UNIT - II

MULTISTAGE AMPLIFIER

For faithful amplification amplifier should have desired voltage gain, current gain and it should match its input impedence with source and output impedence with load. Many times these primary requirement of the amplifier cannot be acheived with single stage amplifier due to the limitation of transistor/FET.

So, In order to avoid and to match the impedences we use Multistage Amplifier.

Multistage Amplifier:-

Connection of 'n' number of amplifier is called multistage amplifier.

This is used for large applications

Methods for Inter stage coupling:-

There are three types of coupling available for developing multistage amplifiers.

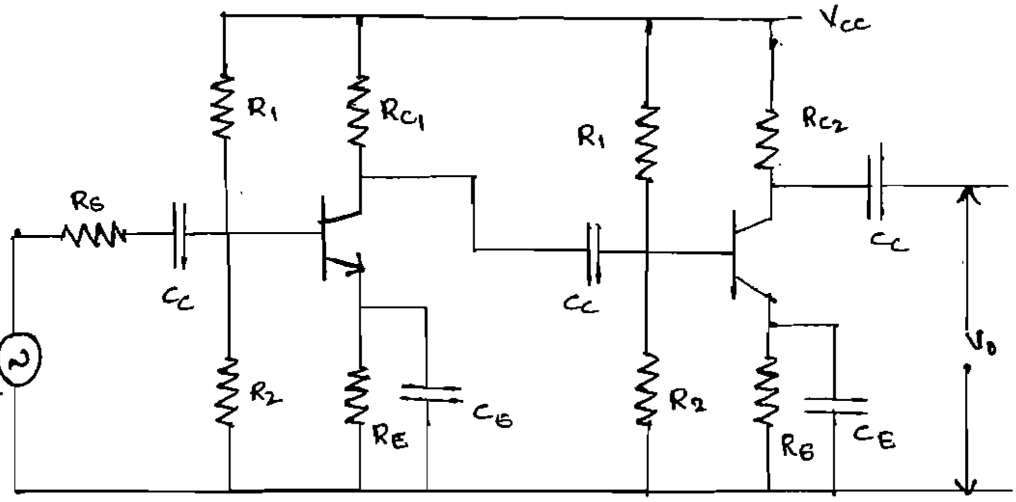
i, RC coupling

ii, Transfer coupling

iii, Direct coupling

RC coupling:-

RC coupled using transistors is shown. The output signal of first stage is coupled to the input of the next stage through coupling capacitor and resistive load at the output terminal of first stage.



Operation:-

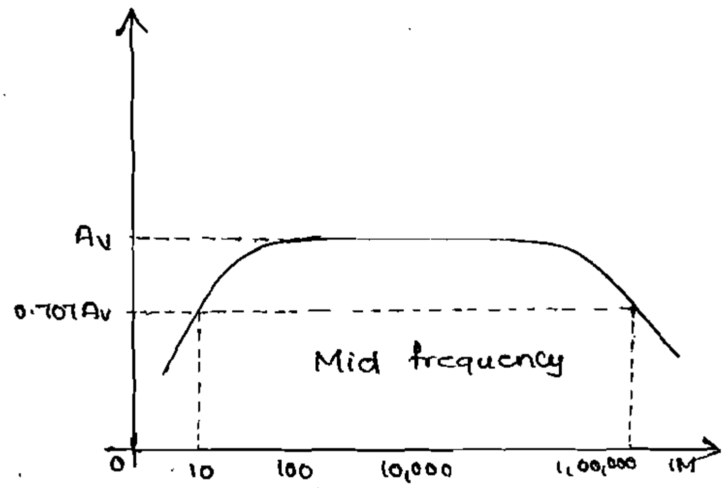
The coupling doesnot effect the quiescent point of the next stage since the coupling capacitor Cc blocks the dc voltage from reaching the base of the second stage. The RC network is broad band in nature. Therefor it gives a wind band frequency response without peak at any frequency.

Reactance of capacitance, $X_C = 1/2\pi fc$

The frequency response drops off at very low frequencies due to coupling capacitors, the gain also decreases. and also at high frequencies due to shunt capacitors such as stray capacitance

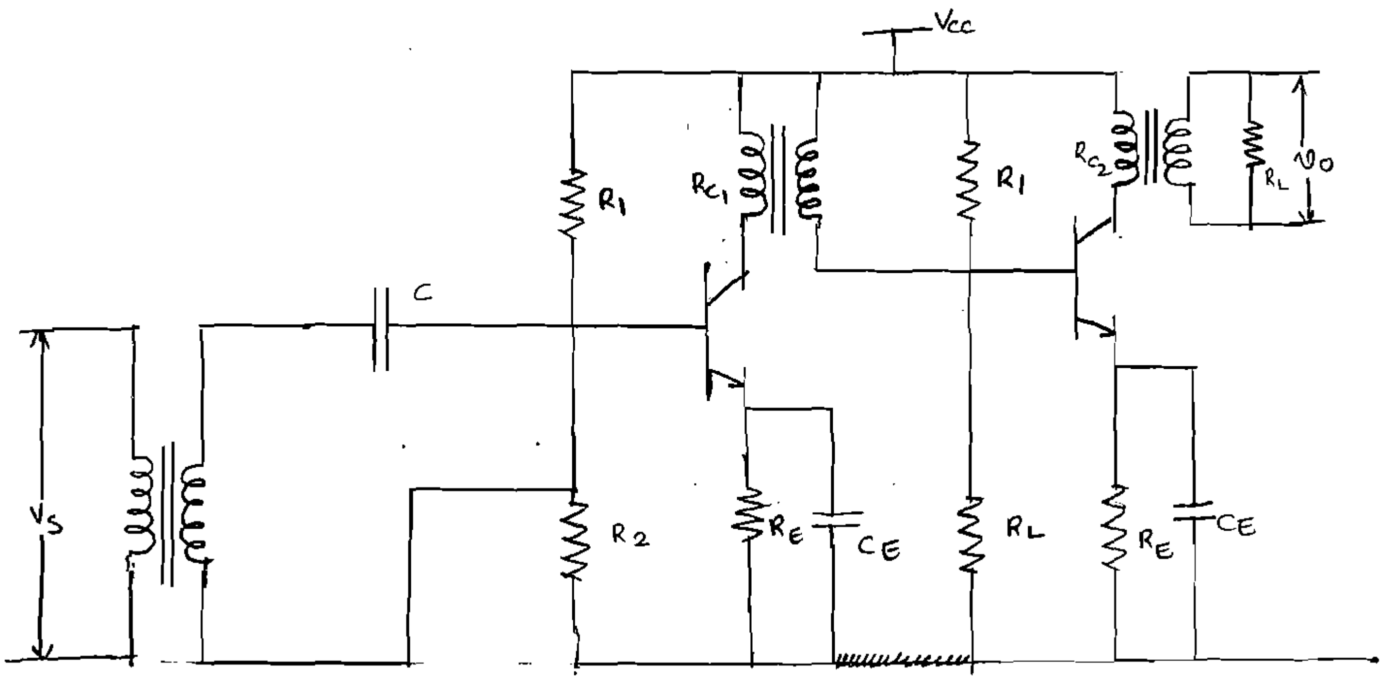
To have faithful amplification the operating point must be constant.

The frequency response of the RC coupled as shown below.



Transformer coupling:-

The output signal of first stage is coupled to the input of the next stage through an impedence matching transformer



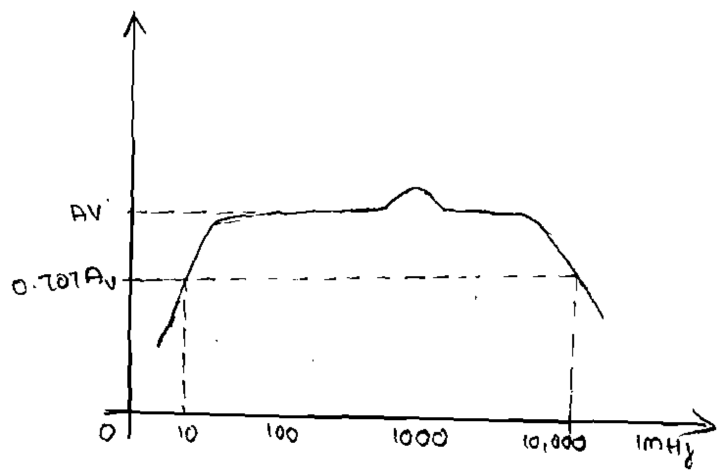
This type of coupling is used to match the impedence between output and input cascade stage. Usually, it is used to match the larger output resistance of AF power amplifier to a low impedence load.

As we know transformer blocks dc, providing dc isolation between the two stages. Therefore, transformer coupling does not effect the quiescent point of the next stage.

Frequency response of transformer coupled amplifier is poor in comparision with that of an RC coupled amplifier. Its lekage inductance and interwinding capacitances does not allow amplifier to amplify the signals at different frequencies equally well. Interwinding capacitance of the transformer coupled may give rise resonance at certain frequencie which makes amplifier to give very high gain at that frequency. By putting shunting capacitors across each winding of the transformer, we can get resonance at any desired RF frequency. Such amplifiers are called tuned voltage amplifier.

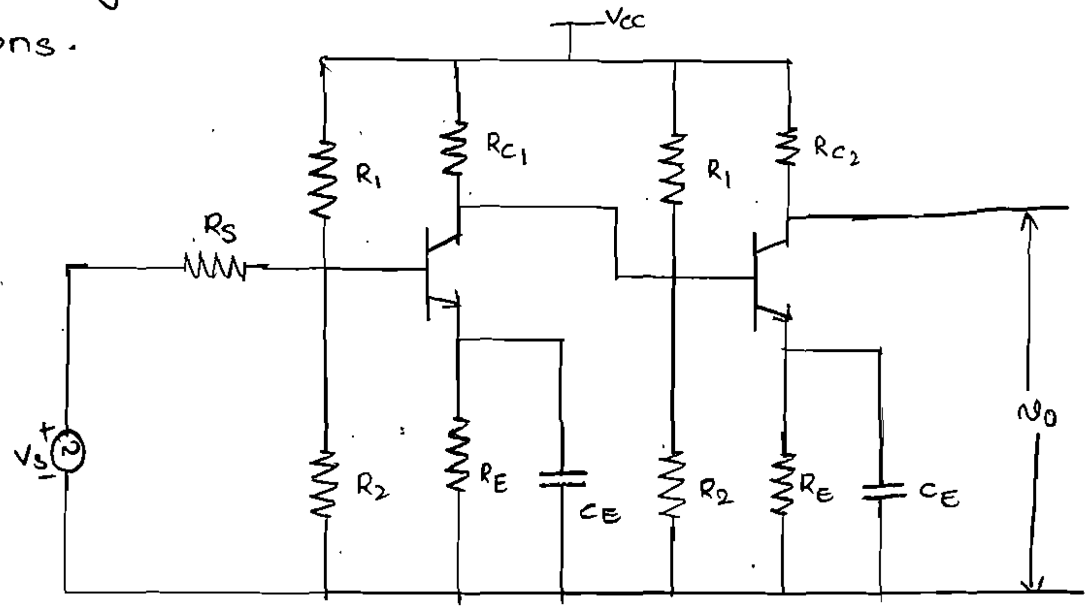
The transformer-coupled amplifiers are used in radio and TV receivers for amplying RF signals.

Frequency Response:-



Direct coupling:-

The output signal of the first stage is directly connected to the input of the next stage. This direct coupling allows the quiescent dc collector current of first stage to pass through base of the next stage, affecting its biasing conditions.



Due to the absence of RC components, its low frequency response is good but at higher frequencies shunting capacitors such as stray capacitances reduce the gain of the amplifier.

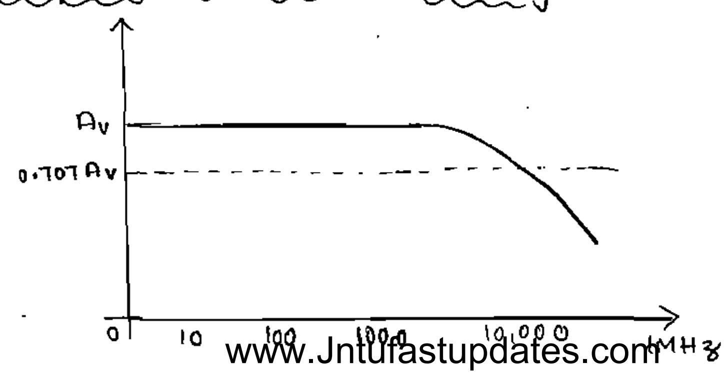
The transistor parameter such as V_{BE} and β change with temperature causing the collector current and voltage to change. Because of direct coupling these changes appear at the base of the base of the next stage and hence in the output. Such an unwanted change in the output is called drift and it is serious problem in the direct coupled amplifiers.

for frequency Response graph Turn back -------

comparision between various cascading methods :-

Parameters	RC coupled	Transformer coupled	Direct coupled.
coupling components	Resistor and capacitor	Impedance matching transformer	–
Block DC	Yes	Yes	No
frequency response	flat at middle frequencies	Not uniform, high at resonant frequency and low at other frequencies.	flat at middle frequencies and improvement in the low frequency response
Impedence matching	Not acheived	Acheived	Not acheived
DC amplification	No	No	Yes
weight	Light	Bulck and heavy	–
Drift	Not present	Not present	present
Application	used in all audio small signal amplifiers. Used in radio receivers, telephone receivers	Used in amplifier whose impedance matching is an imp criteria. Used in RF amplifier stage of the receiver as an tuned voltage amplifier	Used in amplification of slow varying parameters and where DC amplification is required.

frequency Response of direct coupling :-



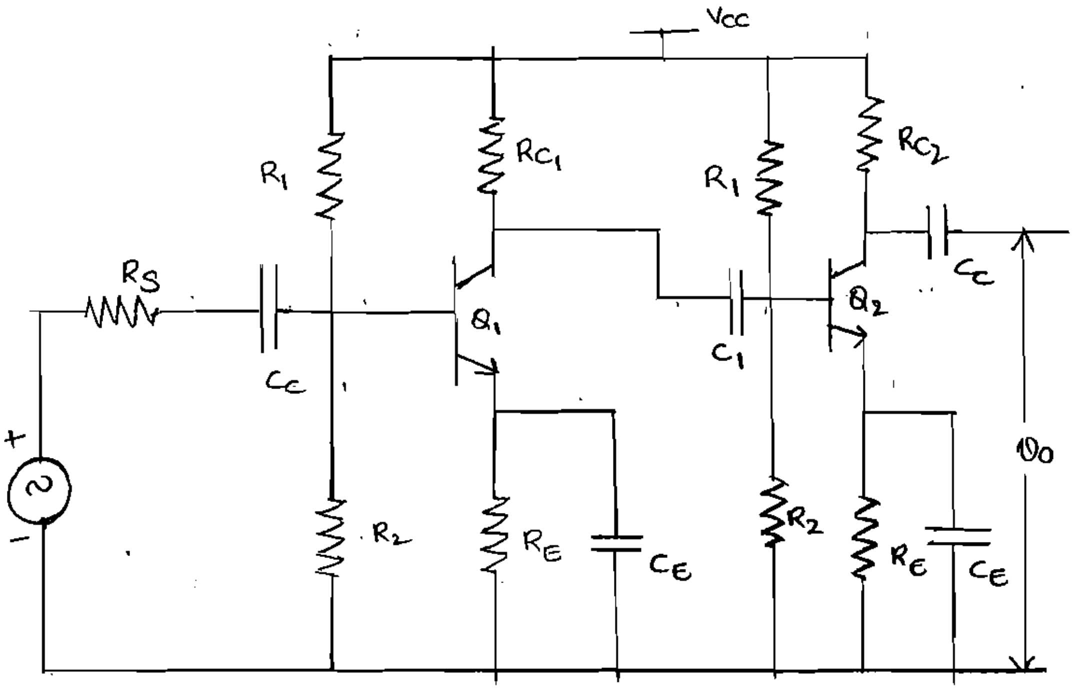
Formulae:- Exact Analysis:-

Parameter	Formulae
current gain, A_i	$\frac{-h_f}{1+h_oR_L}$
input impedence, Z_i	$h_i + h_r A_I R_L$
Voltage gain, A_V	$\frac{A_I R_L}{Z_i}$
voltage gain with source, A_{VS}	$A_V \cdot \frac{Z_i}{Z_i+R_S}$ (or) $A_V \cdot \frac{R_i}{R_i+R_S} = A_I \cdot \frac{R_L}{R_i+R_S} = \frac{A_{IS} \cdot R_L}{R_S}$
current gain with source, A_{IS}	$A_I \cdot \frac{R_S}{R_i+R_S}$
output admittance (Y_o)	$h_o - \frac{h_f h_r}{h_i + R_S}$.

Simplified (or) approximate analysis:-

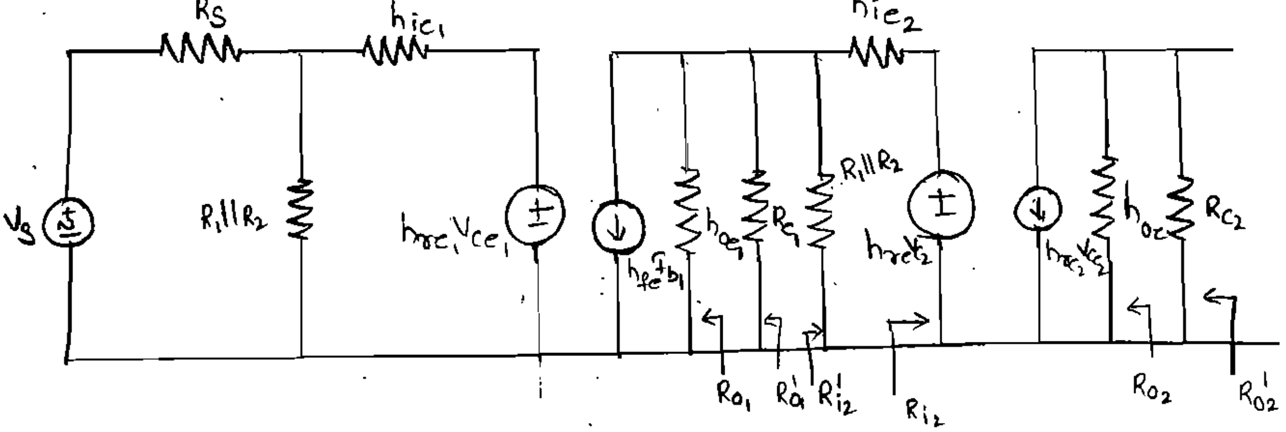
Parameter	CE	CC	CB
A_I	$-h_{fe}$	$1+h_{fe}$	$\frac{h_{fe}}{1+h_{fe}}$
R_i	h_{ie} when we use R_E, we have $R_i = h_{ie}+(1+h_{fe})R_E$	$h_{ie}+(1+h_{fe})R_L$	$\frac{h_{ie}}{1+h_{ie}}$
A_V	$A_I \cdot \frac{R_L}{R_i}$	$A_I \cdot \frac{R_L}{R_i}$	$h_{fe}\left[{R_L}/{h_{ie}}\right]$
R_O	∞	$\frac{R_S+h_{ie}}{1+h_{fe}}$	∞

Two stage RC coupled CE-CE cascade amplifier:-



Assuming all capacitors arbitarily large and act as a short circuit for ac signal we can draw h-parameter equivalent circuit for CE-CE cascade amplifier.

let us calculate R_i, A_I, A_V, R_i', A_{VS}, A_{IS} ... if circuit parameters are $R_S = 1K$, $R_{C_1} = 15K$, $R_{E_1} = 100\Omega$, $R_{C_2} = 4K$, $R_{E_2} = 330\Omega$ with $R_1 = 200k$, $R_2 = 20k$ for first stage and $R_1 = 47k$, $R_2 = 4.7k$ for 2nd stage assume that $h_{ie} = 1.2\,k\Omega$, $h_{fe} = 50$, $h_{re} = 2.5 \times 10^{-4}$ and $h_{oe} = 25 \times 10^{-6}$ A/V.



Analysis of second stage:- $h_{oe}R_L$

where $R_L = R_{C_2}$

$\Rightarrow h_{oe}R_{C_2} = (25 \times 10^{6})(4K)$

$= 0.1$

we can use approximate analysis

a) current gain (A_{I_2}):-

$$A_{I_2} = -h_{fe} = -50$$

b) Input resistance (R_{i_2}):-

$$R_{i_2} = h_{ie} = 1.2\,k\Omega$$

c) Voltage gain (A_{V_2}):- $A_{V_2} = A_I \left(\frac{R_L}{R_{i_2}}\right)$ ~~where $R_{i_2} = R_1 \| R_2$~~

where $R_L = R_{C_2}$

$$= A_I \left(\frac{R_{C_2}}{R_{i_2}}\right) = -50\left[\frac{4 \times 10^3}{1.2 \times 10^3}\right]$$

$$= -166.67$$

Analysis of first stage:-

$h_{oe} \cdot R_L'$

where $R_L' = R_{C_1} \| R_1 \| R_2 \| R_{i_2} = 880.8\,\Omega$

$$h_{oe} \cdot R_L' = 1/40 \times 10^{-3} \times 880.8 = 0.083$$

As $h_{oe} \cdot R_L' < 0.1$ we can use approximate analysis.

a) current gain (A_{I_1}):-

$$A_{I_1} = -h_{fe} = -50$$

b) Input resistance (R_{i_1}):- $R_{i_1} = h_{ie} = 1.2\,K\Omega$

c) Voltage gain (A_{V_1}):- $A_{V_1} = A_{I_1} \cdot \frac{R_{L_1}}{R_{i_1}}$

where $R_{L1} = R_{i2} = 21.56\,\Omega$

$$A_{V1} = -50 \times \frac{21.5}{1.1k}$$

$$= -36.74$$

overall gain (A_V):-

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

$$= (-166.67) \times (-36.74) = 6123.45$$

overall voltage gain $(A_{VS}) \Rightarrow A_{VS} = \dfrac{A_V \times R'_{i1}}{R'_{i1} + R_s}$

$$R'_{i1} = R_1 \| R_2 \| R_{i1} = 200k \| 20k \| 1.2k = 1.13k$$

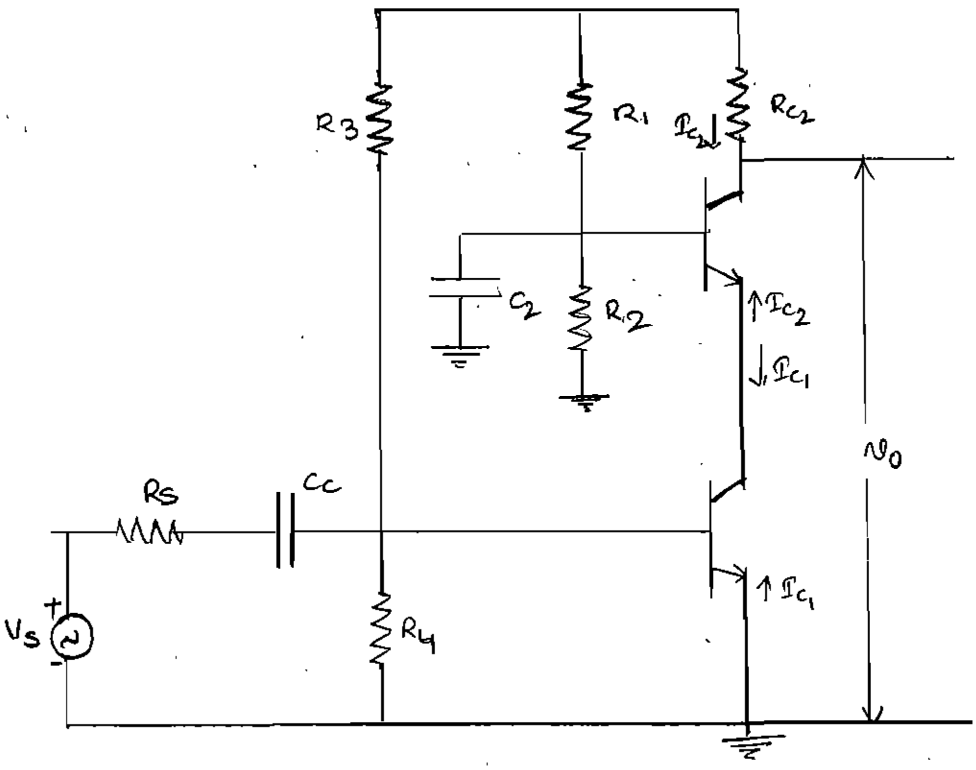
$$A_{VS} = \frac{6123.45 \times 1.13 \times 10^3}{1.13 \times 10^3 + 1 \times 10^3} = 3248.6$$

output resistance (R_0):- $R'_{o1} = R_{o1} \| R_{C1} = \infty \| 15k = 15k$

$$R'_{o2} = R_{o2} \| R_{C2} = \infty \| 4k = 4k.$$

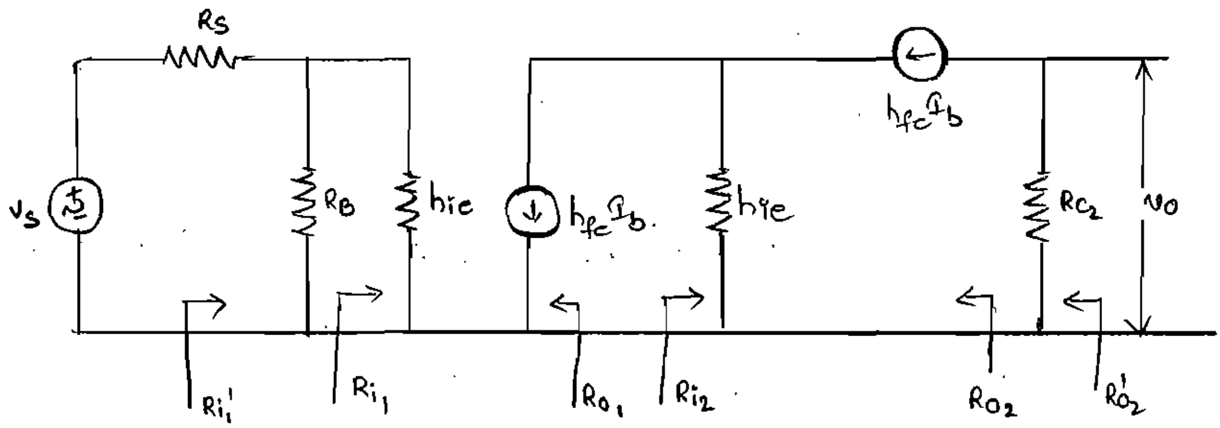
CE - CB cascode amplifier:-

The cascode amplifier consists of a common emitter amplifier stage in series with a common base amplifier stage. It is one approach to solve the low impedance problem of a common base circuit. Transistor, T_1 and its associated components ~~appear~~ operate as a common emitter amplifier stage, while the circuit of T_2 functions as a common base output stage. The cascode amplifier gives the high input impedance of a common emitter amplifier as well as good voltage gain and high frequency performance of a common base circuit.



The equivalent circuit for cascode amplifier. It is drawn by shorting dc supply and capacitors.

The simplified h-parameter equivalent circuits for cascode amplifier is drawn by replacing transistor with their simplified equivalent circuits are as shown below,



let us consider the circuit parameters are $R_s = 1K$, $R_3 = 200K$, $R_4 = 10K$ and $R_L = 3K$ and transistor parameters for both transistors are $h_{ie} = 1.1K$ and $h_{fe} = 50$.

for stage:-2

$$A_{I_2} = \frac{h_{fe}}{1+h_{fe}} = \frac{50}{1+50} = 0.98$$

b) Input Resistance (R_{i_2}):-

$$R_{i_2} = \frac{h_{ie}}{1+h_{fe}} = \frac{1.1K}{1+50} = 21.56\Omega$$

c) Voltage gain (A_{v_2}):-

$$A_{v_2} = \frac{A_{i_2} R_{L_2}}{R_{i_2}} = \frac{0.98 \times 3K}{21.56} = 136.3$$

For stage-1 analysis:-

a) current gain (A_{i_1}):-

$$A_{i_1} = -h_{fe} = -50$$

b) Input Resistance (R_{i_1}):-

$$R_{i_1} = h_{ie} = 1.1K$$

c) Voltage gain (A_{v_1}):-

$$A_{v_1} = \frac{A_{i_1} R_{L_1}}{R_{i_1}}$$ where, $R_{L_1} = R_{i_2} = 21.56\Omega$

$$= \frac{-50 \times 21.56}{1.1K} = -0.98$$

overall voltage gain, $A_V = A_{V_1} \times A_{V_2} = -0.98 \times 136.36 = -133.63$

Overall voltage gain (A_{vs}):-

$$A_{vs} = \frac{V_o}{V_s} = \frac{V_o}{V_i} \times \frac{V_i}{V_s} = A_V \cdot \frac{R_i}{R_i + R_s}$$

$$R_i = R_{i_1} \| R_B = R_{i_1} \| R_3 \| R_4 = 1.1k \| 200k \| 10k = 986.1\Omega$$

$$= 133.63 \cdot \frac{986.1}{986.1 + 1000} = -66.35$$

overall current gain, $A_I = A_{I_1} \times A_{I_2} = -49$

$$A_{Is} = A_I \cdot \frac{R_s}{R_s + R_i'} = -49 \times \frac{1 \times 10^3}{1 \times 10^3 + 986.1} = -24.67$$

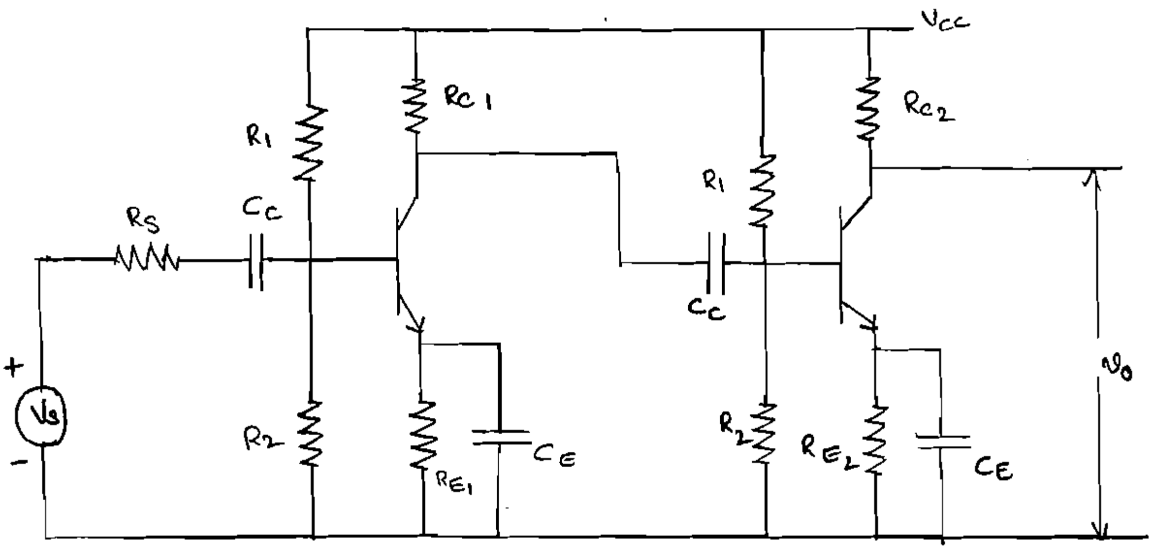
output resistance (R_o):-

$$R_{o1} = \infty, \quad R_{o2} = \infty.$$

$$R_o = R_{o2} \| R_L = \infty \| 3K = 3k.$$

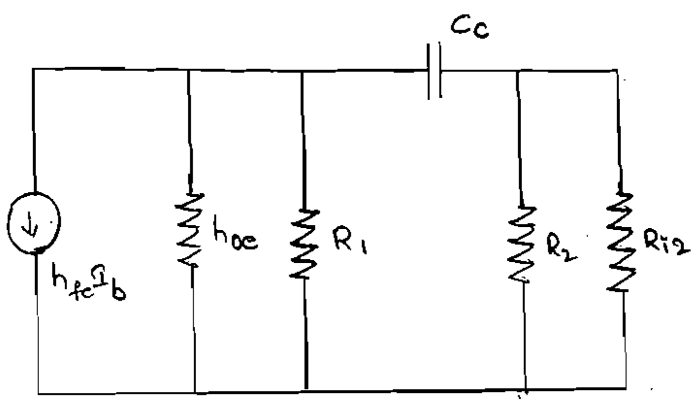
Two stage RC coupled Transistor Amplifier:-

let us consider a typical two RC coupled stage common emitter amplifier.

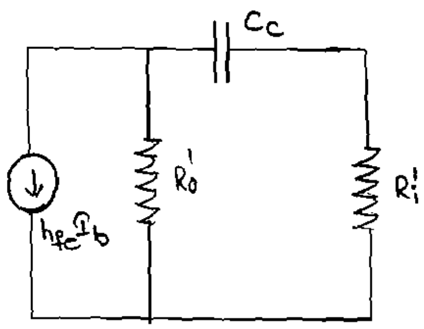


by using h-parameter we can obtain the equation for frequency response of RC coupling.

The figure shows the h-parameter equivalent circuit for output section of the first stage and the input section of the second stage.



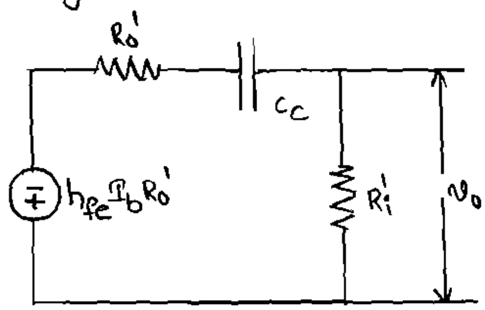
The above h-parameter equivalent circuit can be furthur simplied as below,



$$R_o' = 1/h_{oc} \parallel R_{c_1}$$

$$R_i' = R_1 \parallel R_2 \parallel R_{i2}$$

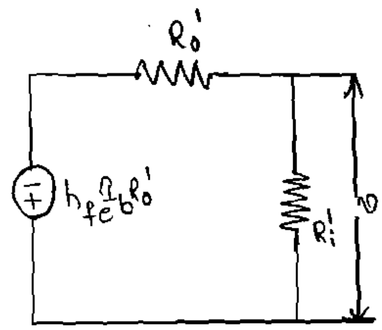
by converting current source into voltage sources.



Analysis by using coupling capacitors:-

At Mid frequencies:-

At mid frequencies coupling capacitors C_c acts as short circuit then the circuit is as shown.



Then the expression of $v_o = \dfrac{-h_{fe}I_b R_o' R_i'}{R_o' + R_i'}$

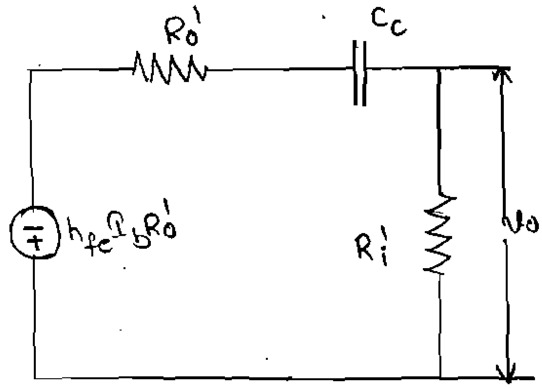
by dividing L.H.S & R.H.S with 'V_i'.

$$\frac{v_o}{v_i} = \frac{-h_{fe}I_b R_o' R_i'}{(R_o' + R_i')v_i}$$

$$A_{v(mid)} = \frac{-h_{fe}I_b R_o' R_i'}{R_o' + R_i'(V_i)} \quad \text{—— (1)}$$

At lower frequencies:-

At lower frequencies the reactance of the capacitance is given as $X_C = 1/j\omega C_C$, then the circuit converts into,



$$V_o = \frac{-h_{fe} I_b R_o' R_i'}{R_o' + X_C + R_i'}$$

$$= \frac{-h_{fe} I_b R_o' R_i'}{R_o' + R_i' + 1/j\omega C}$$

by dividing with 'V_i' on both sides

$$\frac{V_o}{V_i} = \frac{-h_{fe} I_b R_o' R_i'}{R_o' + R_i' + 1/j\omega C} \times 1/V_i$$

$$A_{V(low)} = \frac{-h_{fe} I_b R_o' R_i'}{R_o' + R_i' + 1/j\omega C} \times 1/V_i$$

divide with numerator and denominator with $R_o' + R_i'$.

$$A_{V(low)} = \frac{\dfrac{-h_{fe} I_b R_o' R_i'}{R_o' + R_i'}}{1 + \dfrac{1}{j\omega C(R_o' + R_i')}} \times 1/V_i$$

from equation ①

$$A_{v(low)} = \frac{A_{v(mid)}}{1+\frac{1}{j\omega C_c(R_o'+R_i')}}$$

$$\frac{A_{v(low)}}{A_{v(mid)}} = \frac{1}{1+\frac{1}{j\omega C_c(R_o'+R_i')}}$$

$$= \frac{1}{1-\frac{j}{\omega C_c(R_o'+R_i')}}$$

$$= \frac{1}{1-\frac{j}{2\pi f C_c(R_o'+R_i')}}$$

$$\frac{A_{v(low)}}{A_{v(mid)}} = \frac{1}{1-j(f_L/f)}$$

where $f_L = \frac{1}{2\pi C_c(R_o'+R_i')}$

by applying det on both sides.

$$\left|\frac{A_{v(low)}}{A_{v(mid)}}\right| = \frac{1}{\sqrt{1+(f_L/f)^2}}$$

if $f = f_L$ then $\left|\frac{A_{v(low)}}{A_{v(mid)}}\right| = 1/\sqrt{2}$

$= 0.707$

$= 70\%$

$$A_{v(low)} = \frac{A_{v(mid)}}{\sqrt{2}}$$

voltage at low frequency is equal to $1/\sqrt{2}$ times of voltage at mid frequencies

At high frequencies:-

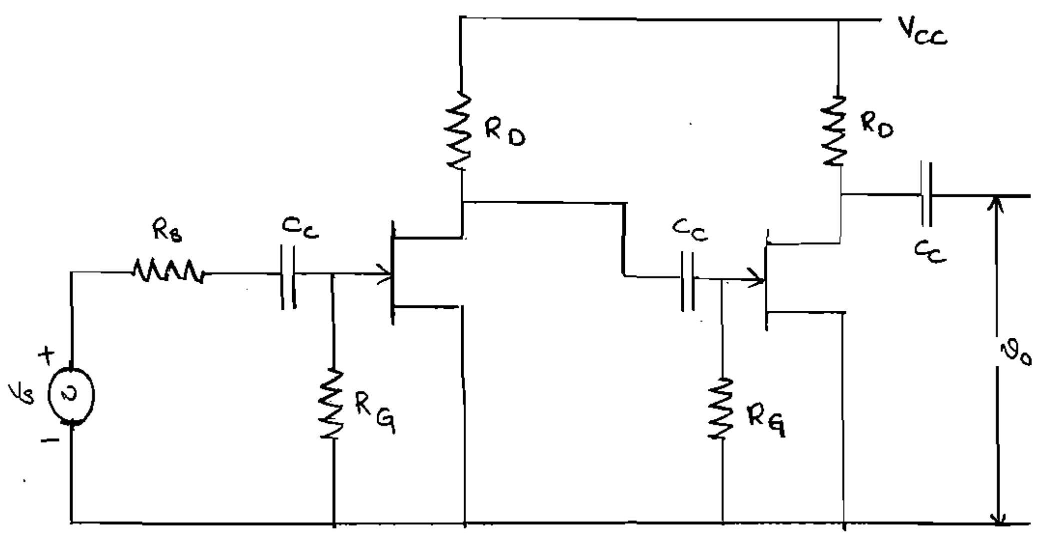
At high frequencies the frequency is generated by stray capacitance in the circuit. similar to the low frequencies.

$$\left|\frac{A_{v(high)}}{A_{v(mid)}}\right| = \frac{1}{\sqrt{1+(f/f_H)^2}}$$

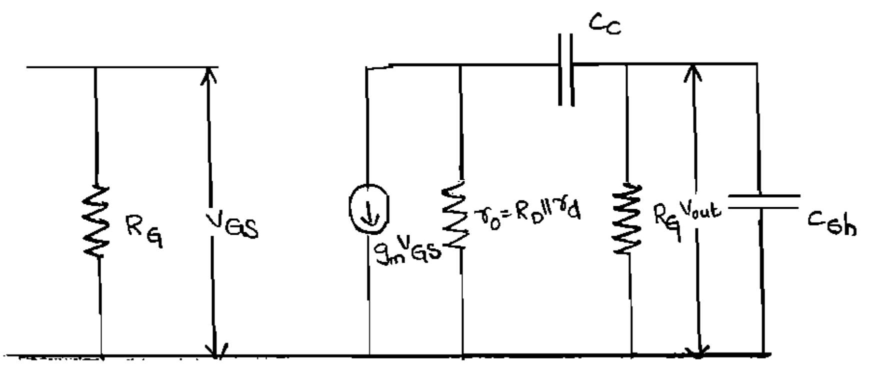
if $f = f_H$ $$\left|\frac{A_{v(high)}}{A_{v(mid)}}\right| = 1/\sqrt{2} = 0.707$$
$$= 70.7\%$$

Two stage RC coupled FET amplifier:-

Now by considering two stage RC coupled common source FET amplifier as shown in figure.



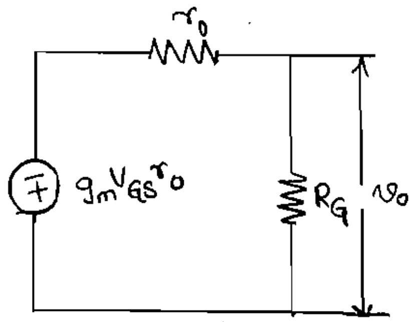
The equivalent circuit for FET amplifier is shown below.



Now we analyse the equivalent circuit for mid frequency, low frequency and high frequency.

At mid frequencies:—

The coupling capacitors acts like a short circuit and stray (or) shunt capacitance acts like a open circuit then the above circuit converts into,



The output voltage V_o is given by,

$$v_0 = \frac{-g_mV_{GS}r_0 \cdot R_G}{r_0 + R_G}$$

divide L.H.S and R.H.S with v_i

$$\frac{v_0}{v_i} = \frac{-g_mV_{GS}r_0 \cdot R_G}{r_0 + R_G} \times 1/v_i$$

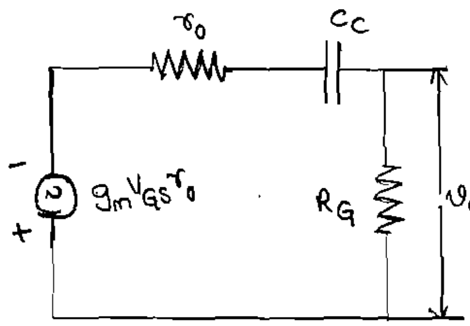
we know that $v_i = V_{GS}$

$$A_{v(mid)} = \frac{-g_m\cancel{V_{GS}}r_0 R_G}{r_0 + R_G} \times \frac{1}{\cancel{V_{GS}}}$$

$$A_{v(mid)} = \frac{-g_m r_0 R_G}{r_0 + R_G}$$

At low frequencies:-

at low frequencies the reactance of the coupling capacitor, $X_C = 1/j\omega C_C$ and stray capacitance acts like a open circuit. Then the circuit converts into



The output voltage $v_0 = \dfrac{-g_m V_{GS} r_0 \cdot R_G}{r_0 + 1/j\omega C_C + R_G}$

by dividing with v_i in L.H.S and R.H.S is

$$\frac{v_0}{v_i} = \frac{-g_m V_{GS} r_0 R_G}{r_0 + \frac{1}{j\omega C} + R_G} \times 1/v_i$$

where $v_i = V_{GS}$

$$A_{V(low)} = \frac{-g_m r_0 R_G}{r_0 + 1/j\omega C + R_G}$$

dividing numerator and denominator by $r_0 + R_G$.

$$A_{V(low)} = \frac{\dfrac{-g_m r_0 R_G}{r_0 + R_G}}{\dfrac{r_0 + 1/j\omega C + R_G}{r_0 + R_G}}$$

$$= \frac{\dfrac{-g_m r_0 R_G}{r_0 + R_G}}{1 + \dfrac{1}{j\omega C(r_0 + R_G)}}$$

$$\frac{A_{v(low)}}{A_{v(mid)}} = \frac{1}{1+\frac{1}{j\omega C_c(r_o+R_G)}}$$

$$= \frac{1}{1-\frac{j}{2\pi f C_c(r_o+R_G)}} = \frac{1}{1-j(f_L/f)}$$

where $f_L = \frac{1}{2\pi C_c(r_o+R_G)}$

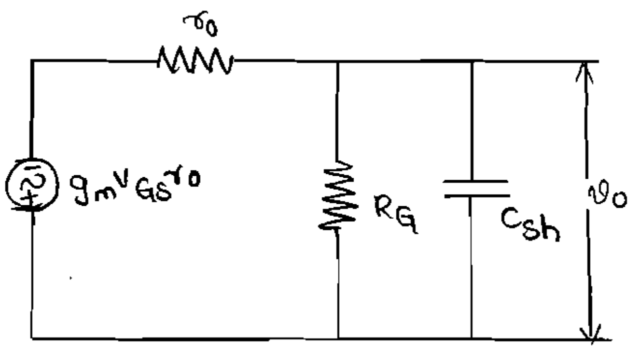
by applying det on both sides,

$$\left|\frac{A_{v(low)}}{A_{v(mid)}}\right| = \frac{1}{\sqrt{1+(f_L/f)^2}}$$

if $f_L = f$ then $\left|\frac{A_{v(low)}}{A_{v(mid)}}\right| = 1/\sqrt{2} = 0.707 = 70.7\%$

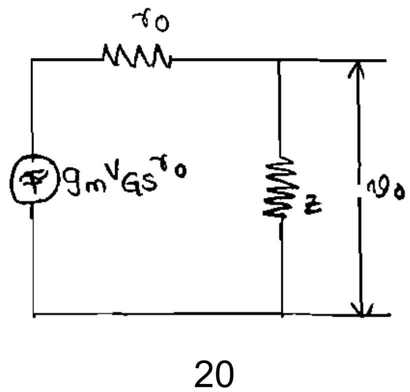
At high frequencies:-

at high frequencies the reactance of stray capacitance is $C_{sh} = \frac{1}{j\omega C_{sh}}$ then the circuit converts into,



when $Z = R_G \parallel X_{sh}$

then it can be converted into,



$$Z = \frac{R_G \times 1/j\omega C_{sh}}{R_G + \frac{1}{j\omega C_{sh}}} = \frac{R_G}{1+j\omega C_{sh} R_G}$$

$$\boxed{Z = \frac{R_G}{1+j\omega C_{sh} R_G}}$$

The output voltage, $V_0 = \frac{-g_m V_{GS} r_0 Z}{r_0 + Z}$

by dividing with 'v_i' on both sides,

$$\frac{v_0}{v_i} = \frac{-g_m r_0 V_{GS} Z}{r_0 + Z} \times \frac{1}{v_i}$$

where $v_i = V_{GS}$

$$A_{v(high)} = \frac{-g_m r_0 Z}{r_0 + Z}$$

by substituting 'z' value,

$$A_{v(high)} = \frac{-g_m r_0 \frac{R_G}{1+j\omega C_{sh} R_G}}{r_0 + R_G / 1+j\omega C_{sh} R_G}$$

$$= \frac{-g_m r_0 R_G}{r_0 + R_G + j\omega C_{sh} R_G R_0}$$

divide numerator and denominator with $R_0 + R_G$

$$= \frac{\frac{-g_m r_0 R_G}{r_0 + R_G}}{\frac{R_G + R_0 + j\omega C_{sh} R_G R_0}{r_0 + R_G}}$$

$$= \frac{1}{1 + \frac{j\omega C_{sh} R_G r_0}{r_0 + R_G}}$$

$$= \frac{1}{1+J\left(f/f_H\right)}$$

where $f_H = \frac{1}{\quad}$

$$\left|\frac{A_{V(high)}}{A_{V(mid)}}\right| = \frac{1}{\sqrt{1+\left(\frac{f}{f_H}\right)^2}}$$

if $f = f_H$

$= 1/\sqrt{2} = 0.707$.

High Input Resistance Transistor Amplifier:-

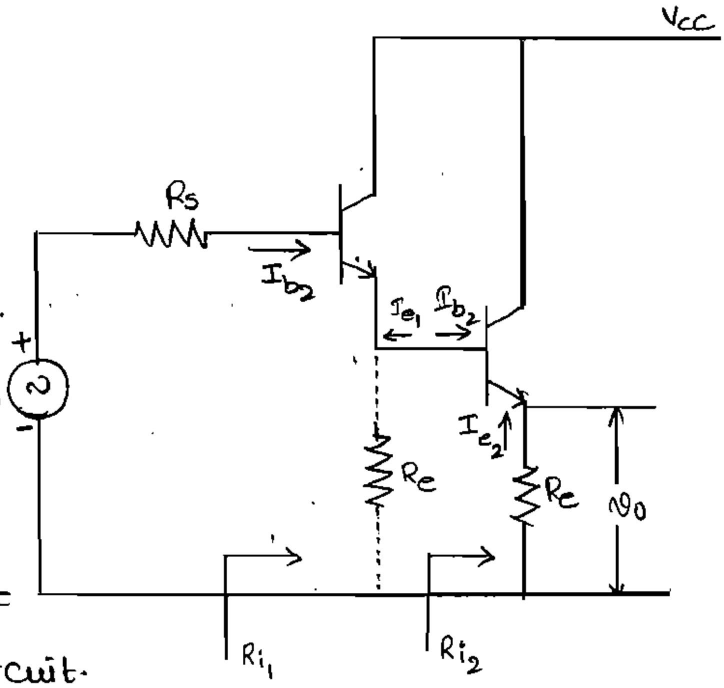
As the input impedance of common collector decreases due to R_1 and R_2 resistors. So, to increase the input impedance of emitter follower it can be improved by direct coupling of two stage of emitter follower amplifier. The input impedance can be increased using two techniques:-

i) Direct coupling (Darlington Pair)

ii) Bootstrap connection.

Direct Coupling (Darlington Pair):-

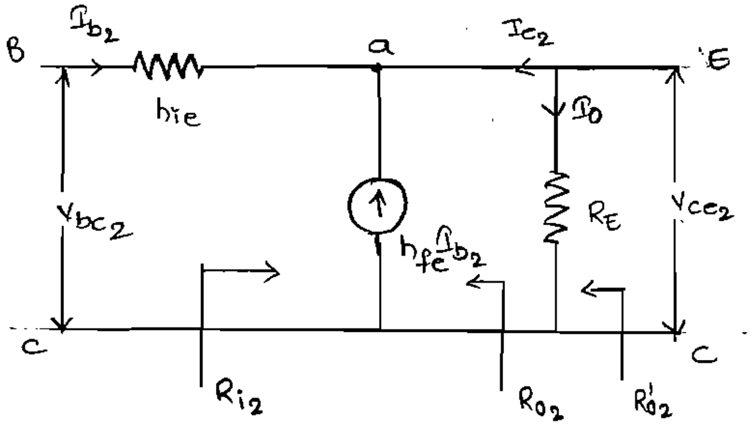
The direct coupling of two stages of emitter follower amplifier. The cascade connections of two emitter followers is called Darlington connection.



For stage:-2

Assuming the value of R_e is very less. so that $h_{oe}R_e < 0.1$. So, that we will go to approximate model.

Here we make collector common to have approximate h-parameter equivalent circuit.



current gain:-

$$A_{I_2} = \frac{I_0}{I_{o_2}} = \frac{-I_{e_2}}{I_{b_2}}$$

At node 'a',
$$I_{e_2} + I_{b_2} + h_{fe}I_{b_2} = 0$$

$$I_{e_2} = -I_{b_2}(1+h_{fe})$$

$$\boxed{A_{I_2} = 1 + h_{fe}}$$

Input impedence:-

$$R_{i_2} = \frac{V_{bc_2}}{I_{b_2}}$$

Apply KVL to the circuit.

$$V_{bc_2} = I_{b_2}h_{ie} + I_0 R_E$$

$$V_{bc_2} = I_{b_2} h_{ie} - I_{c_2} R_E \quad \text{where } I_b = -I_{c2}$$

$$V_{bc_2} = I_{b_2} h_{ie} + I_{b_2} (1 + h_{fe}) R_E$$

$$\boxed{R_{i_2} = h_{ie} + (1 + h_{fe}) R_E}$$

As h_{ie} is far less than $1+h_{fe}$ i.e $h_{ie} <<< 1+h_{fe}$ then,

$$\boxed{R_{i_2} = [1 + h_{fe}] R_E}$$

voltage gain:-

$$A_{V_2} = \frac{A_{I_2} \cdot R_e}{R_{i_2}}$$

$$1 - A_{V_2} = 1 - \frac{A_{I_2} \cdot R_c}{R_{i_2}}$$

$$= \frac{R_{i_2} - A_{I_2} \cdot R_e}{R_{i_2}}$$

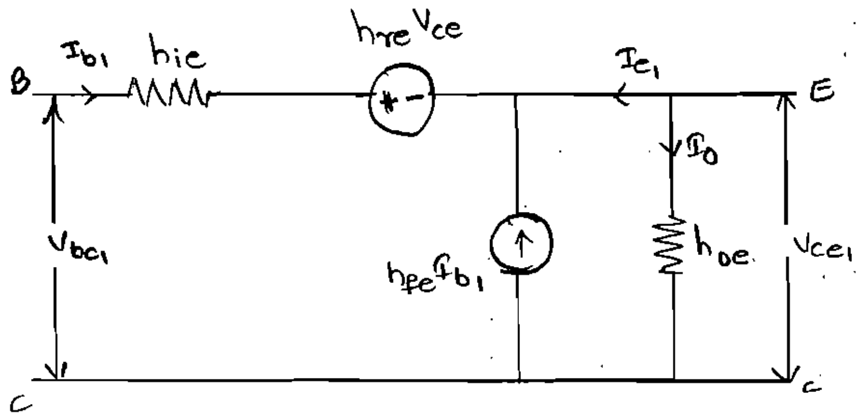
$$1 - A_{V_2} = \frac{h_{ie} + \cancel{[1+h_{fe}]} R_E - \cancel{[1+h_{fe}]} R_E}{R_{i_2}} = \frac{h_{ie}}{R_{i_2}}$$

$$\boxed{A_{V_2} = 1 - \frac{h_{ie}}{R_{i_2}}}$$

for stage:-1

As the load impedence of stage-1 is the input impedence of stage-2 $\therefore R_{i_1} = R_{i_2}$. As the value of R_{i_2} is very large then $h_{oe}R_L > 0.1$

Then we go to exact analysis.



current gain:-

$$A_{I_1} = \frac{I_0}{I_{b_1}} = \frac{-I_{C_1}}{I_{b_1}}.$$

$$I_{e_1} = -[I_{b_1} + I_{C_1}]$$

$$I_{C_1} = h_{fe}I_{b_1} + h_{oe}V_{ce_1}$$

$$= h_{fe}I_{b_1} + h_{oe}[-I_0 R_{i_2}]$$

$$I_{C_1} = h_{fe}I_{b_1} + h_{oe}I_{C_1}R_{i_2}$$

$$I_{e_1} = -[I_{b_1} + h_{fe}I_{b_1} + h_{oe}I_{e_1}R_{i_2}]$$

$$[I_{e_1} + I_{e_1}h_{oe}R_{i_2}] = -I_{b_1}[1+h_{fe}]$$

$$\frac{-I_{e_1}}{I_{b_1}} = \frac{[1+h_{fe}]}{[1+h_{oe}R_{i_2}]} \Rightarrow A_{I_1} = \frac{[1+h_{fe}]}{[1+h_{oe}R_{i_2}]}$$

Input Impedence:-

$$R_{i_1} = \frac{V_{bc_1}}{I_{b_1}}$$

apply KVL to the loop.

$$V_{bc_1} = h_{ie}I_{b_1} + h_{rc}V_{ce} - V_{ce}$$

As the value of h_{rc} is 2.2×10^{-4} which is very small we can neglect $h_{rc}V_{ce}$ term then,

$$V_{bc_1} = h_{ie} I_{b_1} - V_{ce}$$

$$V_{ce} = -I_0 R_{i_2} = I_{e_1} R_{i_2}$$

$$V_{bc_1} = h_{ie} I_{b_1} - I_{e_1} R_{i_2}$$

$$V_{bc_1} = I_{b_1} \left(h_{ie} - R_{i_2} \frac{I_{e_1}}{I_{b_1}} \right)$$

$$\frac{V_{bc_1}}{I_{b_1}} = h_{ie} + A_{I_1} R_{i_2}$$

$$\boxed{R_{i_1} = h_{ic} + A_{I_1} R_{i_2}}$$

Voltage gain for stage-2 (A_{V_2}) :-

$$A_{V_2} = A_{I_2} \cdot \frac{R_{L_2}}{R_{i_2}}$$

$$1 - A_{V_2} = 1 - A_{I_2} \cdot \frac{R_{L_2}}{R_{i_2}}$$

$$1 - A_{V_2} = \frac{R_{i_2} - A_{I_2} R_{L_2}}{R_{i_2}}$$

$$1 - A_{V_2} = \frac{h_{ie} + \cancel{(1+h_{fe})} R_E - \cancel{A_{I_2}} R_E}{R_{i_2}}$$

$$\boxed{A_{V_2} = 1 - \frac{h_{ie}}{R_{i_2}}}$$

Voltage gain (A_{V_1}) :-

Similarly, $A_{V_1} = 1 - \frac{h_{ie}}{R_{i_1}}$

overall current gain, $A_I = A_{I_1} \times A_{I_2}$

$$A_I = (1+h_{fe}) \frac{(1+h_{fe})}{1+h_{oe} R_{i_2}}$$

$$A_I = \frac{(1+h_{fe})^2}{1+h_{oe}R_{i_2}}$$

overall voltage gain,

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

$$= \left(1-\frac{h_{ie}}{R_{i_2}}\right)\left(1-\frac{h_{ie}}{R_{i_1}}\right)$$

$$= 1-\frac{h_{ie}}{R_{i_2}}-\frac{h_{ie}}{R_{i_1}}+\frac{h_{ie}^2}{R_{i_1}R_{i_2}}$$

As the value of R_{i_2} is very large we may neglect highest terms.

$$\boxed{A_V = 1-\frac{h_{ie}}{R_{i_1}}}$$

output impedence:-

$$R_{i_2} = \frac{V_{ce}}{I_{c_1}} = \frac{1}{\text{output admittance}} = 1/Y_0$$

$$Y_0 = h_{oc} - \frac{h_{fc}h_{rc}}{h_{ic}+R} = h_{oe} - \frac{-(1+h_{fe})}{h_{ie}+R_s}$$

since $h_{oc} = h_{oe}$

$$h_{fc} = -(1+h_{fe})$$

$$h_{ic} = h_{ie}$$

$$Y_0 = h_{oe} + \frac{1+h_{fe}}{h_{ie}+R_s}$$

$$Y_0 = \frac{1+h_{fe}}{h_{ie}+R_s}$$

$$h_{oe} << \frac{1+h_{fe}}{h_{ic}+R_s}$$

$$R_{o_2} = \frac{R_{s_2} + h_{ie_2}}{1 + h_{fe}} = \frac{\left(\frac{h_{ie_1} + R_s}{1 + h_{fe}}\right) + h_{ie_2}}{1 + h_{fe}}$$

$$R_{o_2} = \frac{h_{ie_1} + R_s}{(1 + h_{fe})^2} + \frac{h_{ie_2}}{1 + h_{fe}}$$

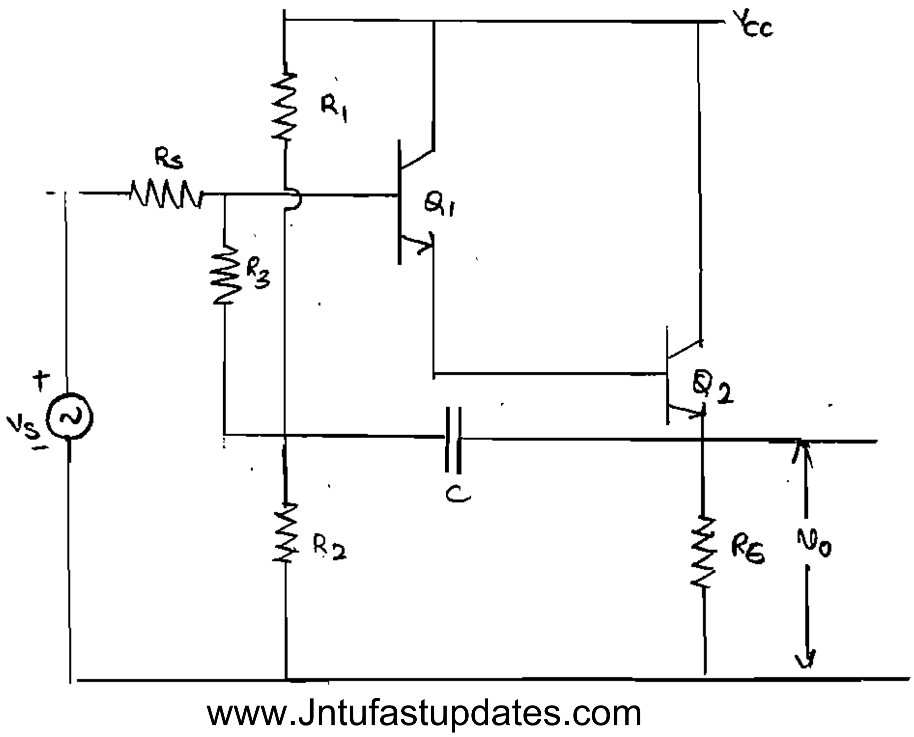
$$R_{o_2} = \frac{(1 + h_{fe})\, h_{ie_2} + R_s}{(1 + h_{fe})^2} + \frac{h_{ie_2}}{1 + h_{fe}}$$

$$R_{o_2} = \frac{h_{ie_2}}{1 + h_{fe}} + \frac{R_s}{(1 + h_{fe})^2} + \frac{h_{ie_2}}{1 + h_{fe}}$$

$$\boxed{R_{o_2} = \frac{R_s}{(1 + h_{fe})^2} + \frac{2\, h_{ie_2}}{1 + h_{fe}}}$$

Boot strap Darlington pair:-

We have seen that, in emitter follower, the input resistance of the amplifier is reduced because of the shunting effect of the biasing resistors. To overcome this problem the emitter follower circuit is modified.

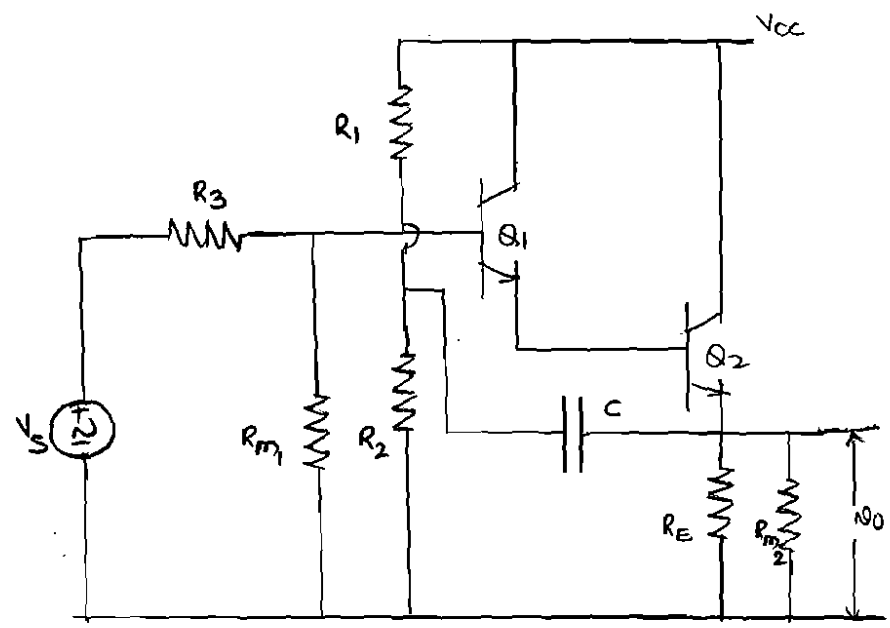


for AC equivalent circuit :-

Here we are using Miller's theorem in which 'R' is given to base it is feedback resistance. By using this theorem we can split 'R' into two resistors one in input and other at output. As we are going for AC analysis the capacitor will be short circuited.

$$R_{M_1} = \frac{R_3}{1-A_V} \quad \& \quad R_{M_2} = \frac{R_3 A_V}{A_V - 1}$$

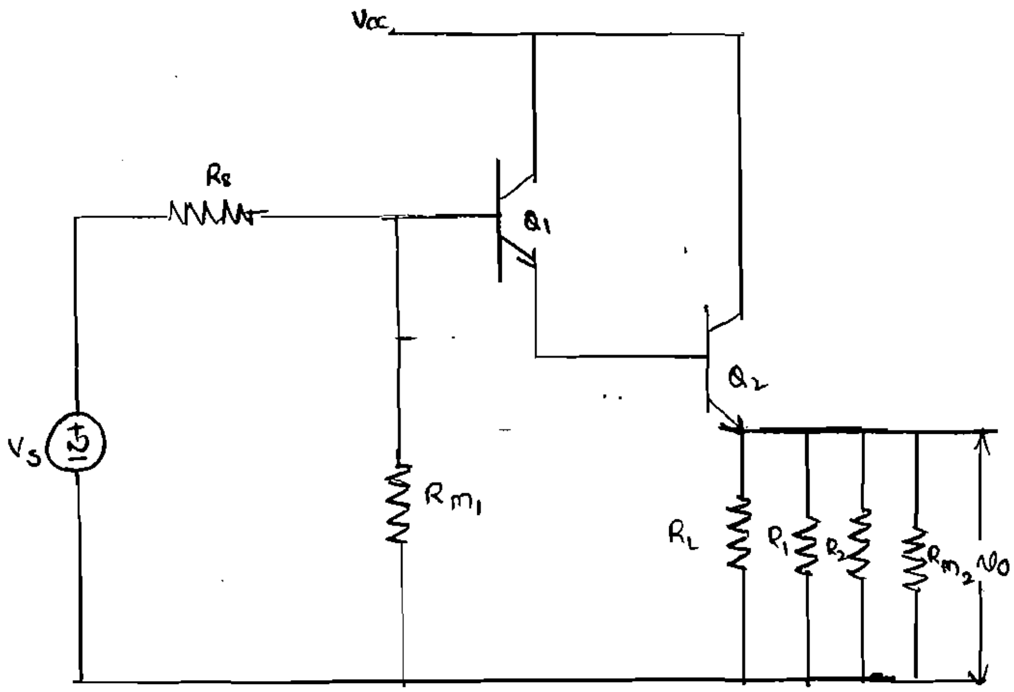
since for an emitter follower A_V approaches unity, then R_{M_2} becomes extremely large.



AC equivalent circuit :-

for AC analysis short the capacitor in the circuit.

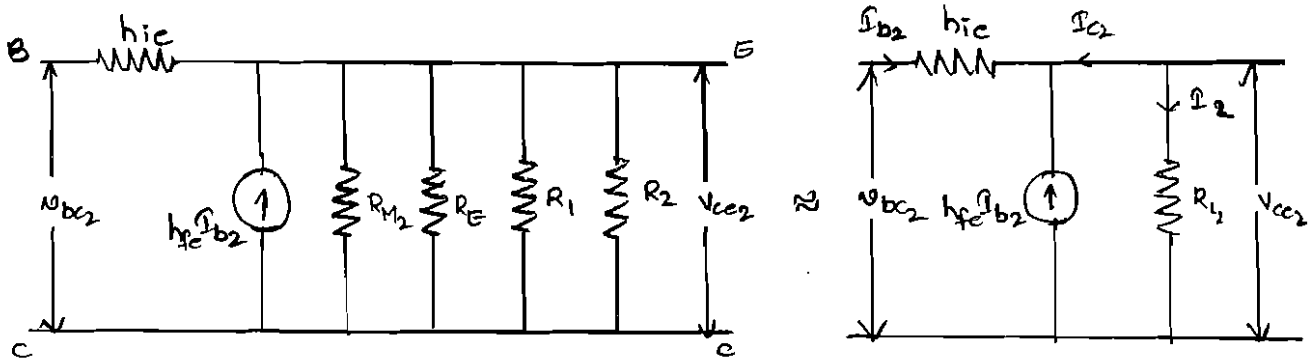
The resistance are connected to ground and hence we can connect them at the emitter terminal



for stage 1-2

Ac equivalent circuit for CE amplifier and convert into CC amplifier.

If the load resistance R_L is small so that $h_{oe} \cdot R_E < 0.1$ then we will goto approximate analysis.



current gain:-

$$A_I = \frac{I_O}{I_1} = \frac{-I_{E2}}{I_{b2}}$$

$$I_{E_2} + I_{b_2} + h_{fe} I_{b_2} = 0$$

$$I_{E_2} = -I_{b_2}(1+h_{fe})$$

$$\boxed{A_I = 1+h_{fe}}$$

Input impedance:-

$$R_{i_2} = \frac{V_{bc_2}}{I_{b_2}}$$

apply KVL to the circuit,

$$V_{bc_2} = h_{ie} I_{b_2} + I_0 R_{C_2}$$

$$V_{bc_2} = h_{ie} I_{b_2} + I_0 R_{L_2}$$

$$= h_{ie} I_{b_2} - I_{e_2} R_{L_2}$$

$$= I_{b_2} h_{ie} + I_{b_2}(1+h_{fe}) R_{L_2}$$

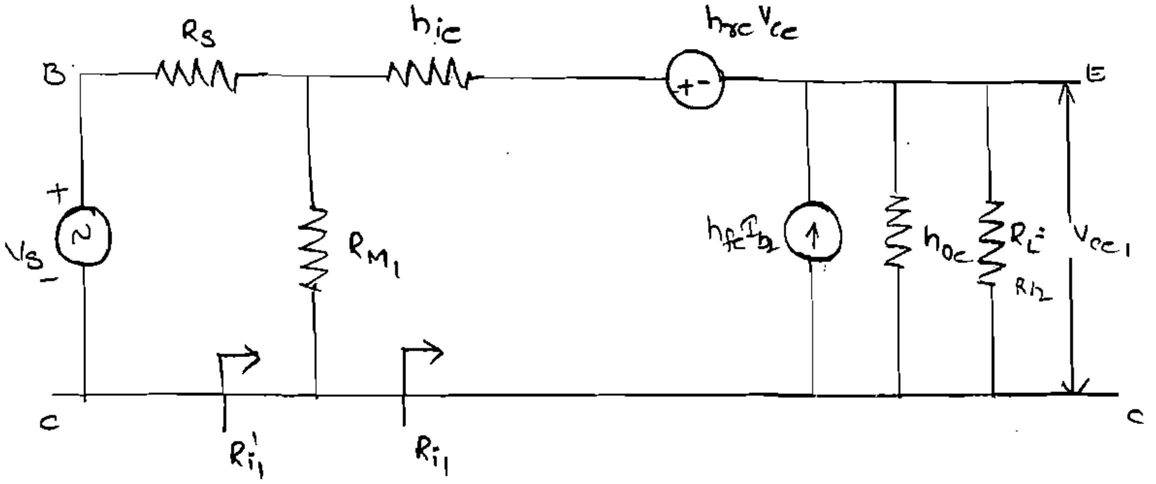
$$= I_{b_2}[1 + h_{ie} + h_{fe}] R_{L_2} = I_{b_2}(h_{ie} + A_{I_2} R_{L_2})$$

$$R_{i_2} = \frac{I_{b_2}(h_{ie} + A_I R_{L_2})}{I_{b_2}}$$

$$\boxed{R_{i_2} = h_{ie} + A_I R_{L_2}}$$

For stage-I

As R_{i_2} is large $h_{oe} R_L > 0.1$, then we will go to exact analysis.



current gain:-

$$A_{I_1} = \frac{I_O}{I_i} = \frac{-I_{E_1}}{I_{b_1}}$$

$$I_{E_1} = -(I_{b_1} + I_{c_1})$$

$$I_{C_1} = h_{fe} I_{b_1} - h_{oe} I_O R_{i_2}$$

$$= h_{fe} I_{b_1} + h_{oe} I_{E_1} R_{i_2}$$

$$I_{E_1} = -I_{b_1} - h_{fe} I_{b_1} - h_{oe} I_{E_1} R_{i_2}$$

$$I_{E_1}(1 + h_{oe} R_{i_2}) = -I_{b_1}(1 + h_{fe})$$

$$A_{I_1} = \frac{-I_{E_1}}{I_{b_1}} = \frac{1 + h_{fe}}{1 + h_{oe} R_{i_2}}$$

$$\boxed{A_{I_1} = \frac{1 + h_{fe}}{1 + h_{oe} R_{i_2}}}$$

Input Impedence :-

$$R_{i_1} = \frac{V_{bc_1}}{I_{b_1}}$$

$$V_{bc_1} = h_{ic} I_{b_1} + h_{rc} V_{ce} - V_{cc_1}$$

As the value of h_{re} is 2.2×10^{-4} which is very small we can neglect $h_{re} V_{ce}$.

$$V_{bc_1} = h_{ic} I_{b_1} - V_{ce}$$

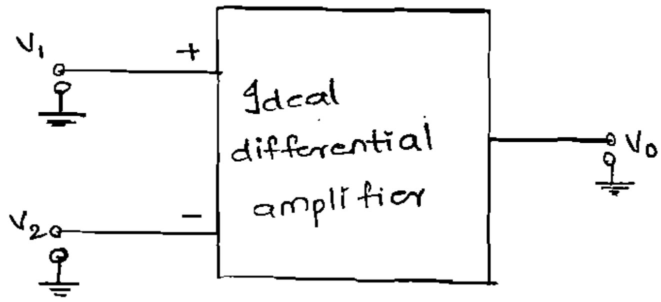
$$= h_{ie} I_{b_1} - I_O R_{i_2}$$

$$= h_{ic} I_{b_1} + I_{E_1}(h_{ic} + A_I R_{i_2}).$$

Differential amplifier:-

A differential amplifier is an electronic circuit which amplifies the difference between the two input signals. Hence, it is called as differential amplifier.

considering an ideal differential amplifier,



V_1 and V_2 are the two input signals while V_0 is the single ended output.

In an ideal differential amplifier the output voltage V_0 is proportional to the difference between the two input signals, Hence we can write

$$V_0 \propto (V_1 - V_2)$$

Differential voltage gain (A_d):-

$$V_0 = A_d V_i$$

$$V_0 = A_d (V_1 - V_2)$$

where A_d is the constant of proportionality. The A_d is the gain with which differential amplifier amplifies the difference between two input signals. Hence it is called differential gain of the differential amplifier.

Hence the differential gain is expressed as,

$$A_d = \frac{V_0}{V_d}$$

Generally the differential gain is expressed in its decibel (dB) value as,

$$\boxed{A_d = 20\log_{10}(A_d) \text{ in dB}}$$

Common mode gain A_c:-

In a practical amplifier, when $V_1 = V_2$ the output of differential amplifier is not equal to zero. There the output exists due to noise signal generated in the ckt. Here the output voltage V_0 is proportional to common voltage between input and output

$$V_0 \propto \left(\frac{V_1 + V_2}{2}\right)$$

$$V_0 \propto V_c$$

And the gain produced at this stage is known as common gain.

$$V_0 = A_c V_c$$

The total output of differential amplifier is known as,

$$\boxed{V_0 = A_d V_d + A_c V_c}$$

Here $A_d >> A_c$

At this stage we can define one important parameter of differential ~~equation~~ amplifier known as common mode rejection ratio (CMRR).

Common Mode Rejection Ratio :- (CMRR)

It is defined as the ratio of differential gain to that of common voltage.

$$CMRR = \rho = \frac{A_d}{A_c}$$

ideally the common mode voltage gain is zero, hence the ideal value of CMRR is infinite.

For a practical differential amplifier A_d is large and A_c is small hence the value of CMRR is also very large.

CMRR is also expressed as, in dB

$$CMRR \text{ in } dB = 20\log\left|\frac{A_d}{A_c}\right| dB$$

The output voltage can be expressed in terms of CMRR as below,

$$\text{As, } V_0 = A_d V_d + A_c V_c$$

$$= A_d V_d\left[1 + \frac{A_c V_c}{A_d V_d}\right]$$

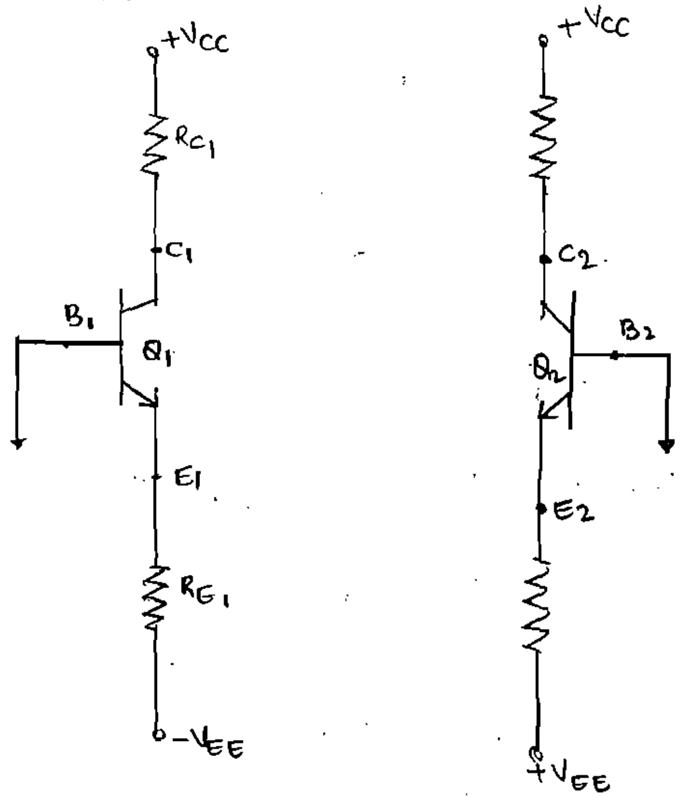
$$= A_d V_d\left[1 + \left(\frac{V_c}{V_d}\right) \Big/ \left(\frac{A_d}{A_c}\right)\right]$$

$$= A_d V_d\left[1 + \frac{(V_c/V_d)}{CMRR}\right]$$

This expression explains that as CMRR is practically very large, though both V_c and V_d components are present, the output is mostly proportional to the difference signal only. The common mode component is ~~generally~~ greatly rejected.

Emitter Coupled Differential Amplifier :-

The transistorised differential amplifier basically uses the emitter biased circuits which are identical in characteristics. such two identical emitter biased circuits are as shown.



The two transistors Q_1 and Q_2 have exactly matched characteristics. The two collector resistances R_{C_1} and R_{C_2} are equal while the two emitter resistances R_{E_1} and R_{E_2} are also equal.

Thus, $R_{C_1} = R_{C_2}$ and $R_{E_1} = R_{E_2}$

The magnitudes of $+V_{CC}$ and $-V_{EE}$ are also same. The differential amplifier can be obtained by using such two emitter biased circuits.

The supply voltages are measured with

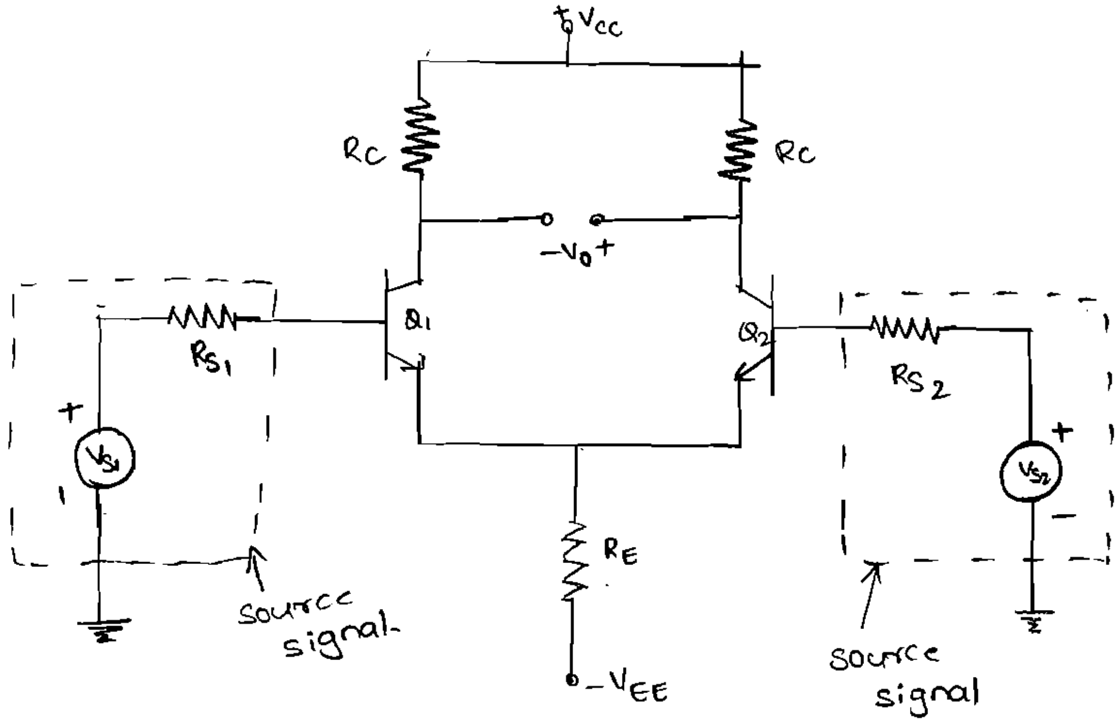
respect to ground. The balanced output is taken between the collector c_1 and Q_1 and collector c_2 of Q_2. such an amplifier is called emitter coupled differential amplifier.

As the output is taken between two terminals, none of them is grounded. it is called balanced output differential amplifier.

let us study the circuit operation in the two modes namely:-

i) Differential mode operation

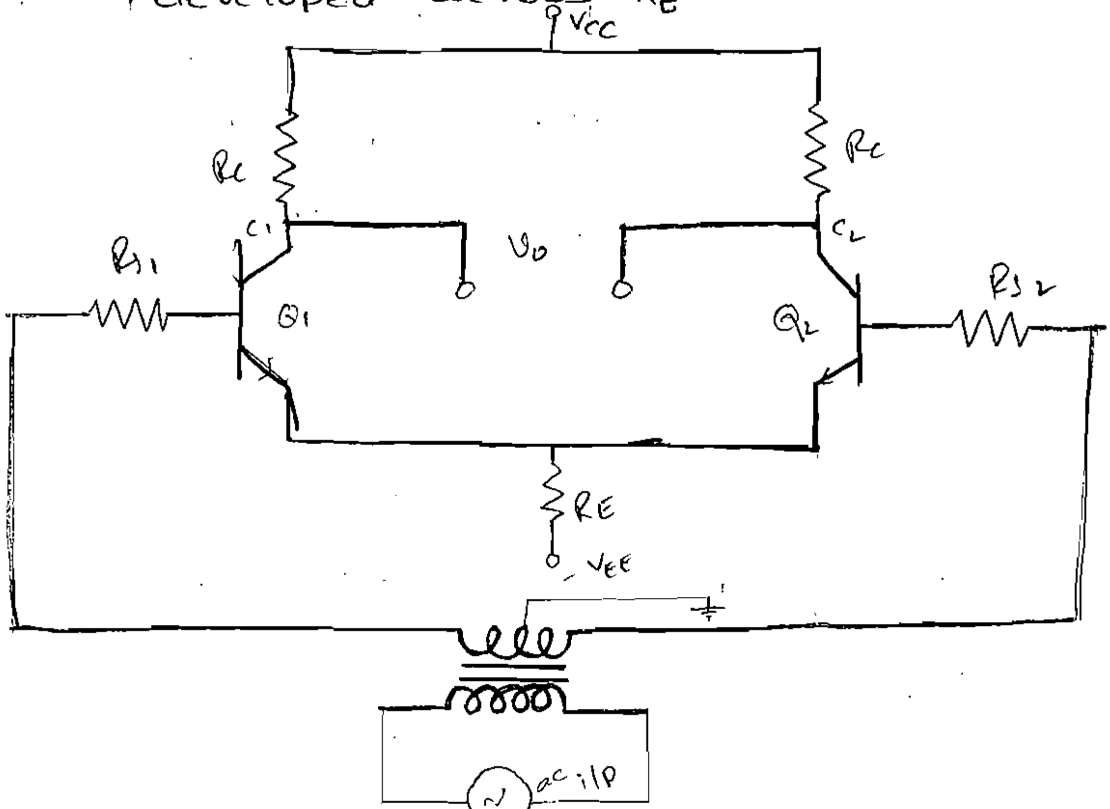
ii) Common mode operation.



Differential Mode operation:-

In differential mode the two input signals are different from each other. considering two input signals which are same in magnitude but 180° out of phase. These signals, with opposite phase can be obtained from the center tap transformer.

Assume that the sine wave on the base of Q_1 is positive going by on the base of Q_2 is negative going with a positive going signal on the base of Q_1, an amplifier -ve going signal develops on the collector of Q_1. due to +ve going signal, current through R_E also increases. Hence a positive going signal is developed across R_E.



Due to -ve going signal on the base of Q_2, an amplifier fastly going signal develops on the collector of 'Q_2' and the -ve going signal develops across R_E. Because the emitter follower action of 'Q_2'.

So signal voltage across R_E, due to the effect of Q_1 and Q_2 are equal in magnitude and 180^0 out of phase, due to matched pair of trasistors. Hence these two signals cancel each other. There is no signal across the emitter resistance.

Hence there is no AC signal current flowing through the emitter Resistance. Hence in this case R_E does not introduce -ve feed back.

while V_0 is the output is taken across collector of Q_1 and collector of Q_2. The two outputs on collector 1 and 2 are equal in magnitude but opposite in polarity. And V_0 is the difference between two signals. Hence the difference output V_0 is twice as large as the signal voltage from either collector to ground.

ii. Common Mode operation:-

In this mode the signal is applied to the base of Q_1 and Q_2 are derived from the same source so, the two signals are equal in magnitude as well as in phase.

In phase signal voltages at the bases of Q_1 and Q_2 causes in phase signal voltages to appear across R_E, which add together. Hence R_E carries a signal current and provides a negative feed back. This feedback reduced the common mode gain of differential amplifier.

while the two-signals causes in phase signal voltages of equal magnitude to appear across the two collectors of Q_1 and Q_2. Now the output voltage is the difference between the two collector voltages which are equal and also in same phase. Thus the output difference V_0 is almost zero, negligebly small. Ideally it should be zero.