Example

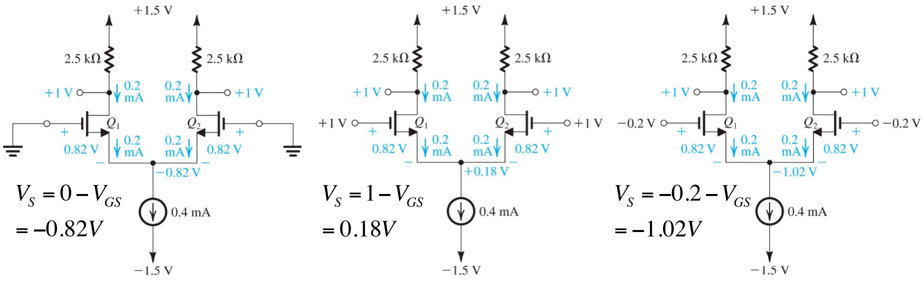
V_{DD}=V_{SS}=1.5V, I=0.4mA, R_D=2.5kΩ. Minimum voltage across current source V_{CS}=0.4V
For Q_1 and Q_2: k_n=4mA/V^2, V_{tn}=0.5V. Find V_S, I_{D1}, I_{D2}, V_{D1}, V_{D2} for 3 different V_{CM} below:

Due to symmetry, $I_{D1} = I_{D2} = I/2$ for all 3 V_{CM} values

$V_{GS} = V_{tn} + \sqrt{I/k_n} = 0.5 + 0.32 = 0.82V$

$V_{D1} = V_{D2} = V_{DD} - 0.5I \cdot R_D = 1.5 - 0.2 \times 2.5 = 1V$

Differential output $V_{D1} - V_{D2} = 0$



$V_S = 0 - V_{GS} = -0.82V$

$V_S = 1 - V_{GS} = 0.18V$

$V_S = -0.2 - V_{GS} = -1.02V$

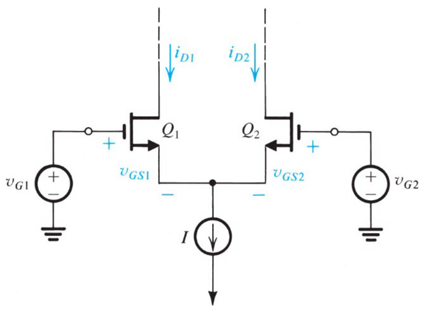
Maximum V_{CM} should keep Q_1 and Q_2 in Saturation

$V_{DS} > V_{GS} - V_{tn}$; $V_D - V_S > V_G - V_S - V_{tn}$; $V_{CM,\max} = V_{G,\max} = V_D + V_{tn} = 1.5V$

Minimum V_{CM} should keep V_S above minimum current source voltage, V_{CS}

$V_{CM,\min} = -V_{SS} + V_{CS,\min} + V_{GS} = -1.5 + 0.82 + 0.4 = -0.28V$

Operation with Differential Input Voltage



$$i_{D1} = \frac{k_n}{2}(v_{GS1} - V_t)^2; \quad i_{D2} = \frac{k_n}{2}(v_{GS2} - V_t)^2$$

$$\sqrt{i_{D1}} - \sqrt{i_{D2}} = \sqrt{\frac{k_n}{2}}(v_{GS1} - v_{GS2}) = \sqrt{\frac{k_n}{2}} v_{id}$$

square both sides, and recall $i_{D1} + i_{D2} = I$

$$2\sqrt{i_{D1} i_{D2}} = I - \frac{k_n}{2} v_{id}^2$$

substitute $i_{D2} = I - i_{D1}$, solve quadratic equation:

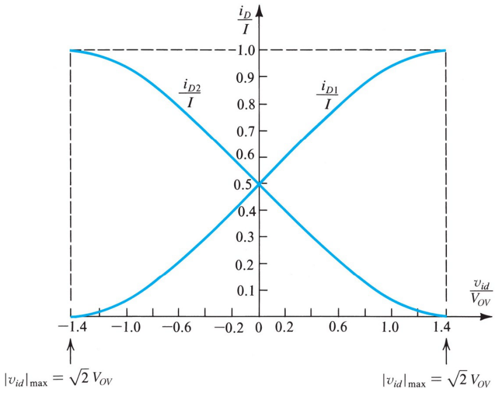
$$i_{D1,2} = \frac{I}{2} \pm \sqrt{k_n I} \frac{v_{id}}{2} \sqrt{1 - \frac{(v_{id}/2)^2}{I/k_n}}$$

$$\frac{I}{2} = \frac{1}{2} k_n V_{OV}^2 \quad \Rightarrow k_n = I/V_{OV}^2$$

$$i_{D1,2} = \frac{I}{2} \pm \frac{I}{V_{OV}} \frac{v_{id}}{2} \sqrt{1 - \frac{(v_{id}/2)^2}{V_{OV}^2}}$$

Operation with Differential Input Voltage

$$i_{D1,2} = \frac{I}{2} \pm \frac{I}{V_{OV}} \frac{v_{id}}{2} \sqrt{1 - \frac{(v_{id}/2)^2}{V_{OV}^2}}$$



Near $v_{id} = 0$:

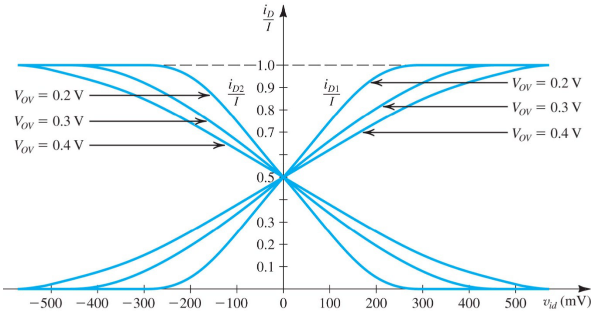
$$\sqrt{1 - \frac{(v_{id}/2)^2}{V_{OV}^2}} \approx 1 \text{ (neglect high-order terms)}$$

$$i_{D1} = \frac{I}{2} + \frac{I}{V_{OV}} \frac{v_{id}}{2}$$

$$i_{D2} = \frac{I}{2} - \frac{I}{V_{OV}} \frac{v_{id}}{2}$$

Current of Differential Pair for Various Overdrive Voltage

$$i_{D1,2} = \frac{I}{2} \pm \frac{I}{V_{OV}} \frac{v_{id}}{2} \sqrt{1 - \frac{(v_{id}/2)^2}{V_{OV}^2}}$$



The linear range of operation of the MOS differential pair can be extended by operating the transistor at a higher value of V_{OV}