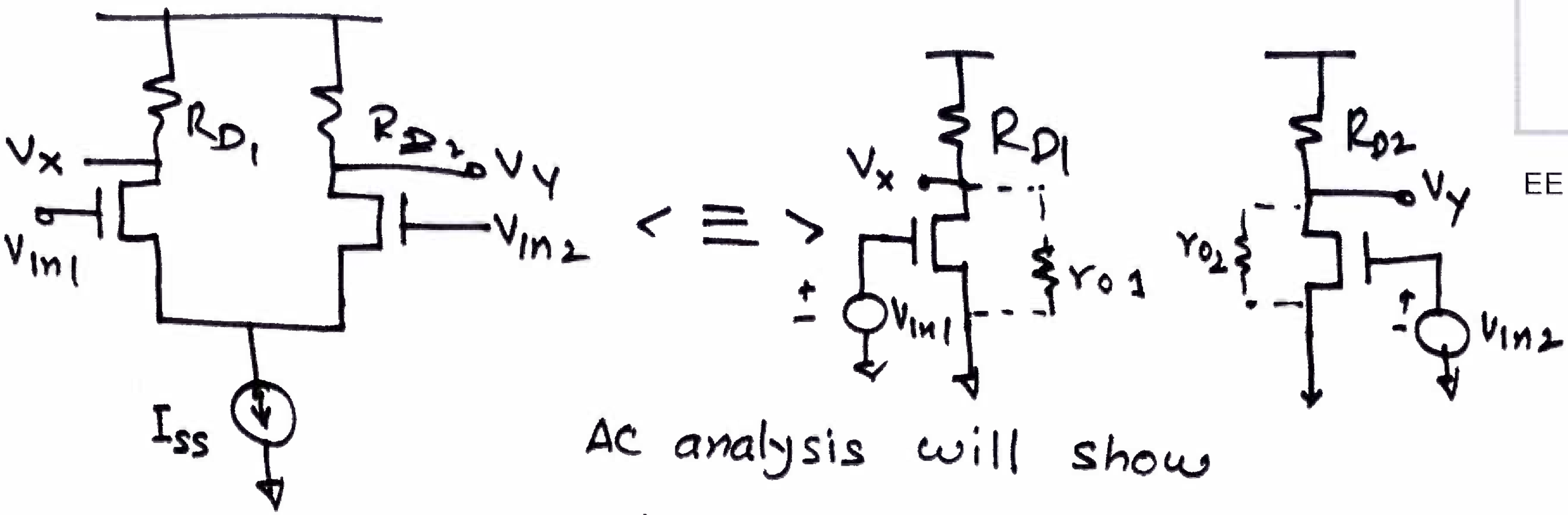
Using Half Circuit theorem we have



AC analysis will show

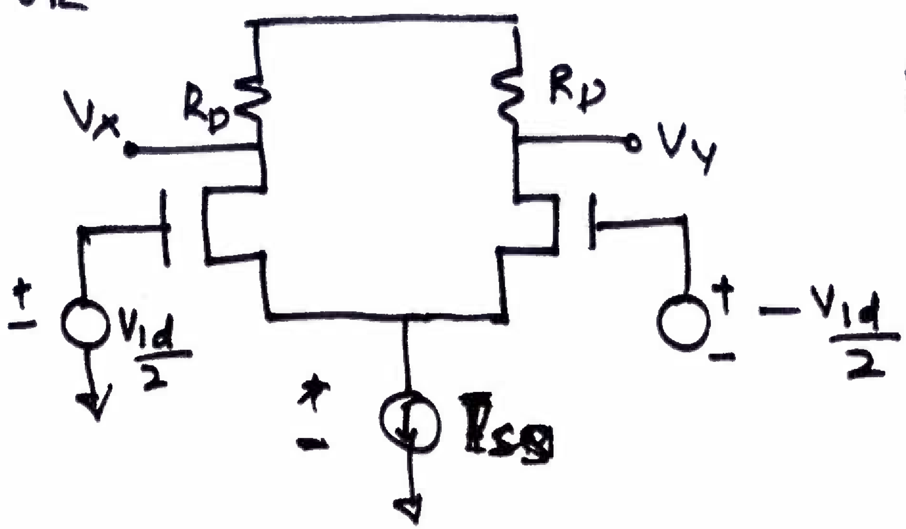
$$\frac{V_x}{\Delta V_{in1}} = -g_{m1}(R_{D1} \| r_{o1})$$

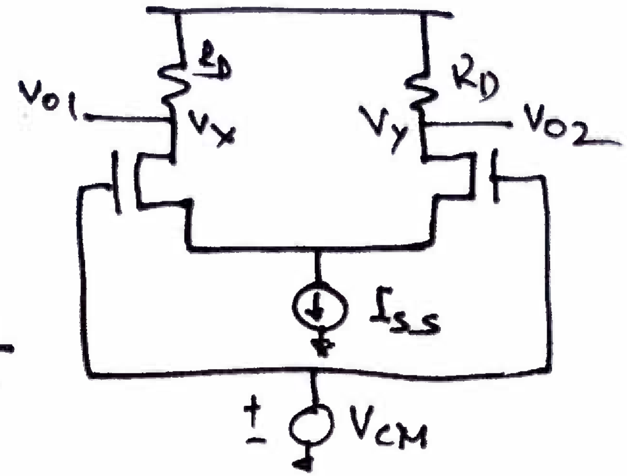
& $$\frac{V_y}{-\Delta V_{in1}} = \frac{V_y}{+\Delta V_{in2}} = -g_{m2}(R_{D2} \| r_{o2})$$

or $$\frac{V_x - V_y}{\Delta V_{in1}} = \frac{V_x - V_y}{\Delta V_{in}} = \frac{\Delta V_o}{\Delta V_{in}} = A'_{vo} = -g_{m1}(R_{D1} \| r_{o1}) - g_{m2}(R_{D2} \| r_{o2})$$

or $A'_{vo} = -2g_m(R_D \| r_o)$ if $g_m = g_{m1} = g_{m2}$ & $r_o = r_{o1} = r_{o2}$, $R_D = R_{D1} = R_{D2}$

OR





For Difference Mode case

$$V_x = -g_{m1}(R_D \| r_{o1})\frac{V_{id}}{2}$$

$$V_y = +g_{m2}(R_D \| r_{o2})\frac{V_{id}}{2}$$

or $$\frac{V_x - V_y}{V_{id}} = -g_m(R_D \| r_o)$$

$$\left\{ \begin{array}{l} g_m = g_{m1} = g_{m2} \\ r_{o1} = r_{o2} = r_o \end{array} \right.$$

or $$A_{v_{DM}} = -g_m R_D \quad \text{if } r_o \gg R_D$$

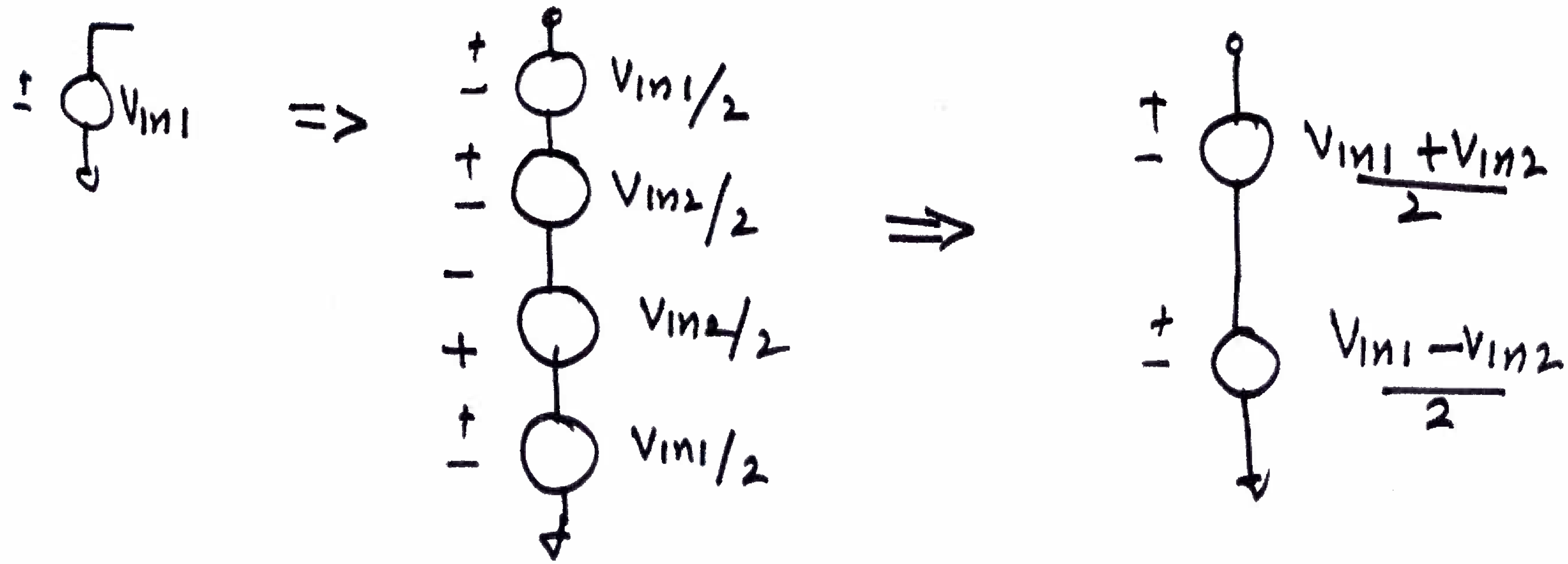
For Common Mode $V_{in1} = V_{in2} = V_{CM} = \frac{V_{in1} + V_{in2}}{2}$

$$\therefore \quad A_{v_{CM}} = \frac{V_x - V_y}{V_{CM}} = \frac{V_x - V_x}{V_{CM}} = 0$$

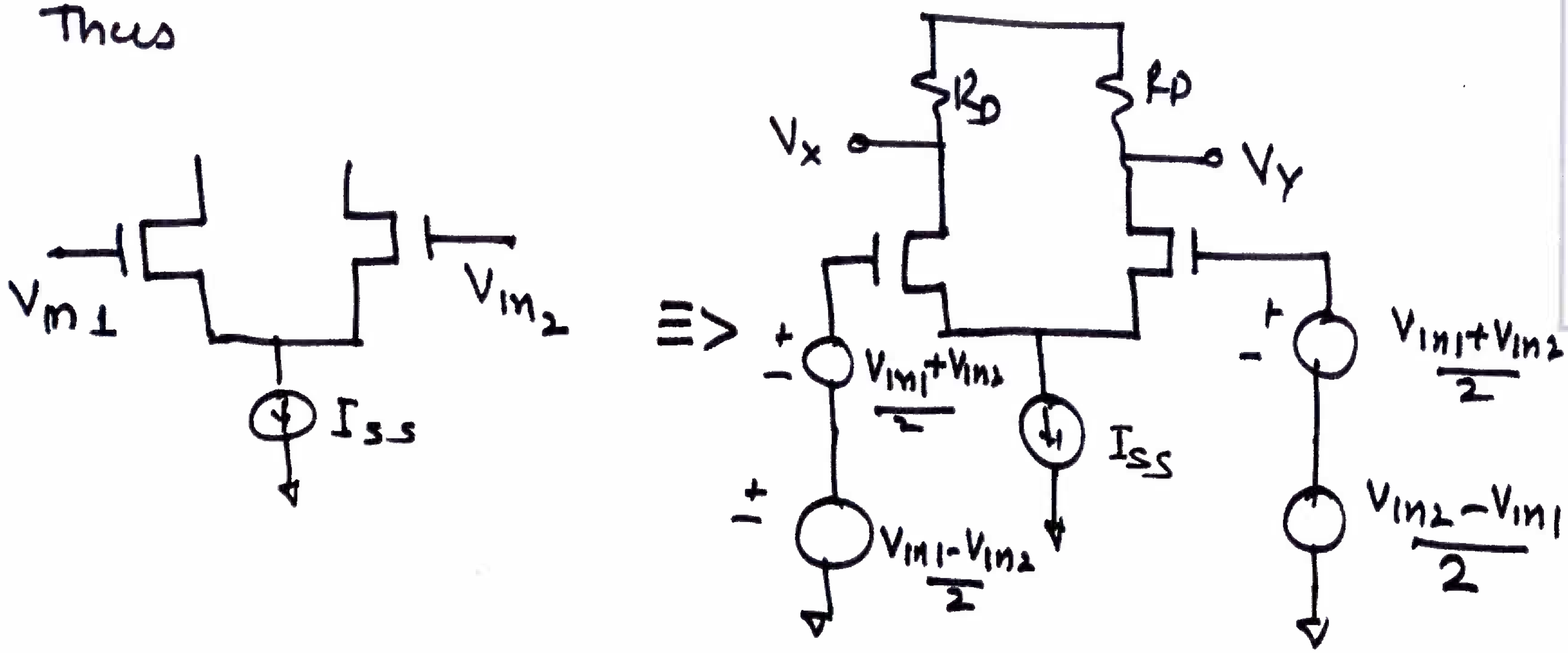
However $A_{V_{BM}}$ is defined as $\dfrac{\Delta V_o}{2\Delta V_{in}}$

or $$\frac{V_{o1}-V_{o2}}{V_{in1}-V_{in2}} = \frac{V_x - V_y}{V_{in1}-V_{in2}} = A_{V_{DM}} = -g_m(R_D \| r_o)$$

In case two inputs are not Fully Differential, we still can use Half Ckt concept



Thus



We define V_{CM} = Common Mode Voltage $= \frac{V_{in1}+V_{in2}}{2}$

& V_{DM} = Difference Mode Voltage $= V_{id} = V_{in1} - V_{in2}$

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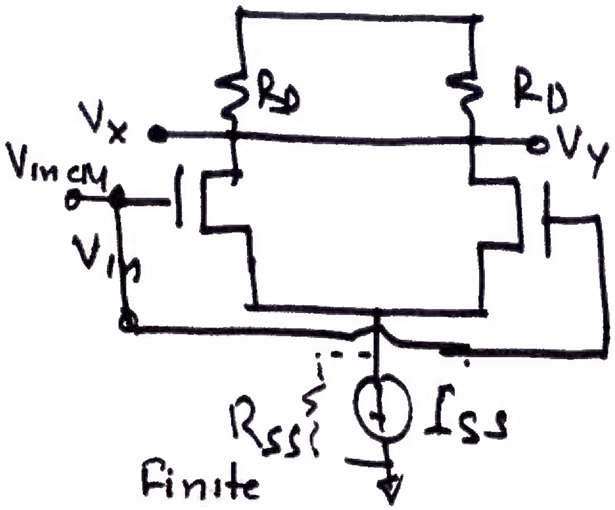
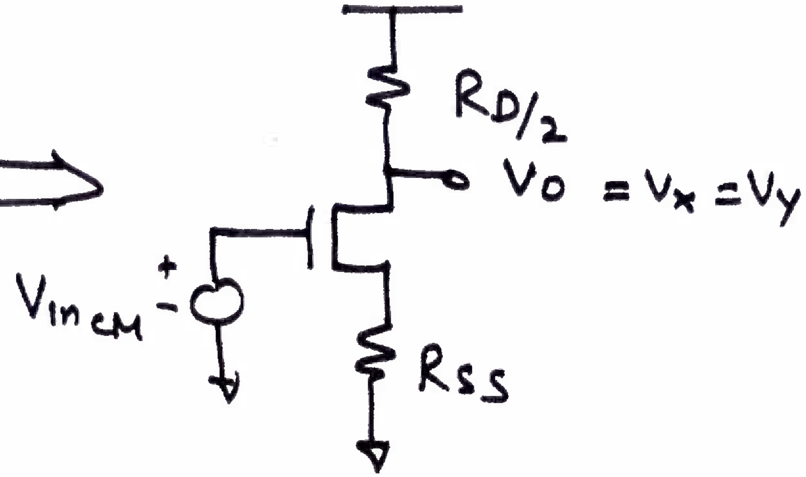
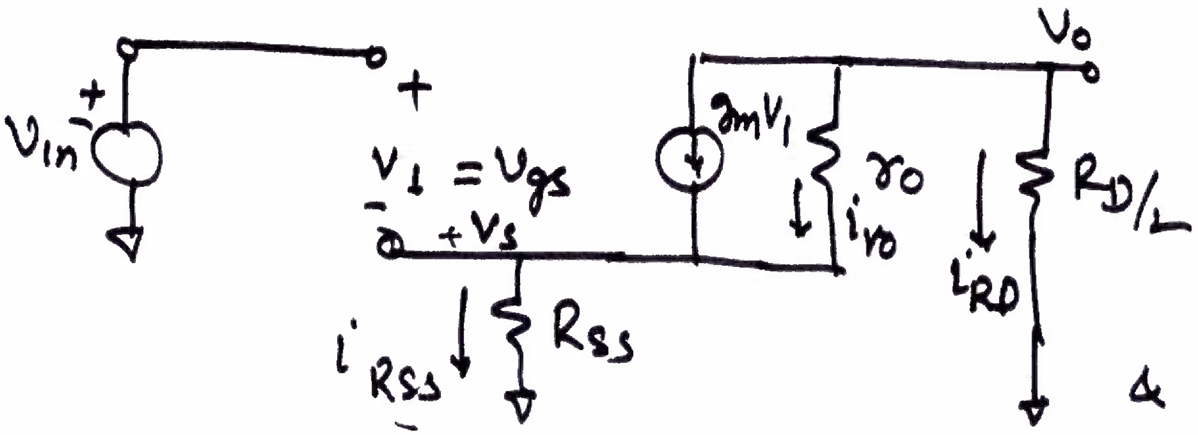
We relook A_{vCM} again



$\Longrightarrow$





$$i_{RD} = -i_{R_{SS}}$$

$$V_s = i_{R_{SS}} \cdot R_{SS}$$

$$i_{RD} = \frac{V_o}{R_D/2}$$

& $g_m V_1 + i_{ro} = i_{R_{SS}} = -i_{RD}$

$$v_1 = v_{in} - v_s = v_{in} + \frac{v_o}{R_D/2} R_{SS}$$

$$i_{ro} = I_{R_{SS}} - g_m v_1$$

$$= -\frac{v_o}{R_D/2} - g_m \left(v_{in} + \frac{v_o R_{SS}}{R_D/2} \right)$$

$$= -\frac{2v_o}{R_D}(1 + g_m R_{SS}) - g_m v_{in}$$

$$\therefore \quad v_o = v_s + i_{ro} \cdot r_o$$

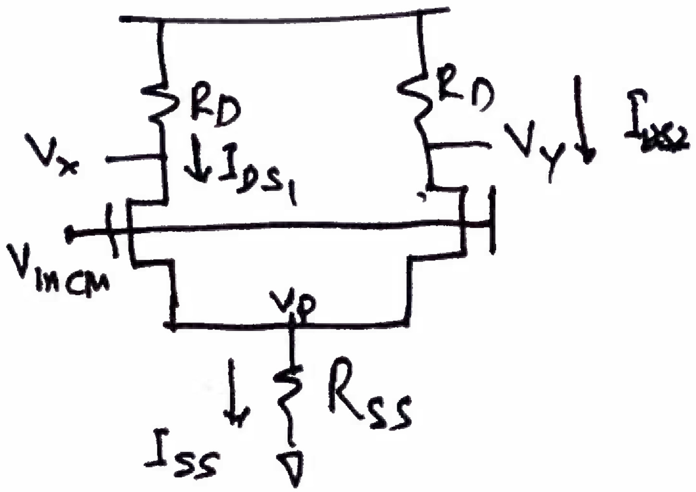
$$= -\frac{2v_o}{R_D} R_{SS} - \frac{2v_o}{R_D}(1 + g_m R_{SS}) r_o - g_m r_o v_{in}$$

$$\text{or} \quad \frac{v_o}{v_{inCM}} = A_{VCM} = \frac{-2 g_m r_o (R_D/2)}{R_D + 2R_{SS} + 2r_o(1 + g_m R_{SS})} \qquad \text{If } R_{SS} \gg \frac{1}{g_m}$$

$$= \frac{-R_D/2}{1/g_m + R_{SS}} \cong -\frac{R_D}{2R_{SS}} = \frac{-g_m R_D}{2(1 + g_m R_{SS})}$$

If M_1 & M_2 do not have Identical Characteristics, due to Mismatches, then $V_x \neq V_y$

Then from the eq. circuit of Symmetry cannot be used.



$$\therefore I_{DS1} = g_{m1}(V_{inCM} - V_P)$$

$$\& \quad I_{DS_2} = g_{m2}(V_{inCM} - V_P)$$

$$\gamma \quad V_P = (I_{DS1} + I_{DS_2}) \cdot R_{SS}$$

$$= \frac{(g_{m1} + g_{m2}) R_{SS}}{1 + (g_{m1} + g_{m2}) R_{SS}} V_{inCM}$$

Then $V_x = -I_{DS1} \cdot R_D$

$$V_x = -g_{m1}(V_{inCM} - V_P) R_D = \frac{-g_{m1} R_D}{1 + (g_{m1} + g_{m2}) R_{SS}} V_{inCM}$$

Similarly $V_y = -\dfrac{g_{m2} R_D V_{inCM}}{1 + (g_{m1} + g_{m2}) R_{SS}}$

$$\therefore \quad V_x - V_y = - \frac{(g_{m1} - g_{m2}) R_D}{1 + (g_{m1} + g_{m2}) R_{SS}} V_{INCM}$$

or $$A_{VCM-DM} = - \frac{\Delta g_m R_D}{1 + g_m R_{SS}}$$

Where $\Delta g_m = g_{m1} - g_{m2}$

$g_m = g_{m1} + g_{m2}$

Then we define $$CMRR = \frac{A_{VDM}}{A_{VCM-DM}}$$

$$\cong \frac{2 g_m}{\Delta g_m} (1 + g_m R_{SS})$$

$\therefore$ For larger CMRR requirements

1. g_m's be larger $\leftarrow$ I_{DS}, W/L
2. R_{SS} be large
3. Mismatch be minimised: $\Delta g_m \rightarrow$ smaller

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DIFFAMP WITH DIFFERENT LOADS

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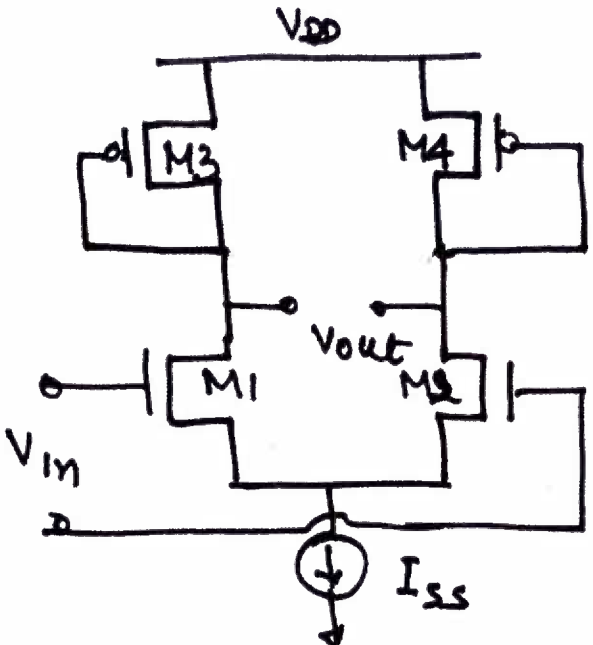
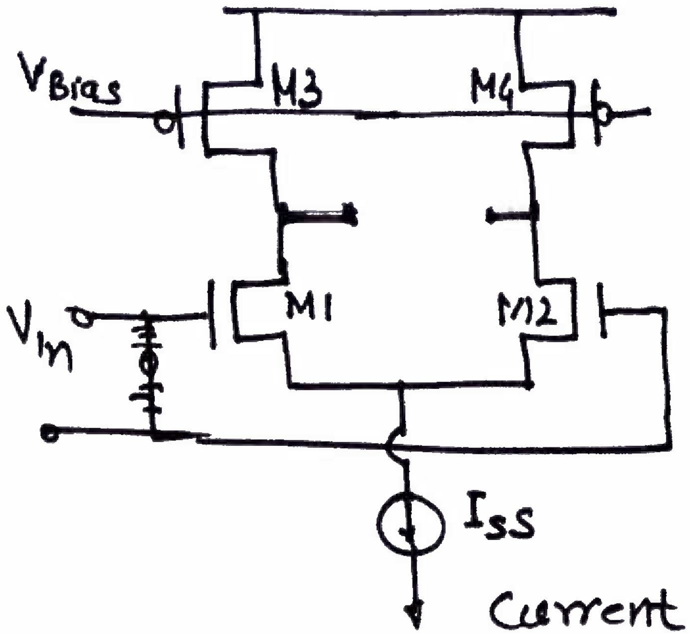
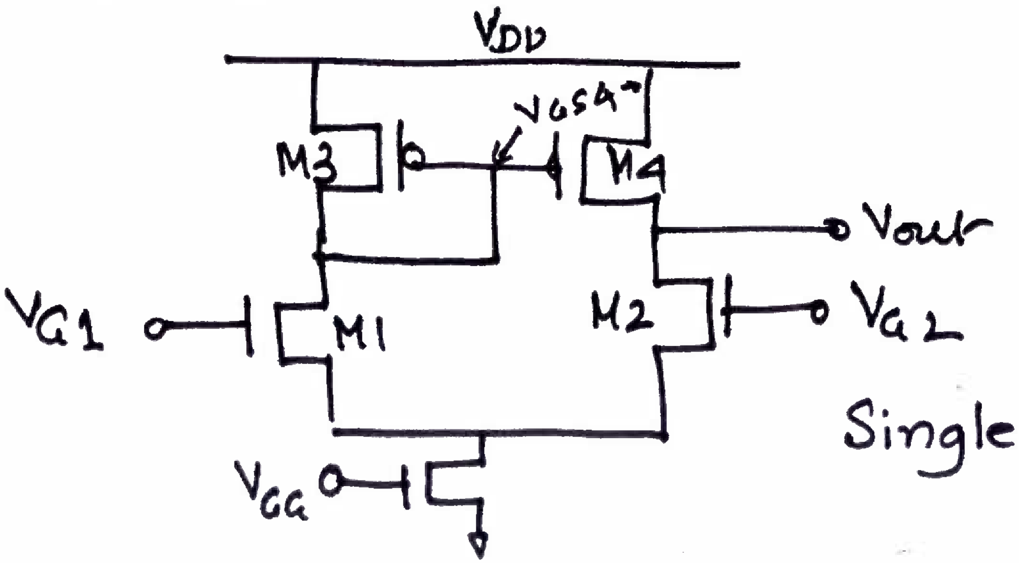


Diode Connected Load



Current Source Load



Single Ended DIFFAMP

For Diode connected load :—

$$R_{Load} = g_{mp}^{-1} \parallel r_{op} \simeq g_{mp}^{-1}$$

Then $A_V = -\dfrac{g_{mn}}{g_{mp}} = \sqrt{\dfrac{\mu_n}{\mu_p} \cdot \dfrac{(W/L)_n}{(W/L)_p}}$

For Current Source load :

$$R_{Load} = r_{op}$$

$$\therefore \quad A_V = -g_{mn} \left(r_{on} \parallel r_{op} \right)$$