CC} - V_{BE} = I_B R_B + \beta I_B R_C + \beta I_B R_E$$

$$= I_B R_B + \beta I_B (R_C + R_E)$$

$$= I_B (R_B + \beta)(R_C + R_E)) \quad (1+\beta)$$

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$$\boxed{I_B = \frac{V_{CC} - V_{BE}}{R_B + \underset{1+\beta}{\beta}(R_C + R_E)}}$$

$$\boxed{\therefore I_C = \beta I_B = \beta \left[\frac{V_{CC} - V_{BE}}{R_B + \beta (R_C + R_E)} \right]}$$

$$\Rightarrow V_{CC} - I_C R_C - V_{CE} - I_E R_E = 0$$

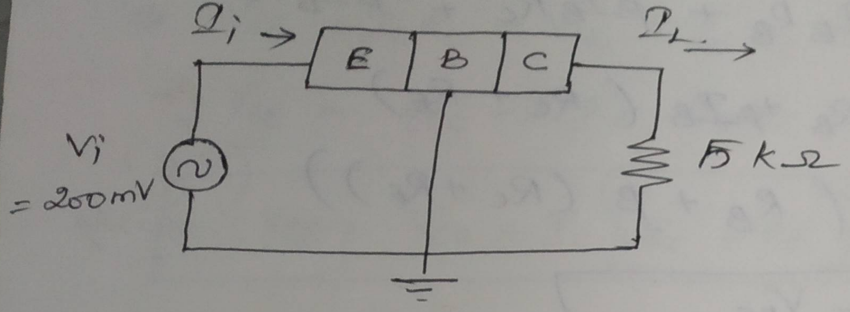
$$\boxed{V_{CE} = V_{CC} - I_C R_C - I_E R_E}$$

$$I_B (R_B + \beta)(R_C + R_E)$$

$$= I_B (R_B \cdot R_C + \beta R_C + R_B \cdot R_E + \beta R_E)$$

$$I_B \; \beta R_C (R_C +$$

AC Analysis



Let $R_i = 20\,\Omega$ $\qquad I_i = V_i / R_i = 10\,mA.$

$I_L = 10\,mA$ $\qquad = \dfrac{200\,mV}{20\,\Omega} = 10\,mA.$

$V_o = R_L \times I_L$

$= 10\,mA \times 5\,k\Omega$

$= 50\,V.$

- An ac signal changes the i/p current (i.e.,) 'Ib', 'Ic' changes.
- If 'Ic' changes Q point shifts.

∴ Therefore ac analysis is necessary.

- AC analysis of a transistor network depends on the magnitude of the i/p signal.

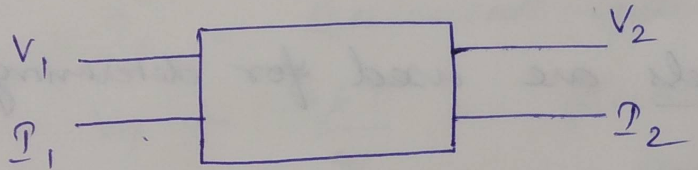
1) small signal analysis
2) large signal analysis

SSA
- re - model
- hybrid equivalent model (h-parameter)
- hybrid π model.

Model

- A model is a combination of circuit elements that best approximates the actual behavior of a semi-conductor device under specific operating conditions.

Hybrid (approx)



$V_1 = h_{11} I_1 + h_{12} V_2$

$I_2 = h_{21} I_1 + h_{22} V_2$

unit

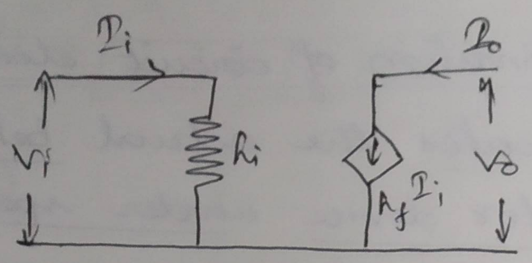
$h_{11} = \frac{V_1}{I_1} \Big/_{V_2 = 0}$ ⇒ I/p impedance (h_i) Ω

$h_{12} = \frac{V_1}{V_2} \Big/_{I_1 = 0}$ ⇒ Reverse transfer voltage gain (h_r)

$h_{21} = \frac{I_2}{I_1} \Big/_{V_2 = 0}$ ⇒ forward transfer current gain (h_f)

$h_{22} = \frac{I_2}{V_2} \Big/_{I_1 = 0}$ ⇒ O/p admittance (h_o) $\mho$

Approximate Model (hybrid)



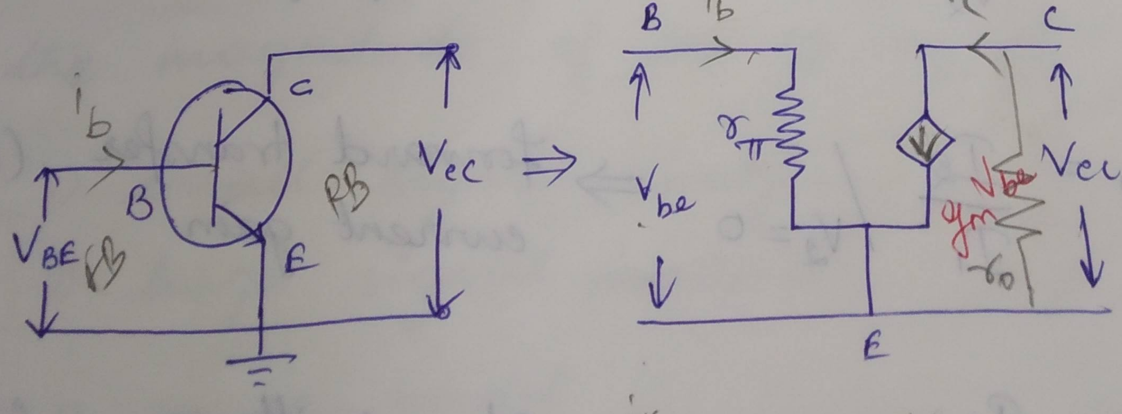
AC analysis of Basic BJT amplifier configurations using classical discrete circuit bias arrangement small scale AC model

- Linear DC models are used for determining the Q point,
- AC model is used for determining the voltage or power gain when the transistor is operated as an amplifier in the active region.

Hybrid π model.

- popular circuit model used for analysing small signal behavior of BJT & FET

These are quite accurate.



$S/\Omega^{-1} \quad \frac{i_b}{V_{be}}$ $\qquad r_\pi = \frac{V_{be}}{I_b}$

The hybrid π is a linearised 2 port network approximation to BJT using small signal base emitter voltage, (as independent variables) V_{ce}, and i_b + i_c as dependent variables.

The various parameters are :

$$g_m = \frac{i_c}{V_{be}}\bigg|_{V_{ce}=0} = \frac{I_c}{V_T} = \text{transconductance}$$

I_c = Quiescent collector current

$V_T = \frac{kT}{q}$ = thermal voltage

$$\begin{cases} k - \text{Boltzman constant} \\ T - \text{temperature in kelvin} \\ q - \text{charge of electron} \end{cases}$$

V_T = 26 mV @ room temperature.

$$\left.\begin{array}{l}\text{diffusion resistance} \\ \text{(or)} \\ \text{base emitter resistor}\end{array}\right\} r_\pi = \frac{V_{be}}{I_b}\bigg|_{V_{ce}=0}.$$

I_b = DC bias base current.

$\beta_0 = \frac{I_c}{I_B}$ is current gain.

$r_o = \frac{V_{ce}}{i_c}\bigg|_{V_{be}=0} \simeq \frac{V_A}{I_c}$ is the o/p resistance due to Early effect.

Note :- Instead of $g_m V_{be}$ we can use βI_B also for derivation.

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

$$V_{be} = r_\pi \times I_b.$$

$$\therefore \; g_m V_{be} = \frac{\beta}{\cancel{r_\pi}} \times \cancel{r_\pi} \times I_B.$$

$$\boxed{g_m V_{be} = \beta I_B.}$$

Common Emitter Amplifier (AC analysis)

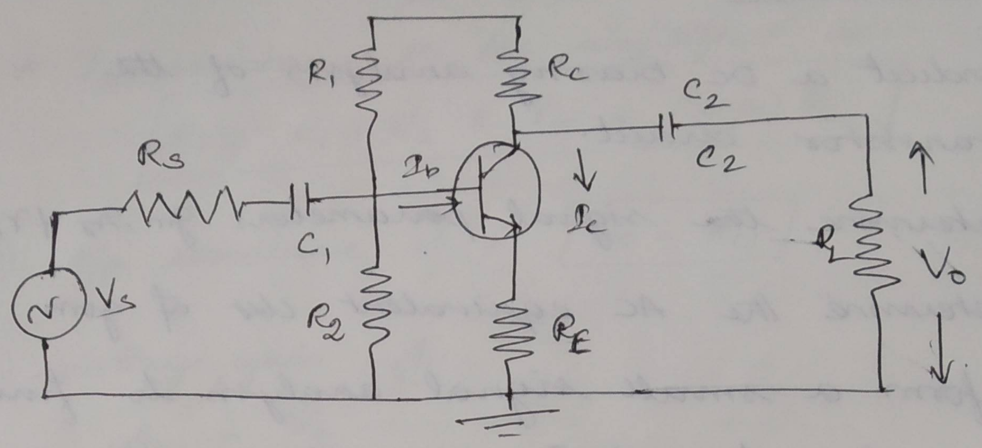


figure shows CE circuit with voltage divider bias. Emitter is at ground potential.

s/g from source is coupled to the base of the transistor through the coupling capacitor.

↳ this provides DC isolation between the amplifier and signal source.

R_1 & R_2 → establish dc transistor biasing & is not disturbed when the current source is capacitively coupled to the amplifier

At high frequencies

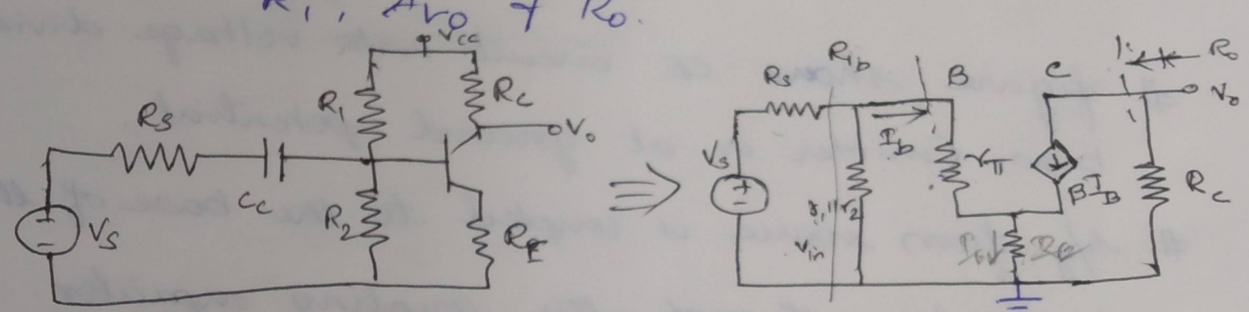
$|Z_c| = 1/2\pi f_c C$, which is very less

∴ capacitor is considered as SC.

signal frequency is high enough to consider any coupling capacitor as short circuit and transistor capacitance as OC. open circuit

Steps involved in analysing an amplifier ckt.

1. conduct a DC biasing analysis of the transistor circuit.
2. Determine the signal parameters g_m, r_π + r_o.
3. Determine the AC equivalent ckt of given
4. Perform a small signal analysis to find R_i, A_{vo} + R_o.



- current gain parameter β is used.

r_o → is neglected since early effect voltage is ∞

$$r_o = \frac{V_A}{I_C} \simeq \infty$$

1) I/p Resistance R_i

$$R_i = R_1 \parallel R_2 \parallel R_{ib}.$$

$R_{ib} = \frac{V_i}{I_b}$ = I/p resistance looking into the base of transistor.

Applying loop equation :- $(I_b + I_c) R_E$

$$V_{in} = I_b r_\pi + (I_b + \beta I_b) R_E$$

$$\frac{V_{in}}{I_b} = R_{ib} = r_\pi + (1+\beta) R_E.$$

This is called resistance reflection rule.

* I/p resistance to the amplifier is

$$\boxed{R_i = R_1 \parallel R_2 \parallel r_\pi + (1+\beta) R_E}.$$

2) O/p resistance is, $\boxed{R_o = R_C}$

3) Voltage gain, A_v.

$$A_{Vo} = \frac{V_o}{V_{in}}$$

$; V_o = -\beta I_b R_C.$

$; V_{in} = I_b r_\pi + (I_b + \beta I_b) R_E.$

$; V_{in} = I_b [r_\pi + (1+\beta) R_E]$

$$\therefore \frac{V_o}{V_{in}} = \frac{-\beta \cancel{I_b} R_C}{\cancel{I_b}[r_\pi + (1+\beta) R_E]}$$

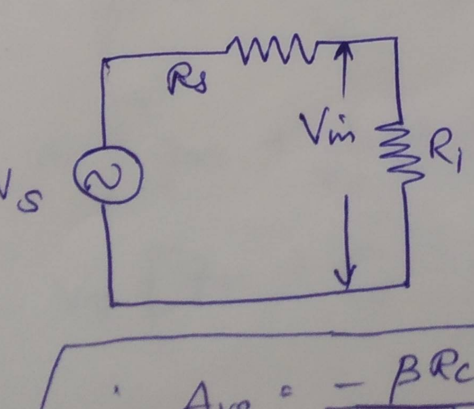
$$\boxed{A_{Vo} = \frac{-\beta R_C}{r_\pi + (1+\beta) R_E}}$$

$r_\pi << (1+\beta) R_E$, then

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

voltage gain including source resistance & V_s

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



using voltage divided rule

$$V_{in} = \frac{V_s \times R_i}{R_s + R_i}$$

$$\frac{V_{in}}{V_s} = \frac{R_i}{R_s + R_i}$$

$$\boxed{\therefore A_{vs} = \frac{-\beta R_C}{r_\pi + (1+\beta) R_E} \cdot \frac{R_i}{R_s + R_i}}$$

A_{VO} can be made high by

→ choosing large value of β_f

→ choosing large value of R_C

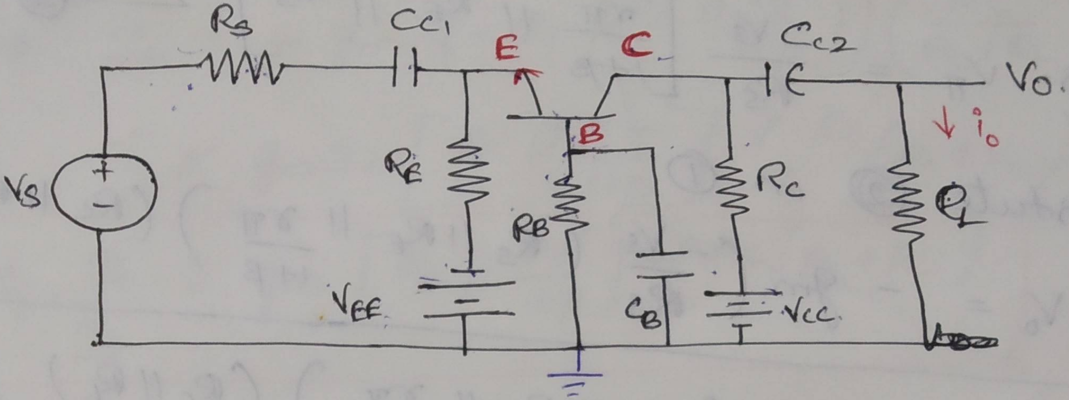
→ choosing low value of R_E & $R_E \simeq 0$.

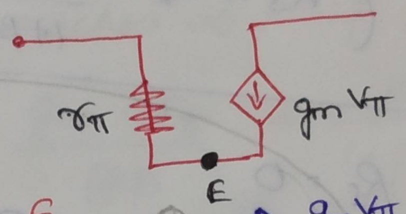
$$A_{VO} = \frac{-\beta_f R_C}{r_\pi} = \frac{-g_m r_\pi R_C}{r_\pi} = -g_m R_C .$$

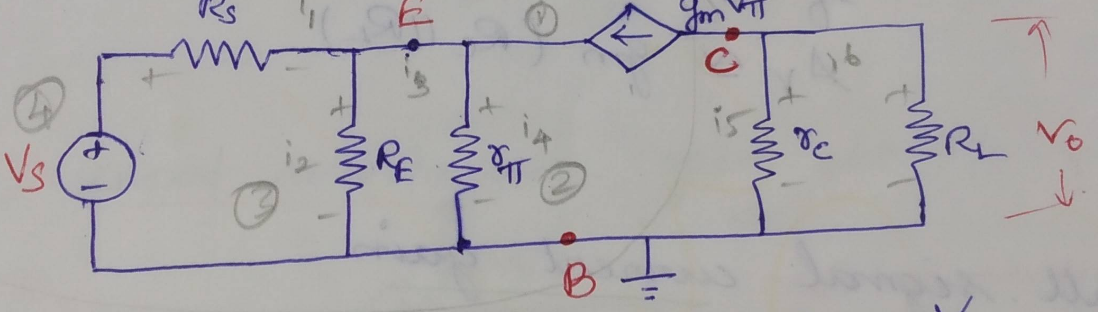
Common Base Amplifier.

Base is at signal ground and i/p is applied to emitter.

$r_o \rightarrow$ assumed to be infinite.







small signal voltage gain $A_V = \dfrac{V_o}{V_s}$ as per ckt. + logic.

$\rightarrow$ $V_o = -g_m V_\pi \times (r_c \parallel r_L)$ —— ①.

$\rightarrow$ KCL @ emitter node.

$$g_m V_\pi + \frac{V_\pi}{r_\pi} + \frac{V_s + V_\pi}{R_S} + \frac{V_\pi}{R_E} = 0.$$

$$= V_\pi \left[g_m + \frac{1}{r_\pi} + \frac{1}{R_E} + \frac{V_S}{R_S} + \frac{1}{R_S} \right] = 0$$

$$= V_\pi \left[g_m + \frac{1}{r_\pi} + \frac{1}{r_e} + \frac{1}{R_S} \right] = -\frac{V_s}{R_S}$$

$$\Rightarrow V_\pi \left[\frac{g_m r_\pi + 1}{r_\pi} + \frac{1}{R_E} + \frac{1}{R_S} \right] = -\frac{V_s}{R_s}$$

$$\Rightarrow V_\pi \left[\frac{1+\beta}{r_\pi} + \frac{1}{R_E} + \frac{1}{R_S} \right] = \frac{-V_s}{R_s}$$

$$\Rightarrow V_\pi = \frac{-V_s}{R_s} \left[\frac{r_\pi}{1+\beta} \parallel R_E \parallel R_s \right] \longrightarrow (2)$$

Substitute (2) in (1)

$$V_o = -g_m \left(\frac{-V_s}{R_S} \left(R_s \parallel R_E \parallel \frac{r_\pi}{1+\beta} \right) \right) (R_C \parallel R_L)$$

$$\boxed{\therefore \frac{V_o}{V_s} = \frac{-g_m}{R_S} \left(R_s \parallel R_E \parallel \frac{r_\pi}{1+\beta} \right) (R_C \parallel R_L)}$$

If $R_S = 0$

$A_V \simeq g_m \, (R_C \parallel R_L)$

Small signal current gain

$$A_i = \frac{I_o}{I_i} \qquad \because I_o = -g_m V_\pi \cdot \frac{R_C}{R_C + R_L} \rightarrow (3)$$

KCL @ i/p.

$$I_i + \frac{V_\pi}{R_E} + \frac{V_\pi}{r_\pi} + g_m V_\pi = 0.$$

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

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

$$\Rightarrow V_\pi \left(\frac{1}{R_E} + \frac{1+\beta}{r_\pi}\right) = -I_i$$

$$\Rightarrow V_\pi = -I_i \left(R_E \parallel \frac{r_\pi}{1+\beta}\right) \quad \text{--- (4)}$$

substitute V_π from (4) in (3)

$$\Rightarrow I_o = -g_m \left(-I_i \left(R_E \parallel \frac{r_\pi}{1+\beta}\right)\right)\left(\frac{R_C}{R_C+R_L}\right)$$

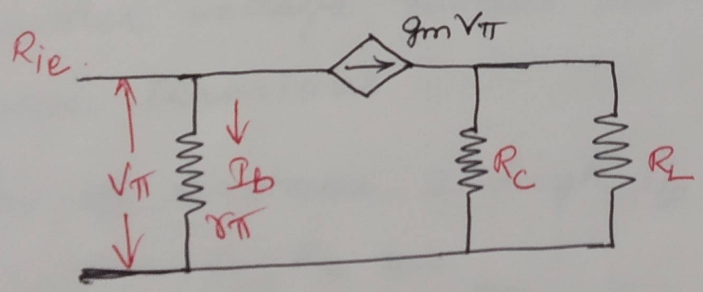
$$= g_m I_i \left[R_E \parallel \frac{r_\pi}{1+\beta}\right] \left(R_C / R_C + R_L\right)$$

$$\boxed{\therefore A_i = \frac{I_o}{I_i} = g_m \left[R_E \parallel \frac{r_\pi}{1+\beta}\right] \left(R_C / R_C + R_L\right)}$$

R_E (when) approaches ∞, if $R_L = 0$.

$$\therefore A_{io} = \frac{g_m \cdot r_\pi}{1+\beta} = \frac{\beta}{1+\beta} = \alpha$$ (common base current gain)

R_i : Input resistance. open ckt i/p side. so



for convenience directions reversed.

$$R_{ie} = \frac{V_\pi}{I_i}$$

$$I_i = I_b + g_m V_\pi$$

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

$$= V_\pi \left[\frac{1}{r_\pi} + g_m\right]$$

$$= V_\pi \left[\frac{g_m r_\pi}{r_\pi}\right]$$

$$= V_\pi \left[\frac{1+\beta}{r_\pi}\right]$$

$$\therefore I_i = V_\pi \left[\frac{1+\beta}{r_\pi} \right]$$

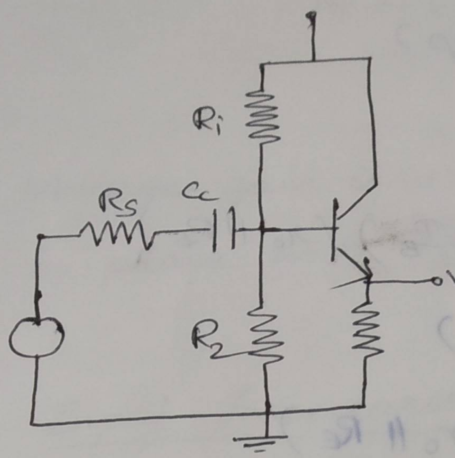
$$\therefore \frac{V_\pi}{I_i} = \cancel{\frac{1+\beta}{r_\pi}}$$

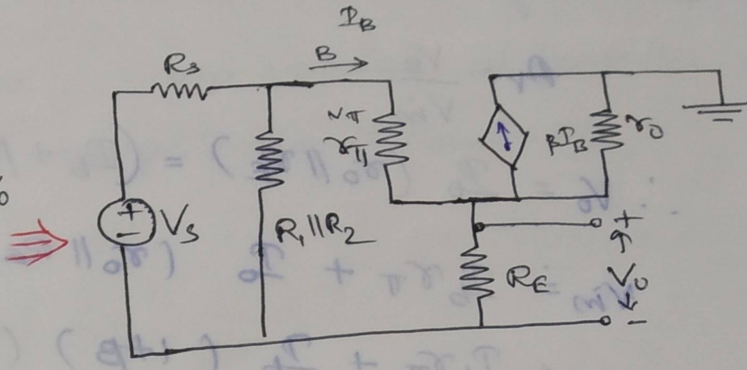
$$\boxed{\therefore \frac{V_\pi}{I_i} = \frac{r_\pi}{1+\beta}} \simeq r_\pi$$

R_o : o/p resis.

$$\boxed{R_o \simeq R_c}$$

Common Collector Amplifier



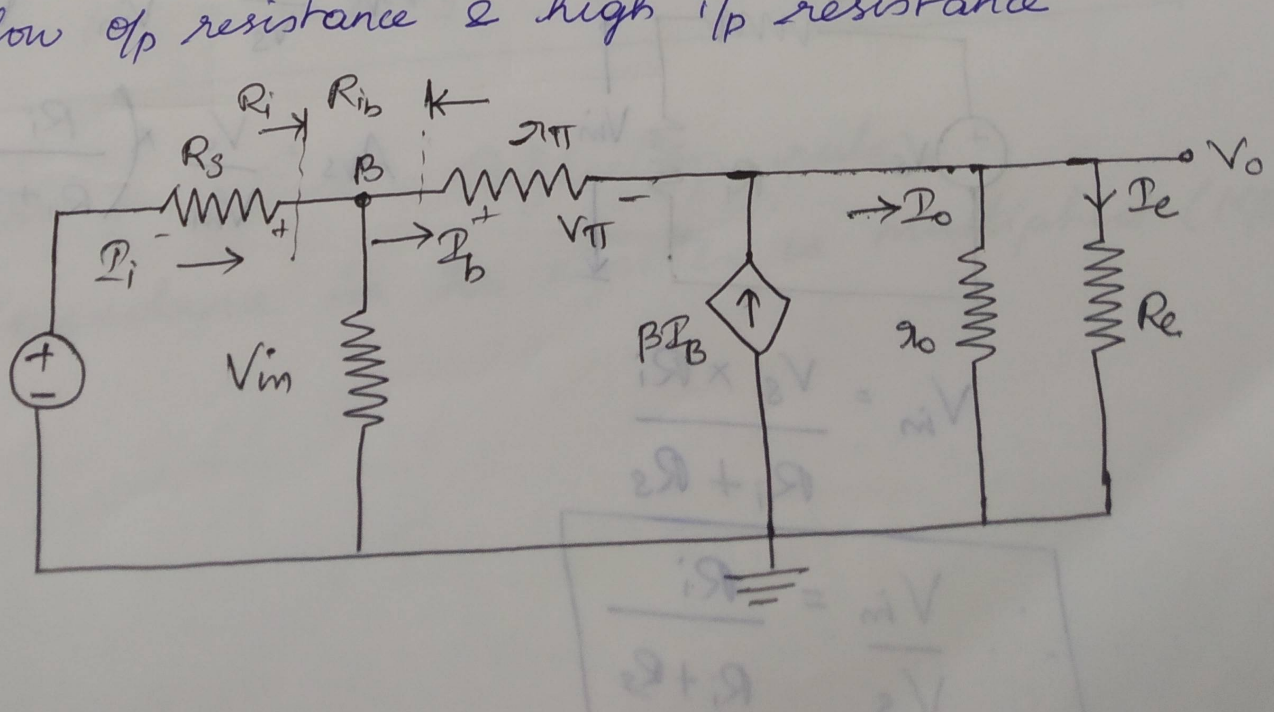


\# The o/p is taken off the emitter with respect to gnd and collector is connected to Vcc.

\# since, Vcc is at signal ground in ac equivalent circuit, we have the name <u>common collector</u>

\# It is known as emitter follower, because the emitter voltage follows the voltage at the base terminal.

\# low o/p resistance & high i/p resistance



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

Voltage Gain A_v (open loop)

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

$$\therefore V_o = I_o \,(r_o \parallel R_E) = (I_b + \beta I_B)(r_o \parallel R_E)$$

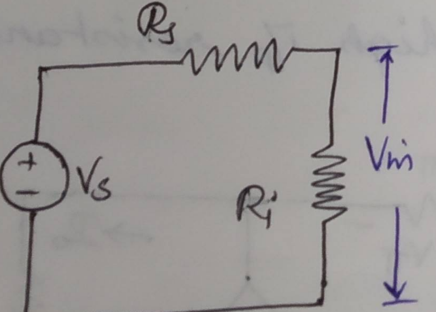
$$V_{in} = I_b r_\pi + I_o \,(r_o \parallel R_E)$$

$$= I_b r_\pi + I_b \,(1+\beta)(r_o \parallel R_E)$$

$$\therefore A_v = \frac{V_o}{V_{in}} = \frac{\cancel{I_b}\,(1+\beta)(r_o \parallel R_E)}{\cancel{I_b}\,(r_\pi + (1+\beta)(r_o \parallel R_E)}$$

$$\boxed{A_v = \frac{(1+\beta)(r_o \parallel R_E)}{r_\pi + (1+\beta)(r_o \parallel R_E)}}$$

loop Gain (closed loop)



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

$$\therefore A_{vs} = \frac{V_o}{V_{in}} \times \left(\frac{R_i}{R_i + R_s}\right)$$

$$V_{in} = \frac{V_s \times R_i}{R_i + R_s}$$

$$\boxed{\therefore \frac{V_{in}}{V_s} = \frac{R_i}{R_i + R_s}}$$

$$A_{vs} = \frac{(1+\beta)(r_o \parallel R_E)}{r_\pi + (1+\beta)(r_o \parallel R_E)} * \frac{R_i}{R_i + R_s},$$

where $R_1 \parallel R_2 \parallel R_{ib}$.

- Voltage gain is (+)ve., ∴ o/p voltage at emitter is in phase with I/p voltage. o/p follows I/p

Input Impedance

$R_i = R_1 \parallel R_2 \parallel R_{ib}$.

$\therefore R_{ib} = \frac{V_{in}}{I_b}$

$V_{in} = I_b r_\pi + I_o (r_o \parallel R_E)$

$= I_b r_\pi + (I_b + \beta I_B)(r_o \parallel R_E)$

$= I_b [r_\pi + (1+\beta) r_o \parallel R_E]$

$\therefore \frac{V_{in}}{I_b} = r_\pi + (1+\beta) r_o \parallel R_E. = R_{ib}.$

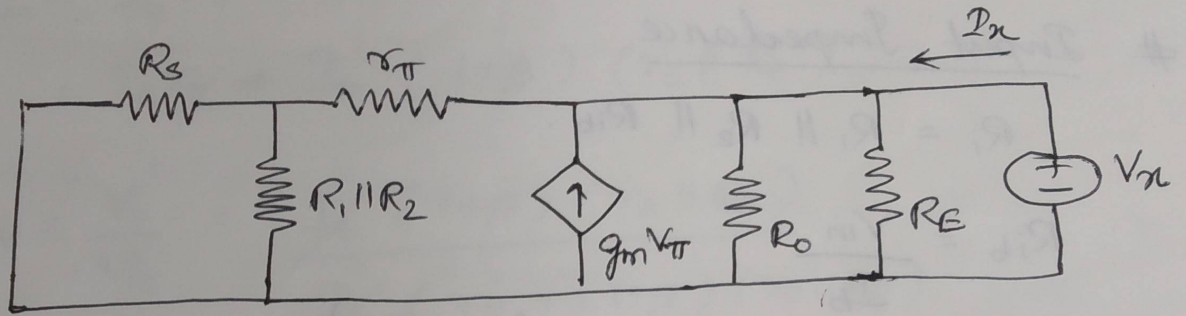
$$\boxed{\therefore R_i = R_1 \parallel R_2 \parallel r_\pi + (1+\beta)(r_o \parallel R_E)}$$

This is called, Reflection rule.

Impedance in the emitter is multiplied $(1+\beta)$

Output Impedance (R_o)

The independant voltage source is set to zero ($V_s = 0$). A test voltage V_x is applied to the o/p terminals and the resulting test current is I_x.



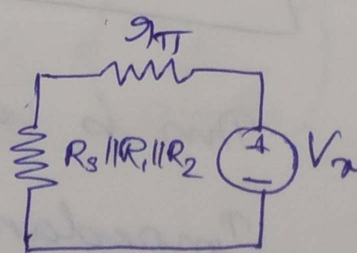
$$\beta I_B = g_m V_\pi$$

$$R_o = \frac{V_x}{I_x}$$

Applying KCL at o/p

$$I_x + g_m V_\pi = \frac{V_x}{R_E} + \frac{V_x}{r_o} + \frac{V_x}{r_\pi + (R_S \| R_1 \| R_2)} \quad \text{—} ①$$

$$V_\pi = \frac{-V_x * r_\pi}{r_\pi + (R_S \| R_1 \| R_2)}$$



$$I_x = \frac{V_x\, g_m r_\pi}{r_\pi + (R_S \| R_1 \| R_2)} + \frac{V_x}{R_E} + \frac{V_x}{r_o} + \frac{V_x}{r_\pi + (R_S \| R_1 \| R_2)}$$

$$I_x = V_x\left[\frac{1}{R_E} + \frac{1}{r_o} + \frac{(1+g_m r_\pi)}{r_\pi + (R_S \| R_1 \| R_2)}\right]$$

$$I_x = V_x\left[\frac{1}{R_E} + \frac{1}{r_o} + \frac{1+\beta}{r_\pi + (R_S \| R_1 \| R_2)}\right]$$

$$\boxed{R_o = \frac{V_x}{I_x} = R_E \,\|\, r_o \,\|\, \frac{r_\pi + (R_S \| R_1 \| R_2)}{1+\beta}}$$

\# Emitter follower is sometimes referred to as an impedance transformer, since the i/p impedance is large and o/p impedance is small

\# This makes it an ideal voltage source, so the o/p is not loaded when used to drive another load

\# This is used as o/p stage in multistage amplifier

\# <u>Small signal current gain A_i</u>

$$A_i = \frac{I_e}{I_i} ;$$

$$I_e = \frac{I_o R_o}{R_o + R_E}$$

$$I_o = I_b + \beta I_b = (1+\beta) I_b$$

$$I_e = (1+\beta) I_b \left(\frac{r_o}{r_o + R_E}\right)$$

$$I_b = I_i \times \frac{R_1 \| R_2}{R_{ib} + (R_1 \| R_2)} \cdot \cancel{\left(\frac{r_o}{r_o + R_E}\right)}$$

$$I_e = (1+\beta) I_i \cdot \frac{R_1 \| R_2}{R_{ib} + (R_1 \| R_2)} \cdot \frac{r_o}{r_o + R_E}$$

$$\Rightarrow \frac{I_e}{I_i} = (1+\beta) \cdot \frac{R_1 \| R_2}{R_{ib} + (R_1 \| R_2)} \cdot \left(\frac{r_o}{r_o + R_E}\right)$$

$$\Rightarrow \boxed{A_i = \frac{I_e}{I_i} = (1+\beta) \frac{R_1 \| R_2}{R_{ib} + (R_1 \| R_2)} \cdot \frac{r_o}{r_o + R_E}}$$

$R_1 \| R_2 >> R_{ib}$ $\qquad$ $r_o >> R_E$

$$\boxed{\therefore A_i \approx (1+\beta)}$$

The small signal current gain is greater than 1. ∴ The circuit produces a small power gain.

Multistage amplifiers

Need for cascading

1) when amplification of single stage amplifier is not sufficient, or

2) when the i/p or o/p impedance is not of correct magnitude for a particular application two or more stages are connected in cascade.

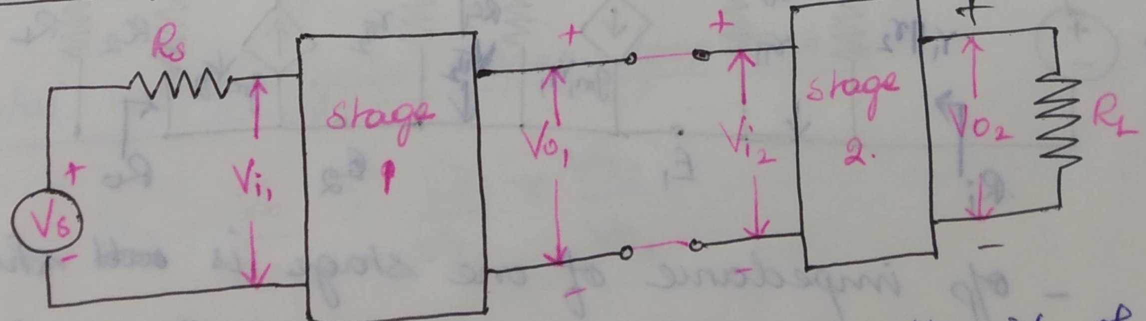
such an amplifier with two or more stages is known as multistage amplifier.

Limitations

1) The bandwidth of multistage amplifier is always less than that of a single stage amplifier.

2) Non-linear distortion is more in a multistage amplifier

Two stage cascade amplifier



o/p of first stage is connected to the i/p of 2nd stage

$\boxed{V_{o_1} = V_{i_2}}$

$$A_V = \frac{V_{o_2}}{V_{i_1}} = \frac{V_{o_2}}{V_{i_2}} \times \frac{V_{i_2}}{V_{i_1}}$$

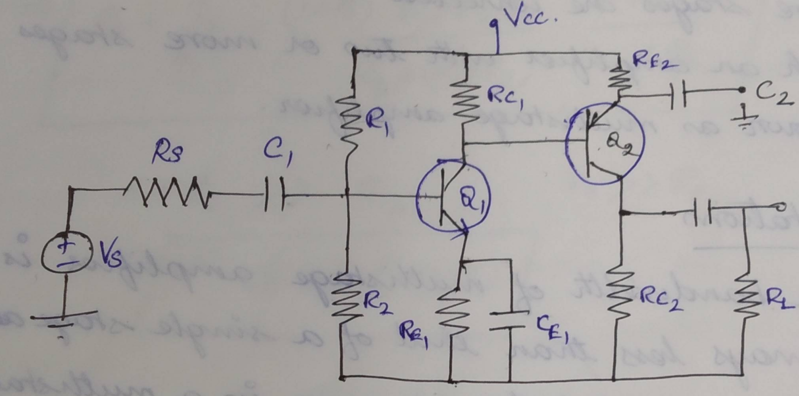
$$= \frac{V_{o_2}}{V_{i_2}} \times \frac{V_{o_1}}{V_{i_1}}$$

$$\boxed{A_v = A_{v_2} \cdot A_{v_1}}$$

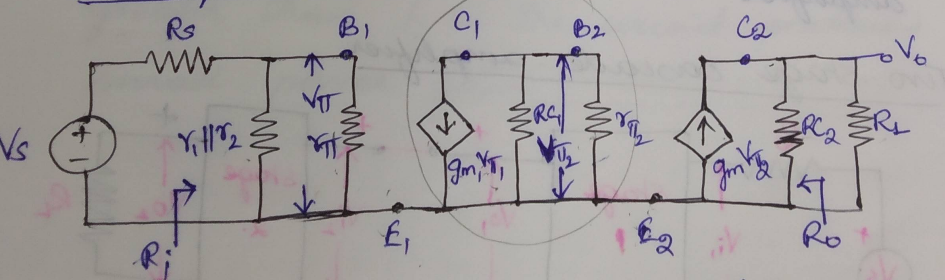
* Voltage gain of multistage amplifier is the product of voltage gains of the individual stages.

2 stage CE amplifier

* for ac analysis all capacitors are shorted & each transistors o/p resistance (r_0) is infinite.



AC equivalent circuit



- o/p impedance of one stage is ~~~~ shunted by the input impedance of the next stage.

stage 2:-

1) I/p impedance R_{i_2}

$$R_{i_2} = r_{\pi_2}$$

2) Voltage gain A_{V_2}

$$A_{V_2} = \frac{V_o}{V_{\pi_2}} \quad ; \quad V_o = g_{m_2} V_{\pi_2} (R_{C_2} \| R_L)$$

(Vin)

$$A_{V_2} = \frac{V_o}{V_{\pi_2}} = \frac{g_{m_2} V_{\pi_2} (R_{C_2} \| R_L)}{V_{\pi_2}}$$

$$\boxed{A_{V_2} = g_{m_2} (R_{C_2} \| R_L)}$$

Stage 1:-

1) Input impedance R_{i_1}

$$R_{i_1} = R_1 \| R_2 \| r_\pi$$

2) Voltage gain A_{V_1}

$$A_{V_1} = \frac{V_{\pi_2}}{V_{\pi_1}} = g_{m_1} V_{\pi_1} (R_{C_1} \| r_{\pi_2})$$

Total voltage gain (open loop) A_{V_o}.

$$A_{V_o} = \frac{V_o}{V_{\pi_1}} = \frac{V_o}{V_{\pi_2}} \times \frac{V_{\pi_2}}{V_{\pi_1}}$$

$$= \frac{V_o}{V_{\pi_2}} \times \frac{V_{\pi_2}}{V_{\pi_1}}$$

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

$$\boxed{A_{V_o} = g_{m_1} (R_{C_1} \| r_{\pi_2})\, g_{m_2} (R_{C_2} \| R_L)}$$

$$Av_s = \frac{V_o}{V_s} = \frac{V_o}{V_{\pi_2}} \times \frac{V_{\pi_2}}{V_{\pi_1}} \times \frac{V_{\pi_1}}{V_s}.$$

$$= Av_2 \times Av_1 \times \frac{R_i}{R_i + R_s}.$$

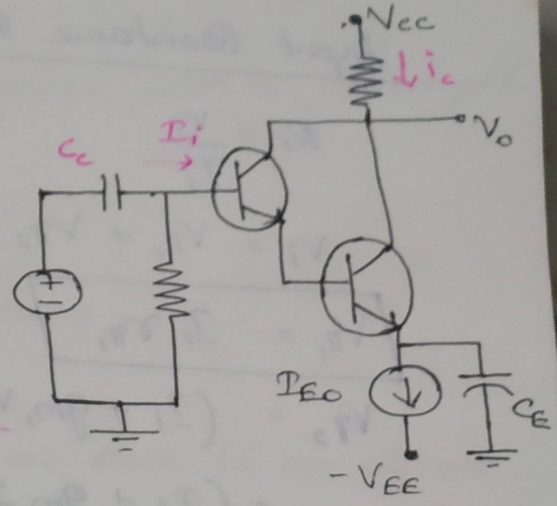
$$\boxed{\therefore Av_s = g_{m_1} g_{m_2} (r_c \parallel r_{\pi_2})(r_{e_2} \parallel r_L) \frac{R_i}{R_i + R_s}.}$$

3) o/p resistance (R_o)

$$\boxed{R_o \approx R_{C_2}}$$

Darlington Transistors.

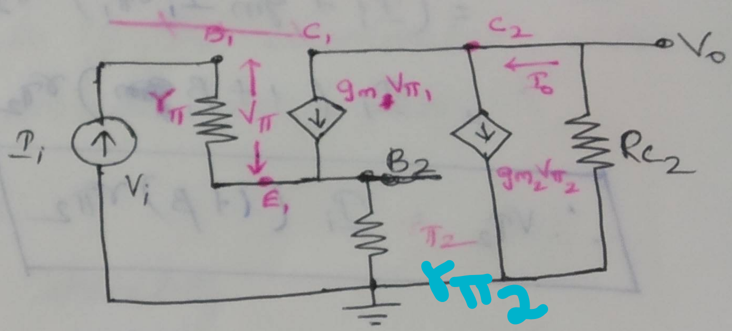
* high input resistance
* Improves current gain.



Small signal current gain A_i

$$A_i = \frac{I_o}{I_i}$$

$$I_o = g_{m_2} V_{\pi_2} + g_{m_1} V_{\pi_1}$$



$$\boxed{V_{\pi_1} = I_i r_{\pi_1}}$$

$$V_{\pi_2} = (I_i + g_{m_1} V_{\pi_1}) r_{\pi_2}$$

$$= (I_i + I_i g_{m_1} r_{\pi_1}) r_{\pi_2}$$

$$= (I_i + I_i \beta_1) r_{\pi_2}$$

$$\boxed{V_{\pi_2} = I_i r_{\pi_2} + I_i \beta_1 r_{\pi_2}}$$

sub V_{π_1} & V_{π_2} in I_o

$$\therefore I_o = g_{m_2}(I_i r_{\pi_2} + I_i \beta_1 r_{\pi_2}) + g_{m_1} I_i r_{\pi_1}$$

$$= I_i g_{m_2} r_{\pi_2} + I_i \beta_1 g_{m_2} r_{\pi_2} + I_i g_{m_1} r_{\pi_1}$$

$$= I_i [\beta_2 + \beta_1 \beta_2 + \beta_1]$$

$$\boxed{A_i = \frac{I_o}{I_i} = \beta_1 + \beta_2 + \beta_1 \beta_2}$$

$$\therefore \boxed{A_i = \beta_1 \beta_2}$$

The overall current gain of a darlington pair is the product of individual current gains

Input Resistance R_i

$$R_i = \frac{V_i}{I_i}$$

$$V_i = V_{\pi_1} + V_{\pi_2}.$$

$$\boxed{V_{\pi_1} = I_i r_{\pi_1}}$$

$$V_{\pi_2} = (I_i + g_{m_1} V_{\pi_1}) r_{\pi_2}$$

$$= (I_i + g_{m_1} I_i r_{\pi_1}) r_{\pi_2}$$

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

$$= I_i (1 + \beta_1) r_{\pi_2}$$

$$\boxed{\therefore V_{\pi_2} = I_i (1+\beta) r_{\pi_2}}$$

Sub V_{π_1} & V_{π_2} in V_i

$$\therefore V_i = I_i r_{\pi_1} + I_i (1+\beta_1) r_{\pi_2}$$

$$= I_i \left(r_{\pi_1} + [1 + \beta_1] r_{\pi_2} \right)$$

$$\boxed{R_i = \frac{V_i}{I_i} = \left[r_{\pi_1} + (1+\beta_1) r_{\pi_2} \right]}$$

$$r_{\pi_1} = \frac{\beta_1}{g_{m_1}} = \frac{\beta V_T}{I_{CQ_1}}$$

Let $I_{CQ_1} = \frac{I_{CQ_2}}{\beta_2}$

$$r_\pi = \frac{\beta_1 V_T}{I_{CQ2}} \cdot \beta_2$$

$$r_\pi = \beta_1 r_{\pi_2}$$

$$R_i = \beta_1 r_{\pi_2} + (1+\beta_1) r_{\pi_2}$$

$$\boxed{R_i \simeq 2\beta_1 r_{\pi_2}}$$

The i/p resistance of darlington pair is large because of β multiplications

Cascode Amplifier

It has a CE stage in series with a CB amplfr

Q_1 - CE ; Q_2 - CB.

Features :-

It provides high I/p impedance.

High voltage gain

Improved I/p - O/p isolation as there is no direct coupling from O/p to I/p. This eliminates miller effect and thus provides much BW.

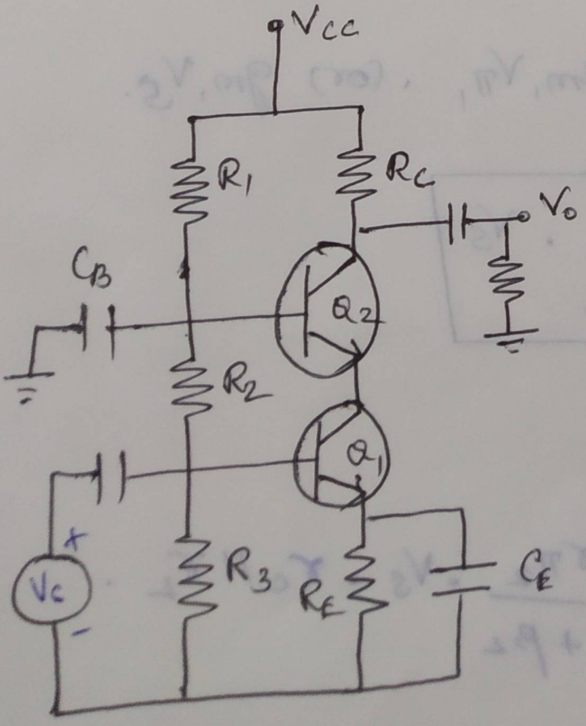
high O/p resistance

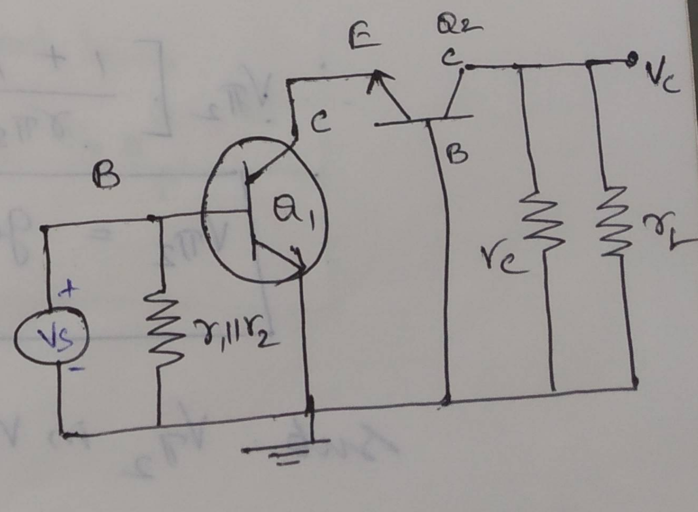
high slew rate & stability

Disadvantages.

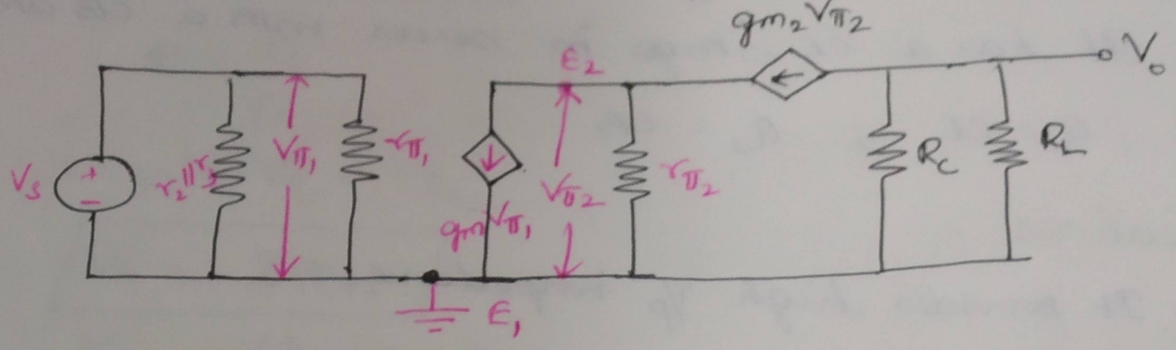
high supply voltage is required &

need for 2 transistors.





AC equivalent circuit diagram.



To find voltage gain A_v

$A_v = \frac{V_o}{V_s}$; $V_o = -g_{m_2} V_{\pi_2} (r_C \| r_L)$

~~$V_s =$~~ ; $V_s = V_{\pi_1}$

apply KCL to E_2

$$g_{m_2}V_{\pi_2} + \frac{V_{\pi_2}}{r_{\pi_2}} = g_{m_1}V_{\pi_1} = g_{m_1}V_s$$

$$\therefore V_{\pi_2} \left[g_{m_2} + \frac{1}{r_{\pi_2}} \right] = g_{m_1}V_{\pi_1} = g_{m_1}V_s$$

$$\therefore V_{\pi_2} \left[\frac{1+\beta_2}{r_{\pi_2}} \right] = g_{m_1}V_{\pi_1} \text{ (or) } g_{m_1}V_s$$

$$\boxed{V_{\pi_2} = g_{m_1} \cdot \frac{r_{\pi_2}}{1+\beta_2} \cdot V_s}$$

Sub. V_{π_2} in V_o

$$V_o = -g_{m_2} \cdot g_{m_1} \cdot \frac{r_{\pi_2}}{1+\beta_2} \cdot V_s \cdot r_C \| r_L .$$

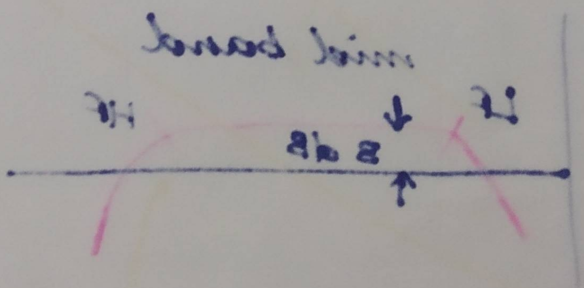
$$\therefore A_v = \frac{v_o}{v_s} = -g_{m1} g_{m2} \cdot \frac{r_{\pi 2}}{1+\beta_2} (r_c \| r_L)$$

$$= -g_{m1} \left(g_{m2} \cdot \frac{r_{\pi 2}}{1+\beta_2} \right) (r_c \| r_L)$$

$$\boxed{A_v = \frac{v_o}{v_s} = -g_{m1} \cdot \frac{\beta_2}{1+\beta_2} (r_c \| r_L)}$$

$$\left[\because \beta_2 / \beta_2 + 1 \cong 1 \right]$$

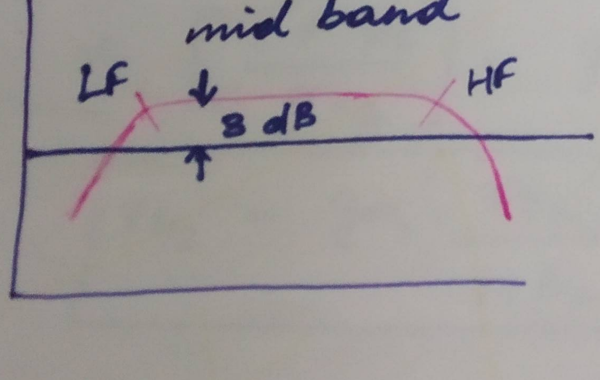
$$A_v = -g_{m1} (r_c \| r_L)$$



Frequency Response analysis of Basic BJT CE amplifier

Amplifier frequence response.

* All amplifier gain factors are functions of signal frequency.
* we have assumed that the signal frequency is high enough such that, coupling and bypass capacitors can be treated as short circuit and at the same time signal frequency is low enough such that the transistor capacitors and stray capacitors are open circuit



Three ranges of frequency

1) Low frequency range :- ($f < f_L$)

The gain decreases as frequency decreases, because of coupling and bypass capacitors effects.

2) High frequency range :- ($f > f_H$)

Stray capacitance and transistor capacitance effects cause gain to decrease as the frequency increases.

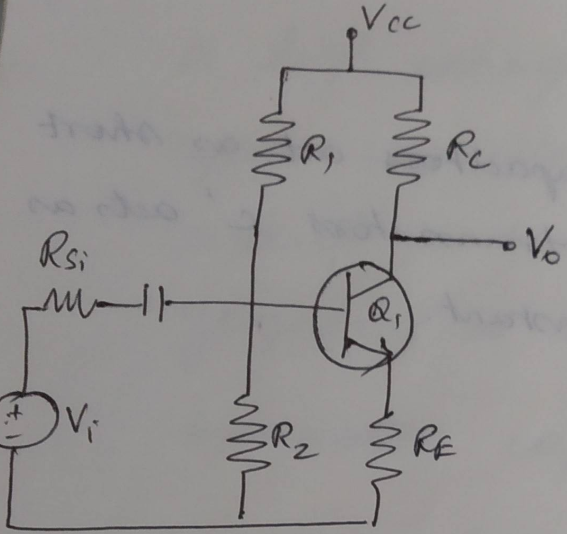
3) Midband range :-

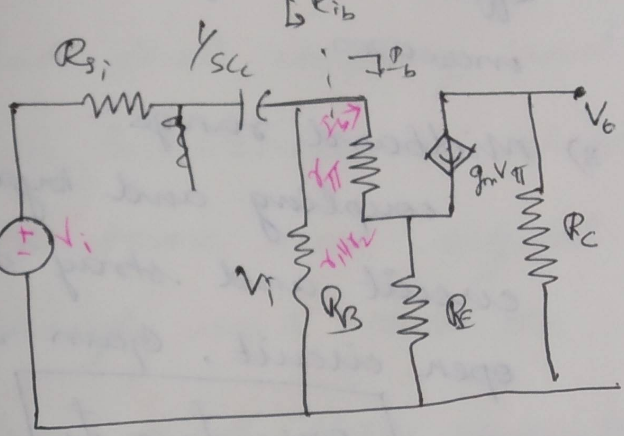
coupling and bypass capacitors act as short circuit and stray and transistors 'c' acts as open circuit, Gain is constant.

$$\boxed{BW = f_H - f_L}$$

Frequency response: Transistor amplifier with capacitor circuit.

- coupling
- bypass
+ load capacitor @ high frequencies.





To determine the transfer $R_B = R_1 \| R_2$

To find $A_v(s)$

$$A_v(s) = \frac{V_o(s)}{V_i(s)}$$

$$\boxed{V_o(s) = -g_m V_\pi R_C}$$

$$V_\pi = I_b r_\pi$$

from i/p circuit

$$R_i = R_1 \| R_2 \| R_{ib}$$

$$R_{ib} = \frac{V_{i_1}}{I_b} \Rightarrow V_{i_1} = V_\pi + (I_b + g_m V_\pi) R_E$$

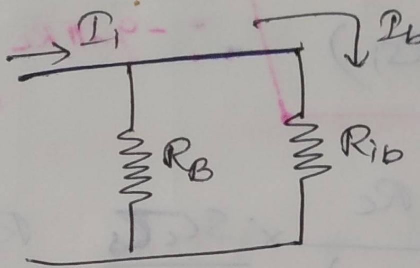
$$= I_b r_\pi + (I_b + g_m I_b r_\pi) R_E$$

$$= I_b \left[r_\pi + (1+\beta) R_E \right]$$

$$\boxed{\therefore \frac{V_{i_1}}{I_b} = r_\pi + (1+\beta) R_E}$$

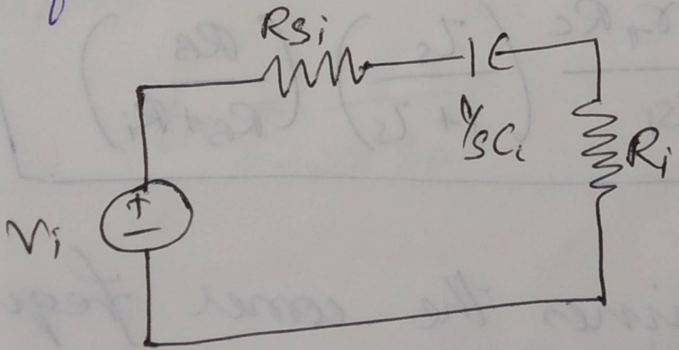
$$\therefore R_i = R_1 \parallel R_2 \parallel r_\pi + (1+\beta) R_E$$

To find I_b in terms of I_i



$$I_b = I_i \times \frac{R_B}{R_B + R_{ib}}$$

To find I_i in terms of V_i



$$V_i = I_i R_{si} + \frac{I_i}{sC_c} + I_i R_i$$

$$= I_i \left[R_{si} + \frac{1}{sC_c} + R_i \right]$$

$$\boxed{\therefore I_i = \frac{V_i}{R_{si} + R_i + \frac{1}{sC_c}}}$$

sub ~~V_π~~ in V_o.

$$\therefore V_o = -g_m R_C I_b r_\pi$$

sub I_b in V_o

$$\therefore V_o = -g_m R_C \cdot I_i \frac{R_B}{R_B + R_{ib}} \cdot r_\pi$$

sub I_i in V_o .,

$$\therefore V_o = -g_m R_c \cdot \frac{V_i}{(R_{si} + R_i) + \frac{1}{SC_c}} \cdot \frac{R_B}{R_B + R_{iB}} \cdot r_\pi$$

$$= -g_m R_C \cdot r_\pi \cdot \frac{V_i\,(SC_c)}{1 + SC_c\,(R_{si} + R_i)} \cdot \frac{R_B}{R_B + R_{ib}}$$

$f = \frac{1}{2\pi RC}$

$= \frac{1}{2\pi (R_s + R_{si}) C_c}$

$\tau = 2\pi (R_s + R_{si}) C_c$

$$A_{V_{i}} = \frac{V_o}{V_i} = -g_m r_\pi R_c \cdot \frac{SC_c}{1 + SC_c\,(R_{si} + R_i)} \cdot \frac{R_B}{R_B + R_{ib}}.$$

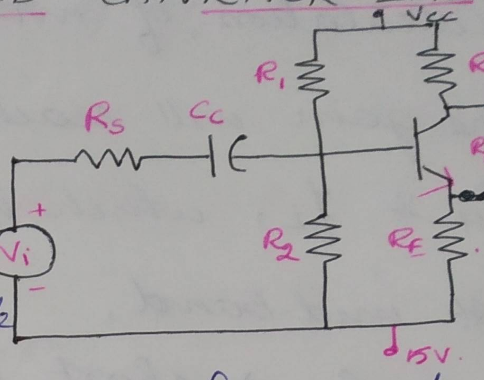
Let $\boxed{\tau_s = SC_c\,(R_i + R_{si})}$ $\therefore -g_m \pi R_c \cdot \frac{SC_c}{1 + \tau_s} \cdot \frac{R_B}{R_B + R_i}$

$$A_V = \frac{V_o}{V_i} = \frac{-g_m \pi R_c}{C_c(R_i + R_{si})} \times \frac{SC_c \tau_s}{1 + \tau_s} \cdot \frac{R_B}{R_B + R_i}$$

$$\boxed{\therefore A_{V_s} = \frac{-g_m r_\pi R_c}{R_i + R_{si}} \left(\frac{\tau_s}{1 + \tau_s}\right)\left(\frac{R_B}{R_B + R_i}\right)}$$

$\tau_s \rightarrow$ determines the corner frequency.

COUPLING & LOAD CAPACITOR EFFECT



The values of the coupling & load capacitances differ by orders of magnitude

- The corner frequencies are far apart and can be treated seperately.

Lower order frequency

$$f_L = \frac{1}{2\pi \tau_s}$$

τ_s → time constant associated with coupling capacitor.

f_L → lower corner frequency

$$\tau_s = (R_S + R_1 \| R_2 \| R_i)\, C_s$$

Upper corner frequency

$$f_H = \frac{1}{2\pi \tau_p}$$

τ_p → time constant associated with load capacitor.

f_H → upper corner frequency

$$\tau_p = (R_C \| R_L)\, C_L$$

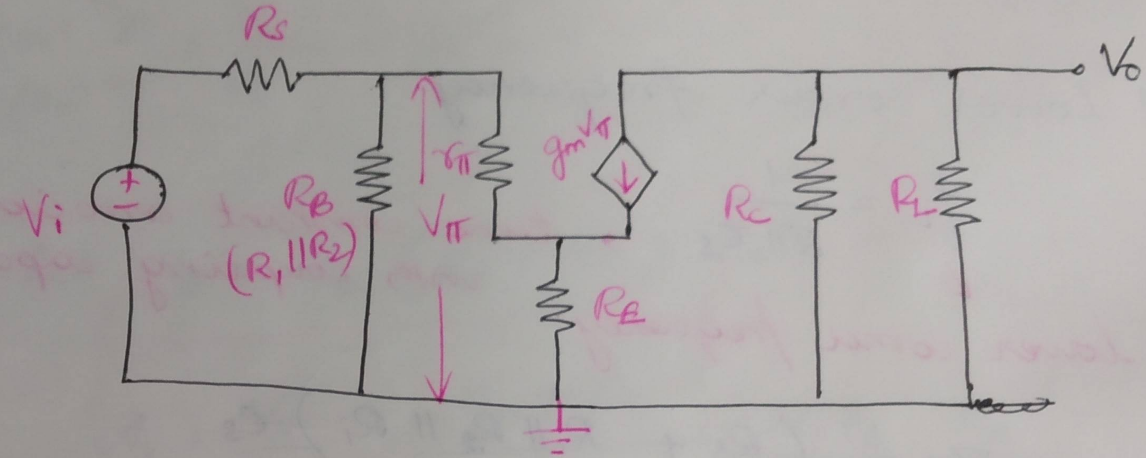
Calculation of midband gain

The gain will reach maximum between f_H & f_L, which is the mid-band.

- At mid-band,

  $C_C \rightarrow$ short circuited

  $C_L \rightarrow$ open circuited



Midband gain $A_v = \frac{V_0}{V_i}$

$$V_0 = -g_m V_\pi \cdot (R_C \| R_L)$$

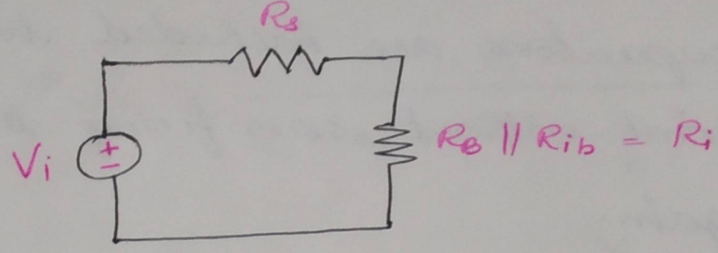
$$= -g_m \cdot I_b r_\pi \cdot (R_C \| R_L)$$

$$I_b = \frac{I_i \times R_B}{R_B + R_{ib}}$$

$$R_{ib} = r_\pi + (1+\beta) R_E$$

$$\therefore V_0 = -g_m \cdot r_\pi (R_C \| R_L) \cdot I_i \cdot \frac{R_B}{R_B + R_{ib}}$$

- To find I_i in terms of V_i



$$\therefore V_i = I_i (R_s + R_i)$$

$$\boxed{I_i = \frac{V_i}{R_s + R_i}}$$

sub in V_o.

$$\therefore V_o = -g_m \cdot r_\pi (R_C \parallel R_L) \cdot \frac{V_i}{R_s + R_i} \cdot \frac{R_B}{R_B + R_{ib}}.$$

$$\therefore \frac{V_o}{V_i} = -g_m r_\pi (R_C \parallel R_L) \cdot \frac{1}{R_s + R_i} \cdot \frac{R_B}{R_B + R_{ib}}.$$

$$\boxed{|A_V| = \left|\frac{V_o}{V_i}\right| = g_m r_\pi (R_C \parallel R_L) \cdot \frac{1}{R_s + R_i} \cdot \frac{R_B}{R_B + R_{ib}}.}$$

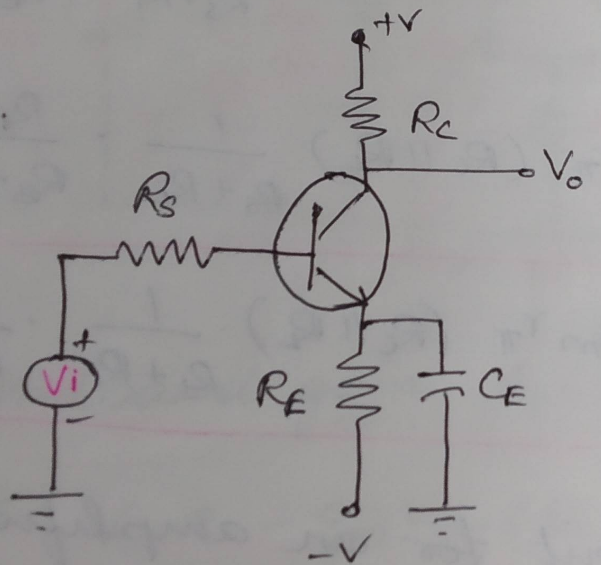
- A figure of merit for an amplifier is the gain - BW product. Assuming the corner frequencies far apart, BW is

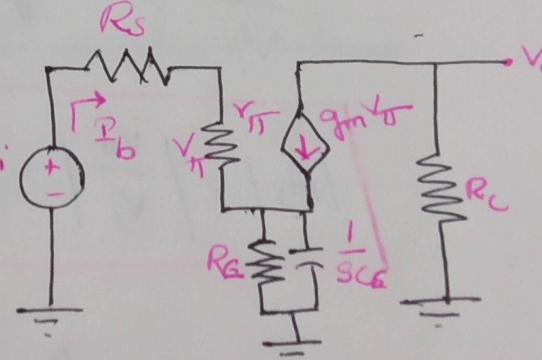
$$f_{BW} = f_H - f_L \approx f_H.$$

$$G_B = |A_V|_{max} \cdot f_H.$$

BYPASS CAPACITOR EFFECT.

- Bypass capacitors are included to stabilize the Q point without sacrificing the small signal gain.
- To choose a bypass capacitor we must determine the circuit response in the frequency range where these capacitors neither open nor short circuit.





The transfer function

$$A_v = \frac{V_o(s)}{V_i(s)}$$

$$V_o = -g_m V_\pi (R_C)$$

$$= -g_m I_b r_\pi R_C \qquad V_\pi = I_b \cdot r_\pi$$

$$V_i = I_b \left[R_s + r_\pi + \left(R_E \parallel \frac{1}{SC_E} \right) (1+\beta) \right]$$

$$\Rightarrow I_b = \frac{V_i}{R_s + r_\pi + \left(R_E \parallel \frac{1}{SC_E} \right)(1+\beta)}$$

$$\therefore V_o = -g_m \cdot r_\pi \cdot R_C \cdot \frac{V_i}{R_s + r_\pi + \left(R_E \parallel \frac{1}{SC_E} \right)(1+\beta)}$$

$$\therefore \frac{V_o}{V_i} = -g_m \cdot r_\pi \cdot R_C \cdot \frac{1}{R_s + r_\pi + \left\{ \frac{R_E \cdot \frac{1}{SC_E}}{R_E + \frac{1}{SC_E}} \right\}(1+\beta)}$$

$$= -g_m \cdot r_\pi \cdot R_C \cdot \frac{1}{R_s + r_\pi + \left\{ \frac{R_E \cdot \frac{1}{\cancel{SC_E}}}{\frac{SC_E R_E + 1}{\cancel{SC_E}}} \right\}(1+\beta)}$$

$$= -g_m \cdot r_\pi \cdot R_C \cdot \frac{1}{R_s + r_\pi + \left\{ \frac{R_E}{R_E SC_E + 1} \right\}(1+\beta)}$$

$$= \frac{-g_m \cdot r_\pi \cdot R_C \cdot (1 + SC_E R_E)}{R_s (1 + SC_E R_E) + r_\pi (1 + SC_E R_E) + R_E (1+\beta)}$$

$$= \frac{-g_m \cdot r_\pi \cdot R_C \cdot (1 + SC_E R_E)}{R_s + R_s SC_E R_E + r_\pi + r_\pi SC_E R_E + R_E (1+\beta)}$$

$$= \frac{-g_m \cdot r_\pi \cdot R_C \cdot (1 + SC_E R_E)}{R_s + r_\pi + R_E (1+\beta) + SC_E R_E (R_s + r_\pi)}$$

@ $\omega = 0$, C_E is open circuited, hence, this eqn straight away goes to the final eqn directly

Taking $R_s + r_\pi + (1+\beta) R_E$ out, in Dr.

$$\therefore \frac{V_o}{V_i} = \frac{-g_m \cdot r_\pi \cdot R_C \ (1 + sC_E R_E)}{R_s + r_\pi + (1+\beta) R_E \left[1 + \frac{sC_E R_E (R_s + r_\pi)}{R_s + r_\pi + (1+\beta) R_E} \right]}$$

$$\therefore A_v = \frac{-g_m \cdot r_\pi \cdot R_C \cdot (1 + \tau_A)}{R_s + r_\pi + (1+\beta) R_E \ (1 + \tau_B)}$$

where $\tau_A = sC_E R_E$

$$\tau_B = \frac{sC_E R_E \ (R_s + r_\pi)}{R_s + r_\pi + (1+\beta) R_E}$$

At $w = 0$, C_E is open circuit.

$$\boxed{\therefore |A_v|_{w=0} = \frac{g_m \cdot r_\pi \cdot R_C}{R_s + r_\pi + (1+\beta) R_E}}$$

At $w = \infty$, C_E is short circuited.

$$\boxed{\therefore |A_v|_{w=\infty} = \frac{g_m \cdot r_\pi \cdot R_C}{R_s + r_\pi}}$$

R_E is short circuited by C_E.

corner frequencies

$f_A = 1/2\pi\tau_A$

$f_B = 1/2\pi\tau_B$