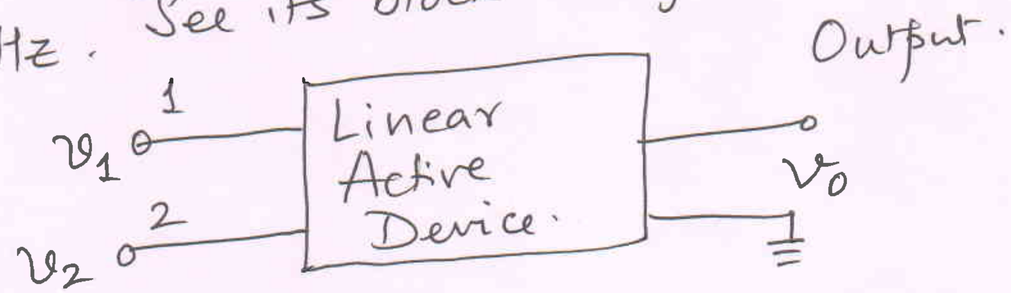
DIFFERTIAL AMPLIFIER

From Millman & Halkias 15.2.

This amplifies amplifies difference between two signals. Usually DA work from DC to MHz. See its block diagram below:



$$v_0 \equiv Ad(v_1 - v_2)$$

where Ad = Differential Voltage Gain in V/V

Thus any signal common on both inputs should not have any effect on output v_0. This is true for an ideal DA. In a practical DA, the output voltage v_0 is also a function of average level or COMMON MODE SIGNAL v_c as follows:

$$v_d \equiv v_1 - v_2 \quad \& \quad v_c \equiv \frac{1}{2}(v_1 + v_2) \quad \text{--- (1)}$$

The above are by definition.

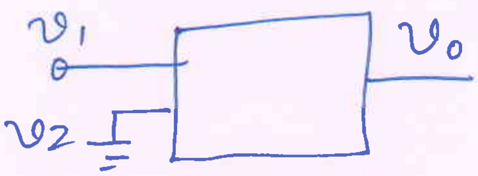
Suppose we have $v_1 = 50\,\mu V$ and $v_2 = -50\,\mu V$ then difference will be $50 - (-50) = 100\,\mu V$.

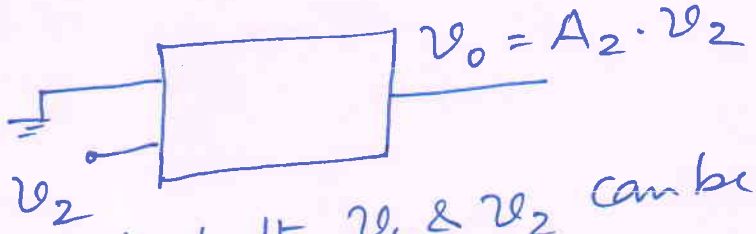
If same v_1 and v_2 are added with a common base level of $1000\,\mu V$ then $v_1 = 1000 + 50 = 1050\,\mu V$ and $v_2 = 1000 - 50 = 950\,\mu V$. Now $v_d = 1050 - 950 = 100\,\mu V$ still as before but $v_c = \frac{1}{2}(1050 + 950) = 1000\,\mu V$

...d such a large v_c may affect v_0.

We define a Figure Of Merit to show the property of a practical DA to reject CM v_c and to respond only to v_d.

Let us consider A_1 and A_2 as voltage gain of input 1 & 2 when only 1 signal is connected and other is grounded.





The actual output v_o due to both v_1 & v_2 can be found using Superposition Theorem, adding two components.

$$v_o = A_1 v_1 + A_2 v_2 \quad \text{-- -- (2)}$$

Solving (1) further, we get

$$v_1 = v_c + \frac{1}{2} v_d \quad \text{and} \quad v_2 = v_c - \frac{1}{2} v_d. \text{ -- (3)}$$

[Remember $1050 = 1000 + \frac{100}{2}$ & $950 = 1000 - \frac{100}{2}$] ?

Substituting (3) & in 2, we get

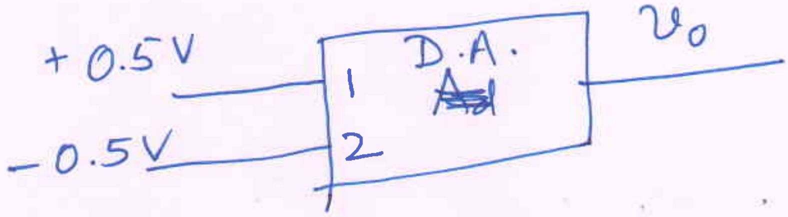
$$v_o = A_d v_d + A_c v_c \quad \text{-- -- (4)}$$

where $A_d = \frac{1}{2}(A_1 - A_2)$ and $A_c = A_1 + A_2$

A_d = Voltage Gain for diff Signal ~~&~~ and

A_c = " " Common mode signal.

To measure A_d directly connect as following: (3)



v_o contains effect of v_d only as v_c is set to be zero.

$v_d = +5 - (-.5V) = 1V$

$$A_d = \frac{v_o}{v_d} = \frac{v_o}{1V}$$

$\therefore$ Measure v_o with Voltmeter & that is A_d value.

Note that at these inputs CM signal is 0 and contribution of $A_c v_c$ in $v_o = 0$.

$\therefore$ measurement gives value of A_d readily.

Ideally we would like to have very large A_d and very small A_c (or zero). A quantity called COMMON MODE REJECTION RATIO (CMRR) $= \rho$ is defined as

$$CMRR = \rho \equiv \left| \frac{A_d}{A_c} \right| \quad -- (5)$$

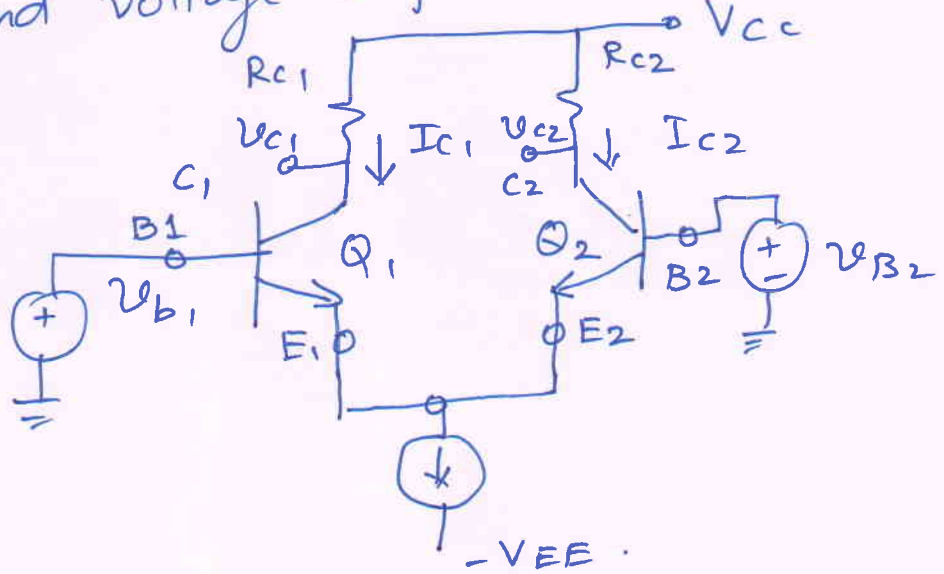
Substituting (5) in (4) we get

$$v_o = A_d v_d \left[1 + \frac{1}{\rho} \frac{v_c}{v_d} \right] \quad -- (6).$$

DA must be designed for very large value of ρ. $\rho = 1000$ means, a CM signal of 1mV will have same effect on v_o as differential signal of $1\mu V$ which is 1000 times less.

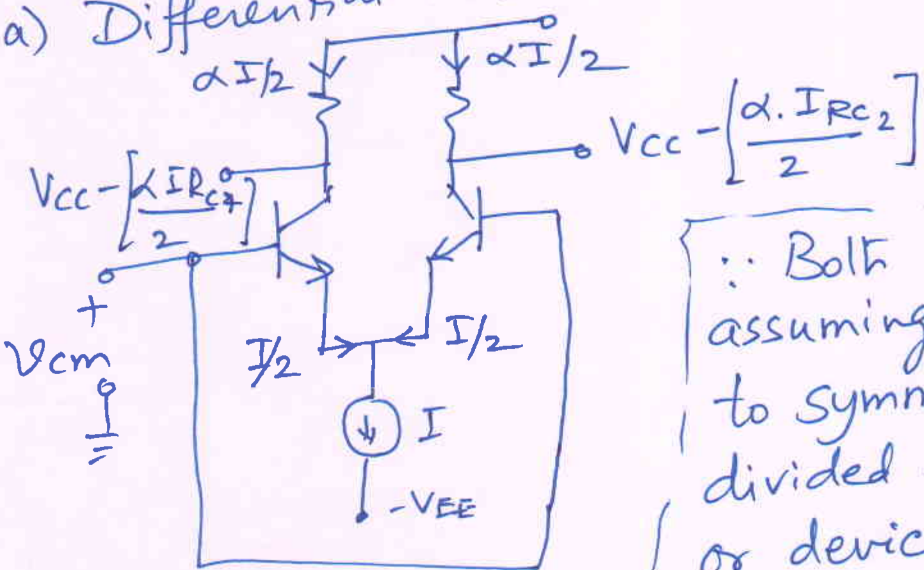
BASIC BJT DIFFERENTIAL PAIR

8.3 Sedra Smith. The Circuit uses 2 BJTs with emitters joined together, input signals are connected to both bases and voltage output is taken at both Collectors:



We consider 4 Cases of Operation:

a) Differential Pair or DA with Common Mode Signal v_{CM}



Same signal is Connected to B_1 & B_2

∵ Both BJT's are identical, assuming ideal source I, due to symmetry it will get divided I/2 in both arms or devices. $i_{E_1} = i_{E_2} = I/2$

Voltage at emitter E_1 & E_2 = $v_{cm} - V_{BE}$

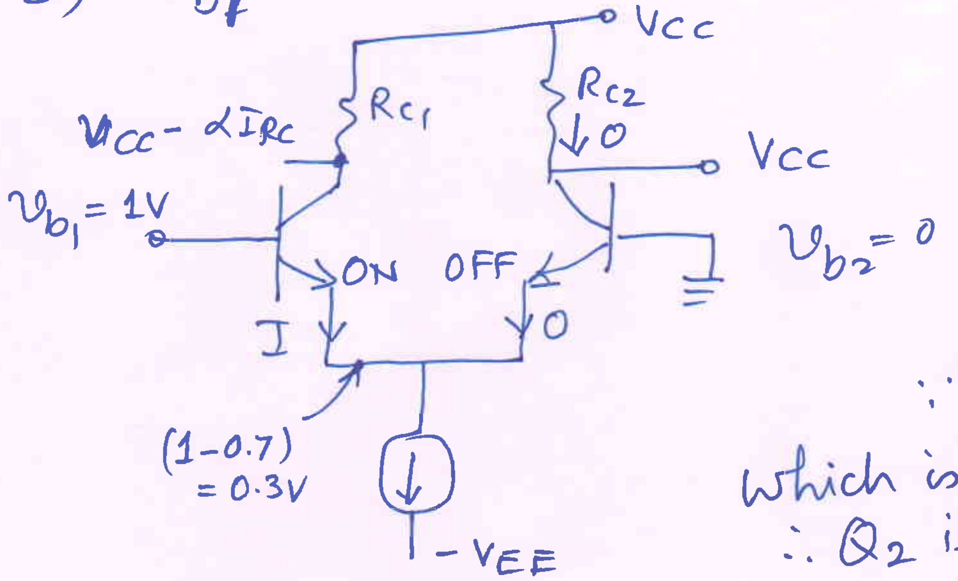
$$v_{c_1} = v_{c_2} = \left[V_{CC} - \alpha \frac{I}{2} \cdot R_C\right] \quad \text{where } R_C = R_{C_1} = R_{C_2}$$

The difference $(v_{C_1} - v_{C_2})$ will be ZERO.

Ideally this circuit will not produce any O/P for CM signal v_{CM}.

difference = $v_{c_1} - v_{c_2} = \boxed{0}$

b) $v_{b_1} = +1V$ and $v_{b_2} = 0V$.



Note that v_{B_1} forward biases Q_1 & $v_{E_1} = v_{E_2}$

$= 1V - 0.7V = 0.3V$.

$\because V_E - v_{B_2} = 0.3V$

which is less than 0.7V

$\therefore Q_2$ is cutoff & $I_{E_2} = 0$.

$\therefore$ all of current source output is diverted to Q_1. Now $I_{E_1} = I_{C_1} = I$

& $v_{C_1} = V_{CC} - \alpha I_{C_1} R_C$.

$\therefore Q_2$ = cutoff, $I_{C_2} = 0$

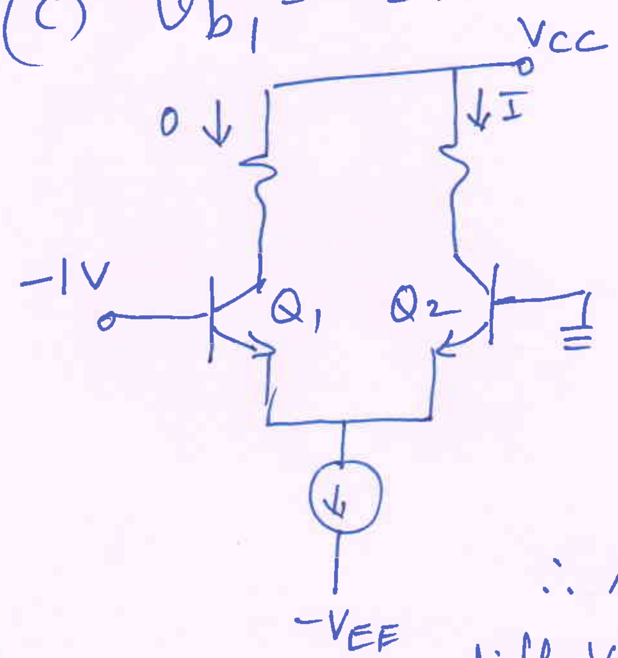
$\therefore v_{C_2} = V_{CC} - \alpha I_{C_2} R_C = V_{CC} - 0 = V_{CC}$

Now we have large difference in output

difference $= v_{C_2} - v_{C_1} = (V_{CC} - \alpha I R_C) - V_{CC}$

$= \boxed{-\alpha I R_C}$

(c) $v_{b_1} = -1V$ and $v_{b_2} = 0$



Using same logic Base of Q_2 will prevail over Emitter and it will fully turn ON.

$v_{e_2} = 0V - 0.7V = -0.7V$.

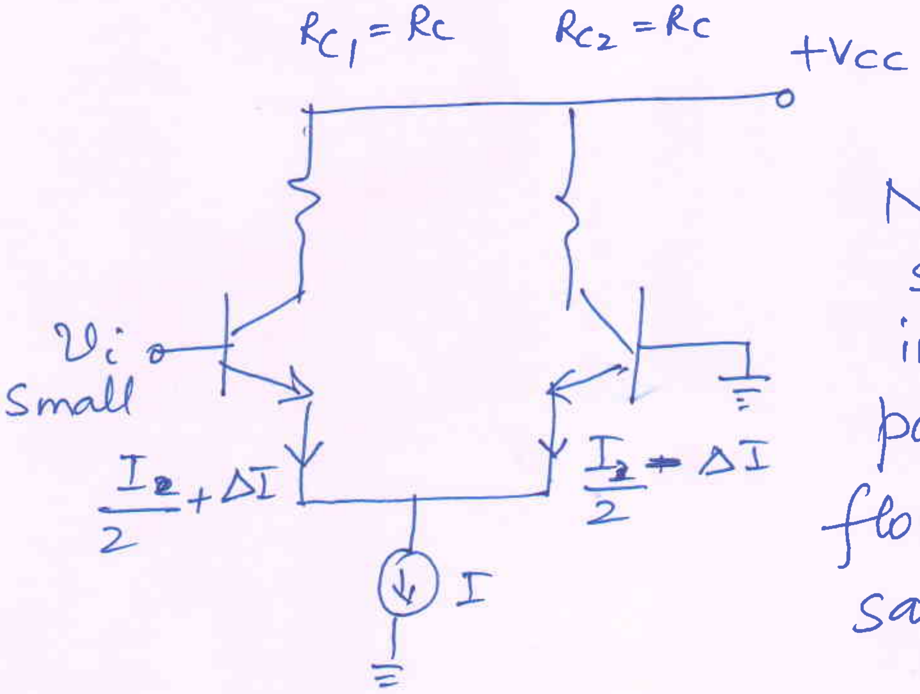
$\because v_{e_1} = v_{e_2}$ is only $-0.3V$ away from v_{B_1}, Q_1 is CUTOFF.

$\therefore$ ALL of I will flow as I_{E_2} & I_{C_2}

$\therefore$ diff. Voltage $= V_{CC} - (V_{CC} - \alpha I R_C)$

$= \boxed{\alpha I R_C}$

Case 4: Assume a very small differential signal is connected to v_{b1} and v_{B2} such that it causes $+\Delta I$ current in Q_1 and $-\Delta I$ in Q_2. 6



Now due to small signal in v_{b1}, a larger part than $I/2$ flows in it — say it is $\frac{I}{2} + \Delta = I_{E1}$

$\therefore$ The source has only I $\therefore$ $I_{E2} = I - I_{E1}$

$$= I - \left(\frac{I}{2} + \Delta I\right)$$

$$I_{E2} = \frac{I}{2} - \Delta I$$

$$v_{C1} = \left[V_{CC} - R_C \alpha\left(\frac{I}{2} + \Delta I\right)\right]$$

$$v_{C2} = \left[V_{CC} - \left\{R_C \alpha\left(\frac{I}{2} - \Delta I\right)\right\}\right]$$

$\therefore$ difference will be $\alpha R_C \Delta I + \alpha R_C \Delta I$

$$= 2\alpha R_C \Delta I$$

Thus, a small differential input signal produces large signal imbalance output voltage. A moderate signal like (1,0) to (−1,0) causes complete switching of current from Q1 to Q2 & vice versa.

8.3.2 Large signal Operation.

If v_E is voltage at Emitter then I_E vs v_{BE} equation for both BJTs can be written as:

$$i_{E1} = \frac{I_S}{\alpha} e^{[(v_{B1} - v_E)/V_T]}$$

and

$$i_{E2} = \frac{I_S}{\alpha} e^{[(v_{B2} - v_E)/V_T]}$$

dividing first by second, we get

$$\frac{i_{E1}}{i_{E2}} = e^{(v_{B1} - v_{B2})/V_T}$$

This is manipulated to produce two relations

$$\frac{i_{E1}}{i_{E1} + i_{E2}} = \frac{1}{1 + e^{(v_{B2} - v_{B1})/V_T}}$$

and

$$\frac{i_{E2}}{i_{E1} + i_{E2}} = \frac{1}{1 + e^{(v_{B1} - v_{B2})/V_T}}$$

The nodal equation is $I = i_{E1} + i_{E2}$

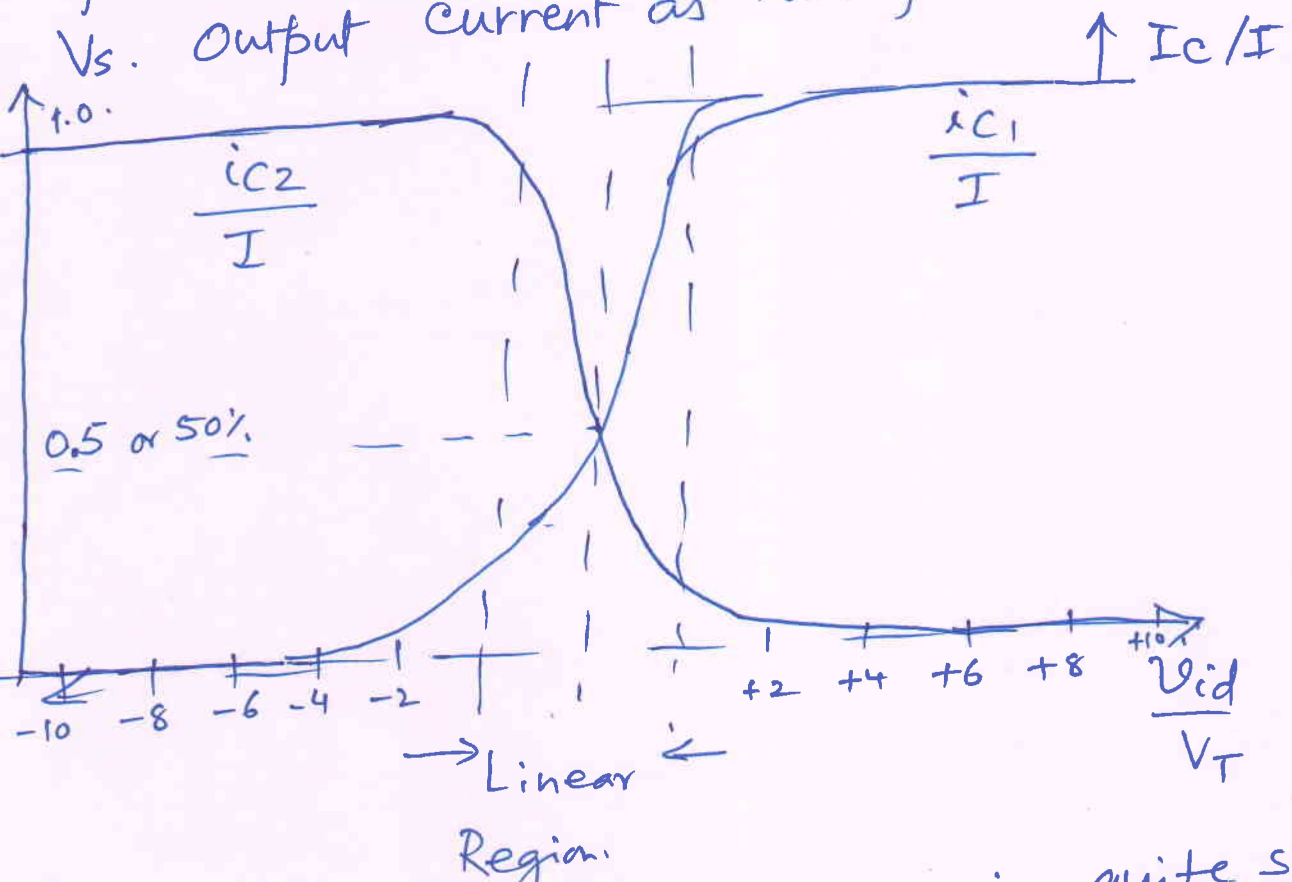
So above two equations simplify to

$$i_{E_1} = \frac{I}{1 + e^{-v_{id}/V_T}} \quad \text{and} \quad i_{E_2} = \frac{I}{1 + e^{v_{id}/V_T}}$$

where v_{id} = input signal diff. = $v_{B_1} - v_{B_2}$.

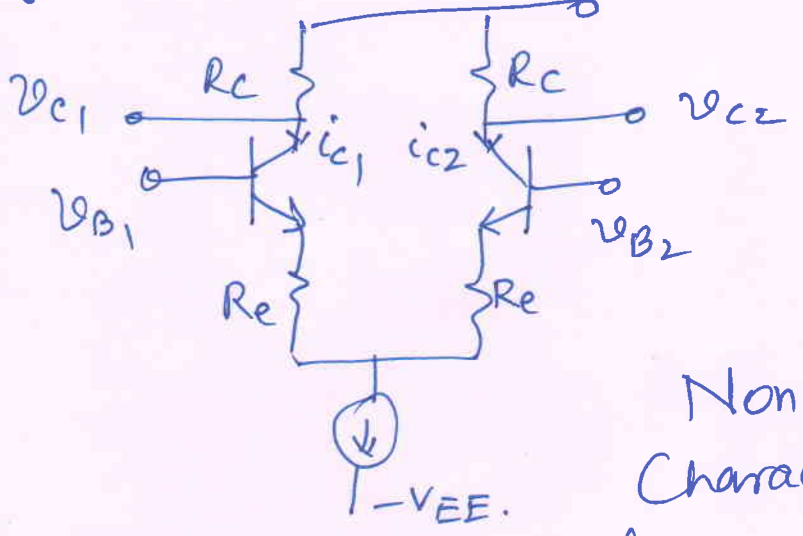
from above we can get I_{C_1} & I_{C_2} by mult. with α.

Note that a very small v_{id} can cause a very large change. If $v_{id} = 4\,V_T = 100\,mV$ then one of the BJTs can become completely OFF and other will pass full current I. If we plot normalised differential input voltage $\frac{v_{id}}{V_T}$ Vs. output current as Transfer Characteristics

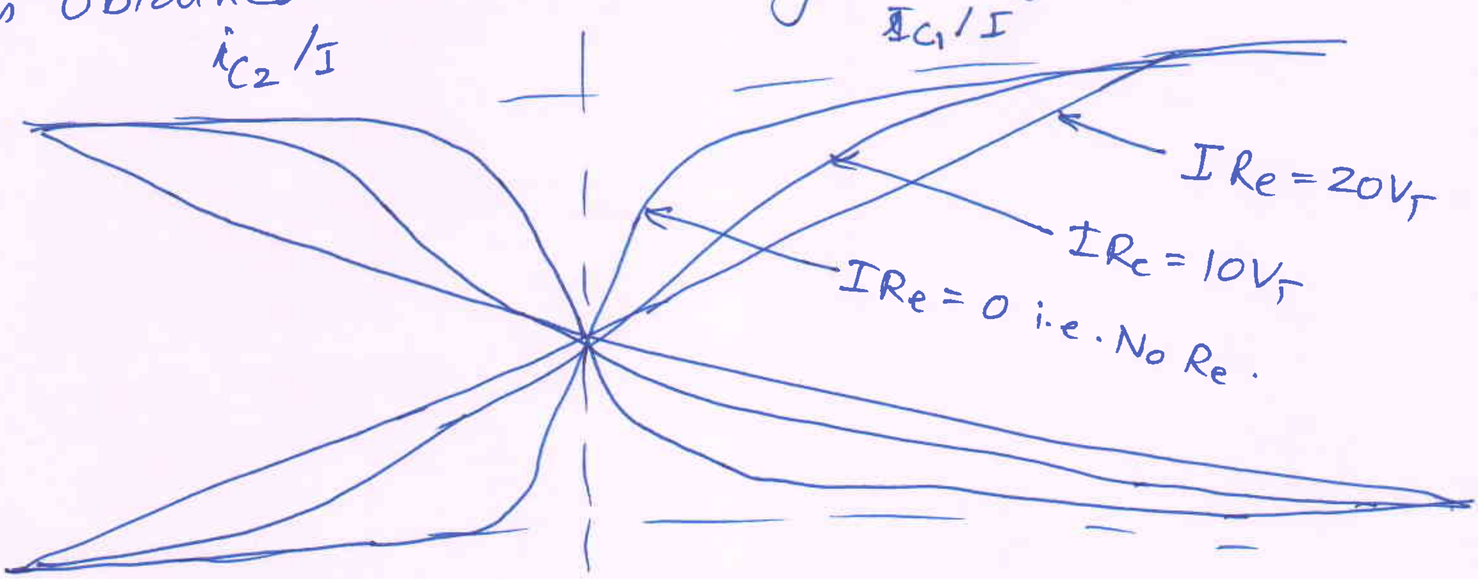


Note that the linear region is quite small.

If we add emitter resistors $R_{E_1} = R_{E_2} = R_e$ then?



If R_e is added like "Degenerated Emitter" then Non-linear Transfer Characteristic gets more linearised. Here the linearisation is obtained at reduced gain or g_m.



Note that as R_e value increases from 0, the sharply rising curve flattens out thus giving linearity over larger zone or region but the slope of the curve is decreased.

DO IT AT HOME YOURSELVES 8.3.3.
Small Signal Operation