ECEN 325
Electronics

MOS Field-Effect Transistors

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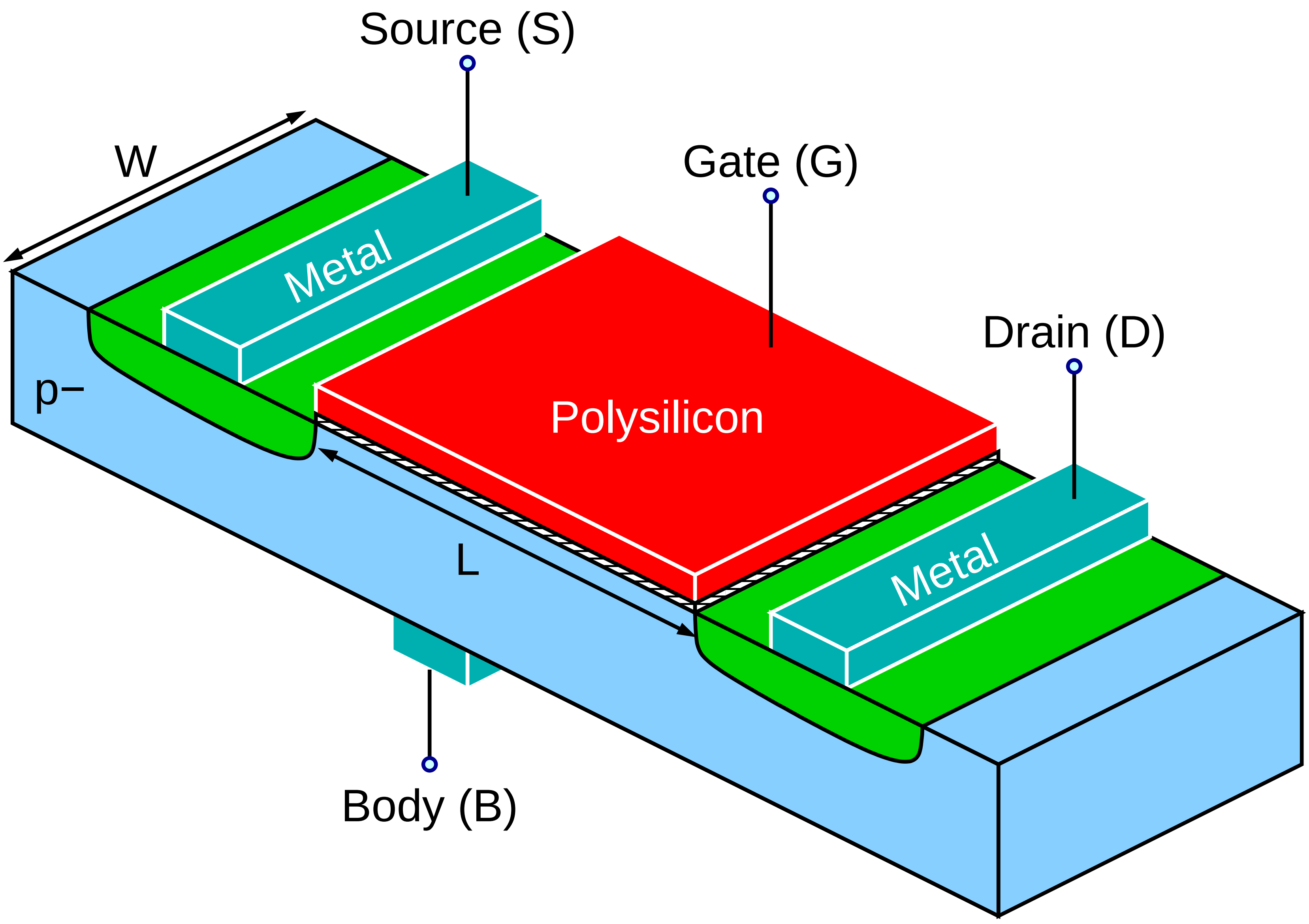
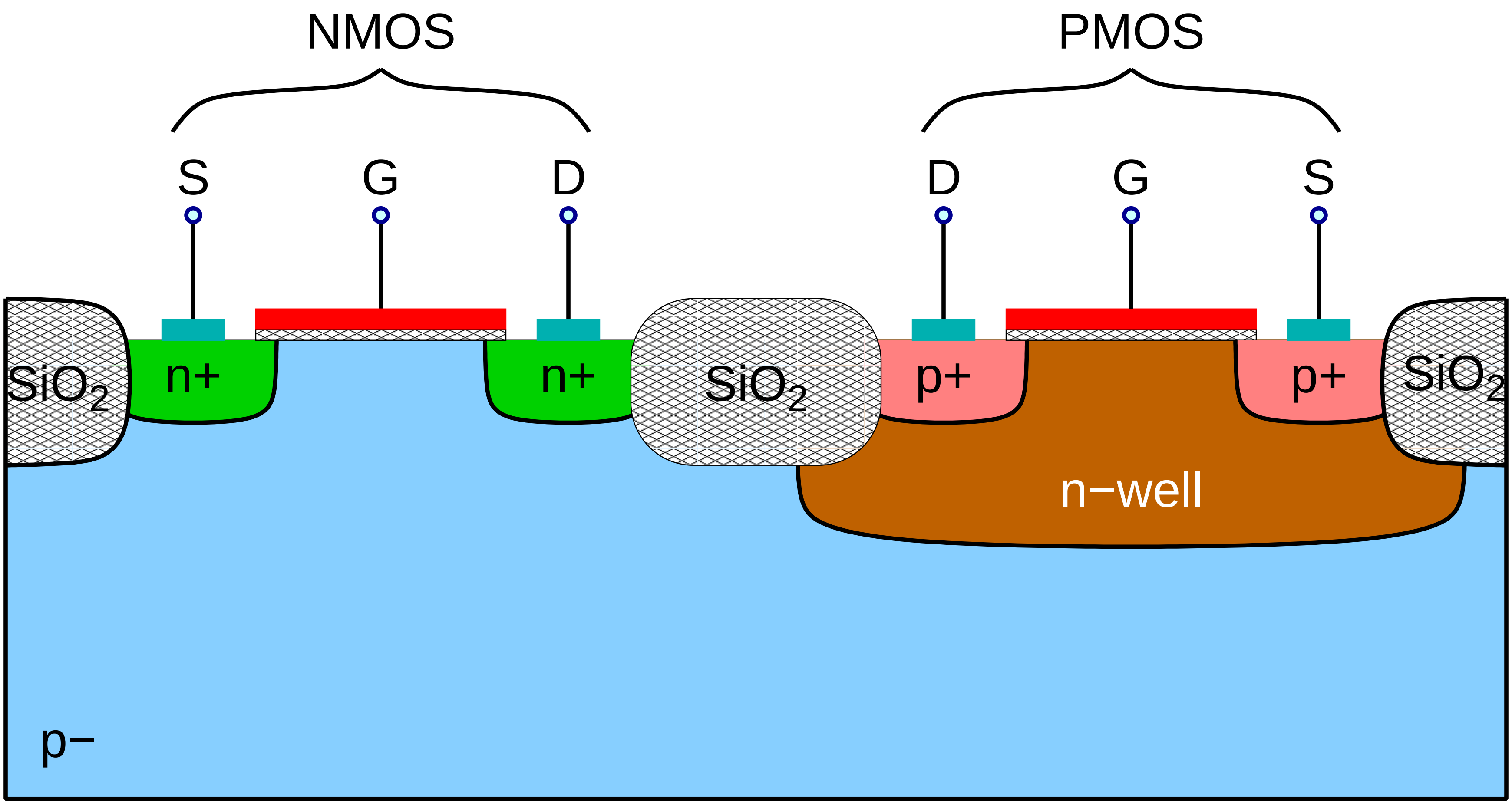
Department of Electrical and Computer Engineering

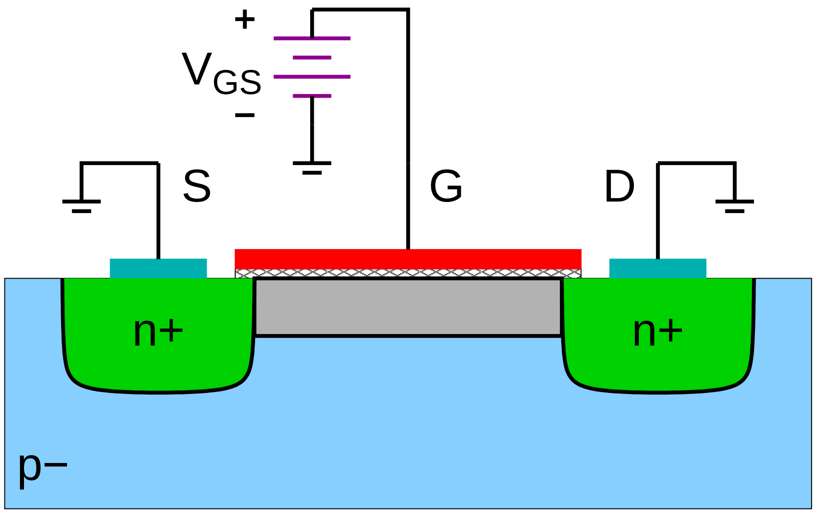
NMOS Physical Structure



CMOS Physical Structure

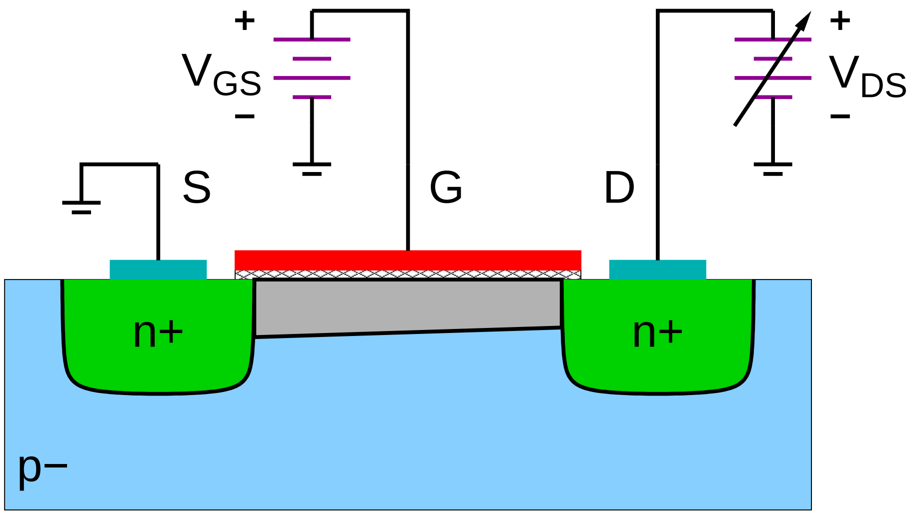


Physical Operation



$\mathbf{V_{GS} > V_{tn}}$

$\mathbf{V_{DS} = 0}$

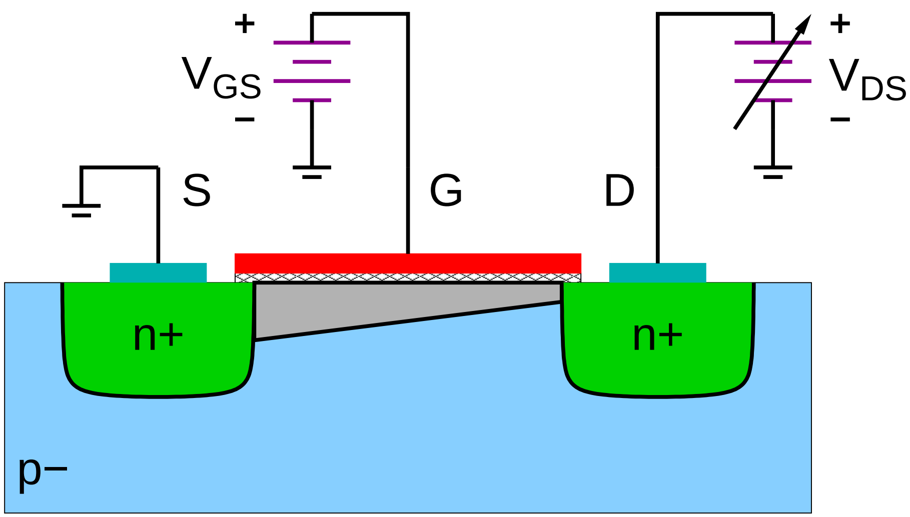


$\mathbf{V_{GS} > V_{tn}}$

$\mathbf{V_{DS}}$ **:** very small

Physical Operation

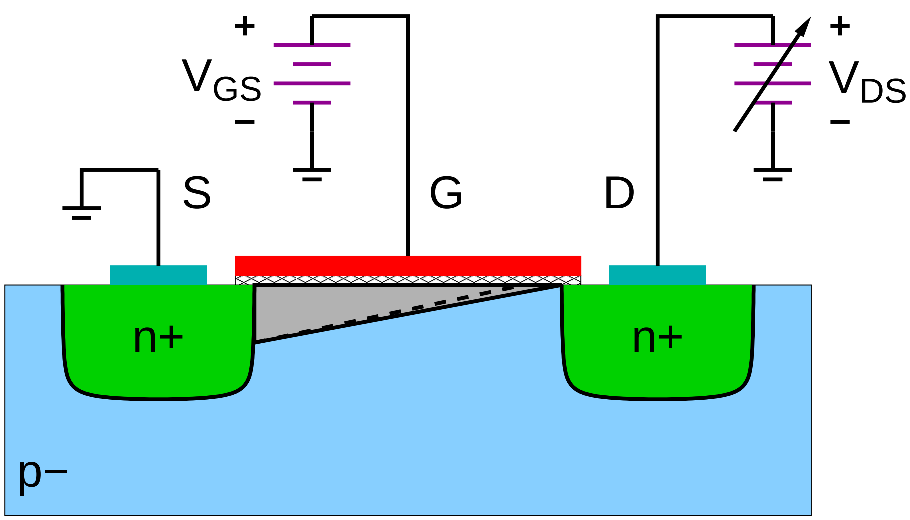
NMOS



$V_{GS} > V_{tn}$

$V_{DS} < V_{ov}$

$V_{ov} = V_{GS} - V_{tn}$

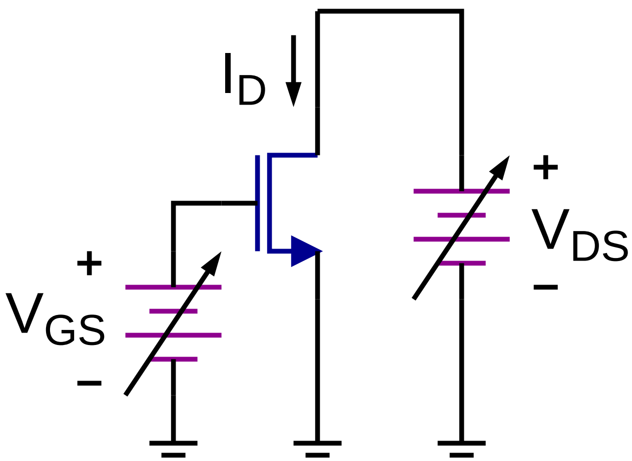


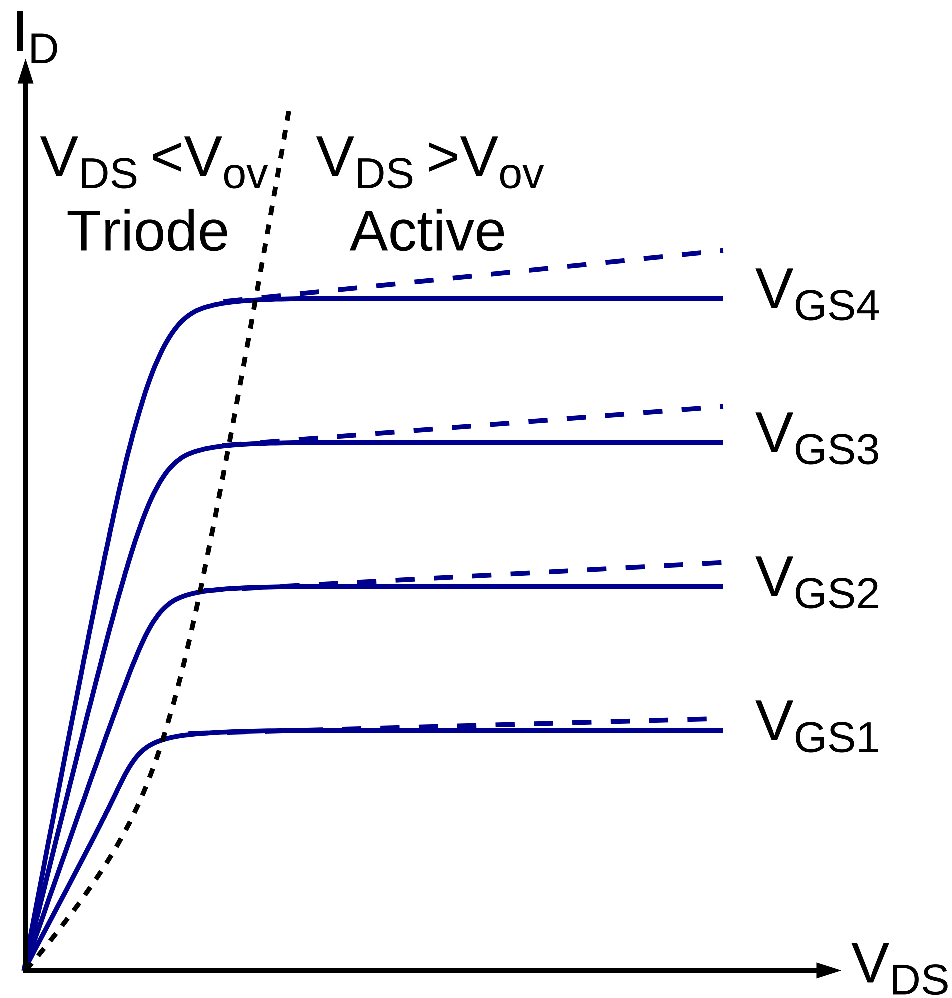
$V_{GS} > V_{tn}$

$V_{DS} > V_{ov}$

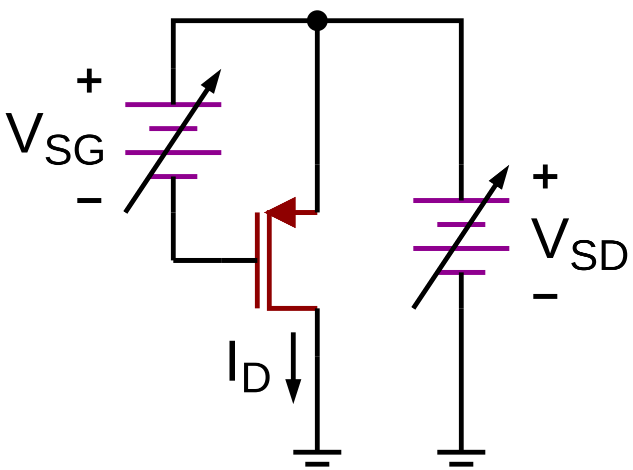
$V_{ov} = V_{GS} - V_{tn}$

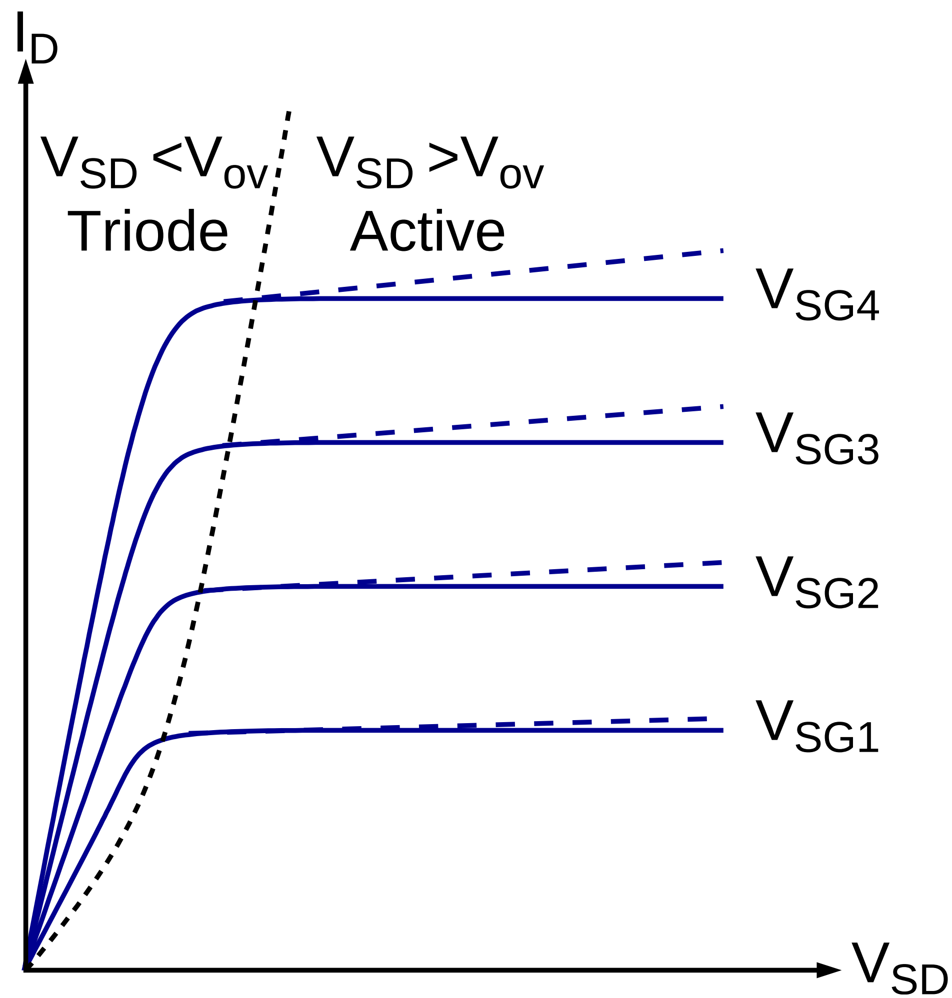
I_D-V_{DS} Characteristics



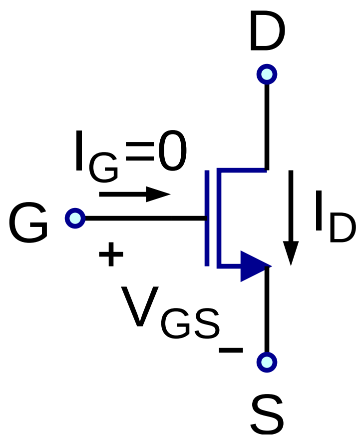


I_D-V_{SD} Characteristics





NMOS DC Operation



$$V_{ov} = V_{GS} - V_{tn}$$

- Cutoff: $V_{GS} < V_{tn}$, $I_D = 0$

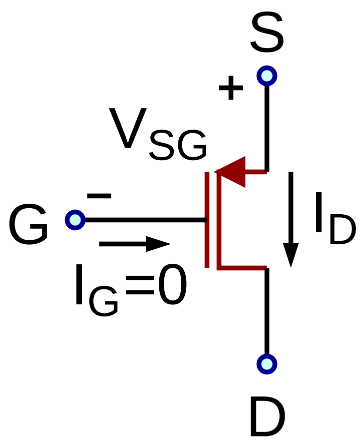
- Triode (linear) region: $V_{DS} < V_{ov}$

$$I_D = k_n' \frac{W}{L}\left(V_{ov}V_{DS} - \frac{V_{DS}^2}{2}\right)$$

- Active (saturation) region: $V_{DS} > V_{ov}$

$$I_D = \frac{k_n'}{2}\frac{W}{L}V_{ov}^2$$

PMOS DC Operation



$$V_{ov} = V_{SG} - |V_{tp}|$$

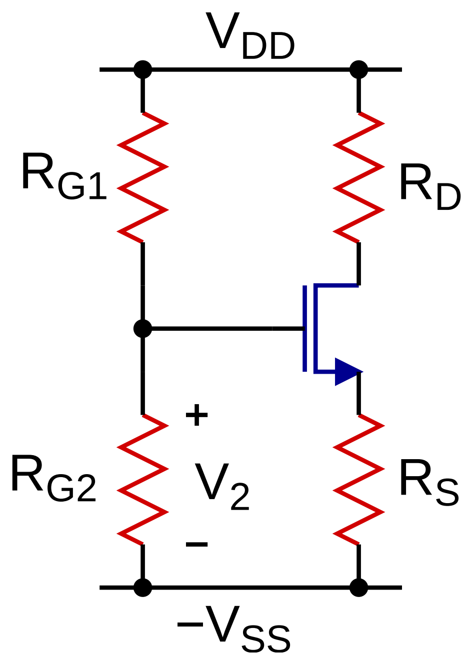
- Cutoff: $V_{SG} < |V_{tp}|$, $I_D = 0$
- Triode (linear) region: $V_{SD} < V_{ov}$

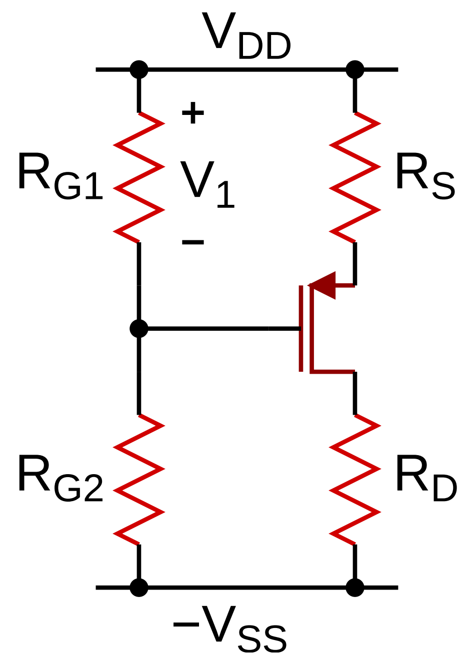
$$I_D = k'_p \frac{W}{L}\left(V_{ov}V_{SD} - \frac{V_{SD}^2}{2}\right)$$

- Active (saturation) region: $V_{SD} > V_{ov}$

$$I_D = \frac{k'_p}{2}\frac{W}{L}V_{ov}^2$$

MOSFET DC Biasing





$$V_2 = \frac{R_{G2}(V_{DD} + V_{SS})}{R_{G1} + R_{G2}}$$

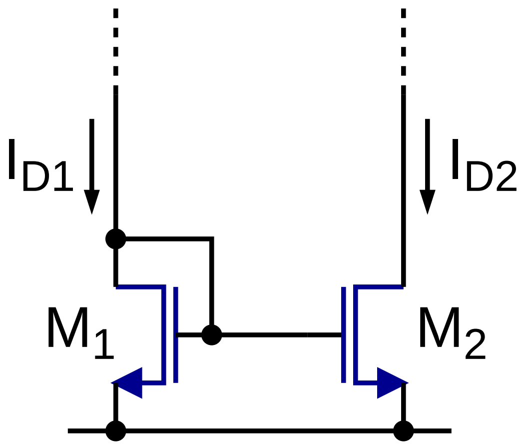
$$V_1 = \frac{R_{G1}(V_{DD} + V_{SS})}{R_{G1} + R_{G2}}$$

$$V_2 = V_{GSn} + R_S I_{Dn}$$

$$V_1 = V_{SGp} + R_S I_{Dp}$$

$$I_{Dn} = \frac{k'_n}{2}\frac{W}{L}(V_{GSn} - V_{tn})^2$$

$$I_{Dp} = \frac{k'_p}{2}\frac{W}{L}(V_{SGp} - V_{tp})^2$$



Assuming $\mathbf{V_{GS1} > V_{tn}}$

$$\mathbf{V_{GS1} = V_{DS1}} \;\Rightarrow\; \mathbf{V_{DS1} > V_{GS1} - V_{tn}}$$

$\Rightarrow$ $\mathbf{M_1}$ is ACTIVE

$$\Rightarrow \mathbf{I_{D1} = \frac{k'_n}{2}\left(\frac{W}{L}\right)_1 (V_{GS1} - V_{tn})^2}$$

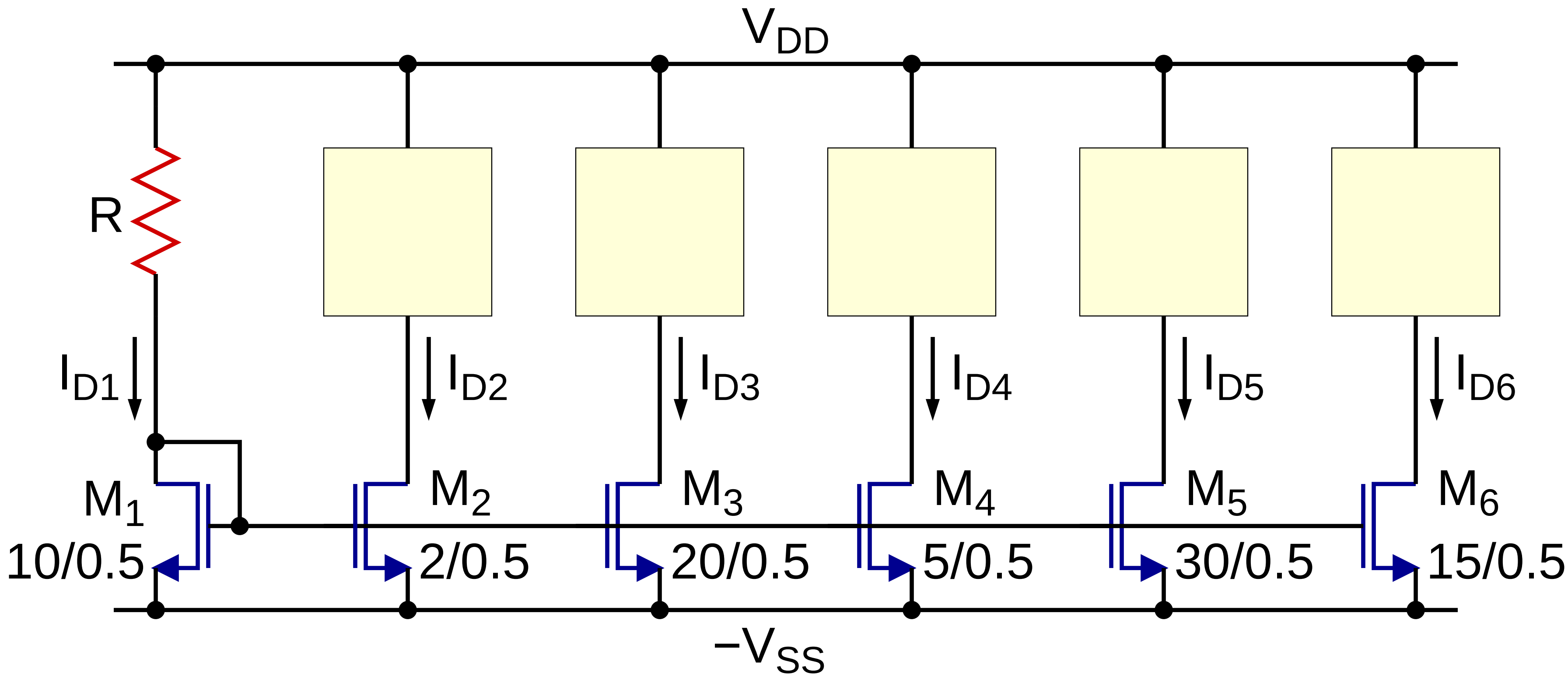
Assuming $\mathbf{M_2}$ is ACTIVE

$$\mathbf{I_{D2} = \frac{k'_n}{2}\left(\frac{W}{L}\right)_2 (V_{GS2} - V_{tn})^2}$$

Since $\mathbf{V_{GS1} = V_{GS2}}$

$$\mathbf{\frac{I_{D1}}{I_{D2}} = \frac{\left(\frac{W}{L}\right)_1}{\left(\frac{W}{L}\right)_2}}$$

NMOS Current Mirror

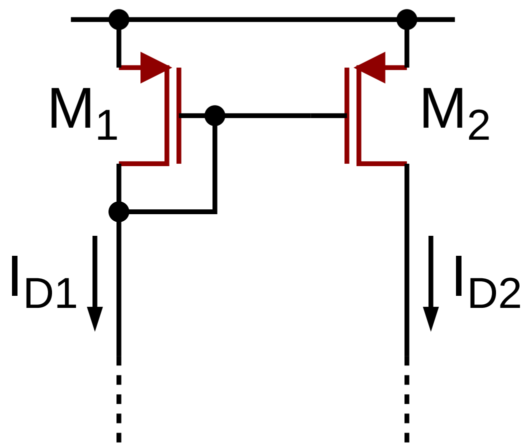


$$\left.\begin{array}{l} V_{DD} + V_{SS} = R_1 I_{D1} + V_{GS1} \\ I_{D1} = \frac{k_n'}{2}\frac{10}{0.5}(V_{GS1} - V_{tn})^2 \end{array}\right\} \Rightarrow \text{ Find } I_{D1}$$

<u>Assuming that all transistors are ACTIVE:</u>

$$I_{D2} = \frac{I_{D1}}{5} \qquad I_{D3} = 2I_{D1} \qquad I_{D4} = \frac{I_{D1}}{2}$$

$$I_{D5} = 3I_{D1} \qquad I_{D6} = \frac{3}{2}I_{D1}$$



Assuming $V_{SG1} > |V_{tp}|$

$V_{SG1} = V_{SD1} \;\Rightarrow\; V_{SD1} > V_{SG1} - |V_{tp}|$

$\Rightarrow$ M_1 is ACTIVE

$$\Rightarrow\; I_{D1} = \frac{k'_p}{2}\left(\frac{W}{L}\right)_1 (V_{SG1} - |V_{tp}|)^2$$

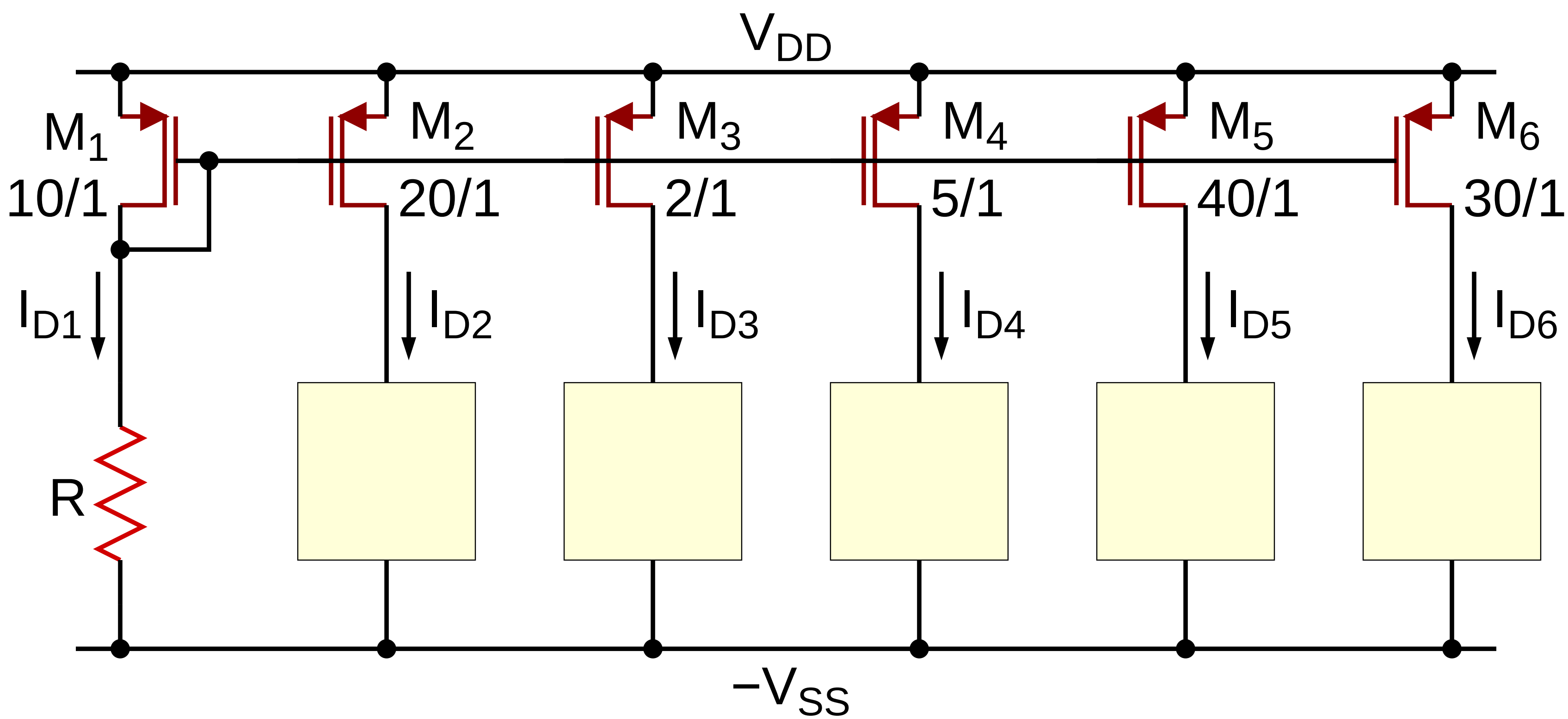
Assuming M_2 is ACTIVE

$$I_{D2} = \frac{k'_p}{2}\left(\frac{W}{L}\right)_2 (V_{SG2} - |V_{tp}|)^2$$

Since $V_{SG1} = V_{SG2}$

$$\frac{I_{D1}}{I_{D2}} = \frac{\left(\frac{W}{L}\right)_1}{\left(\frac{W}{L}\right)_2}$$

PMOS Current Mirror



PMOS Current Mirror

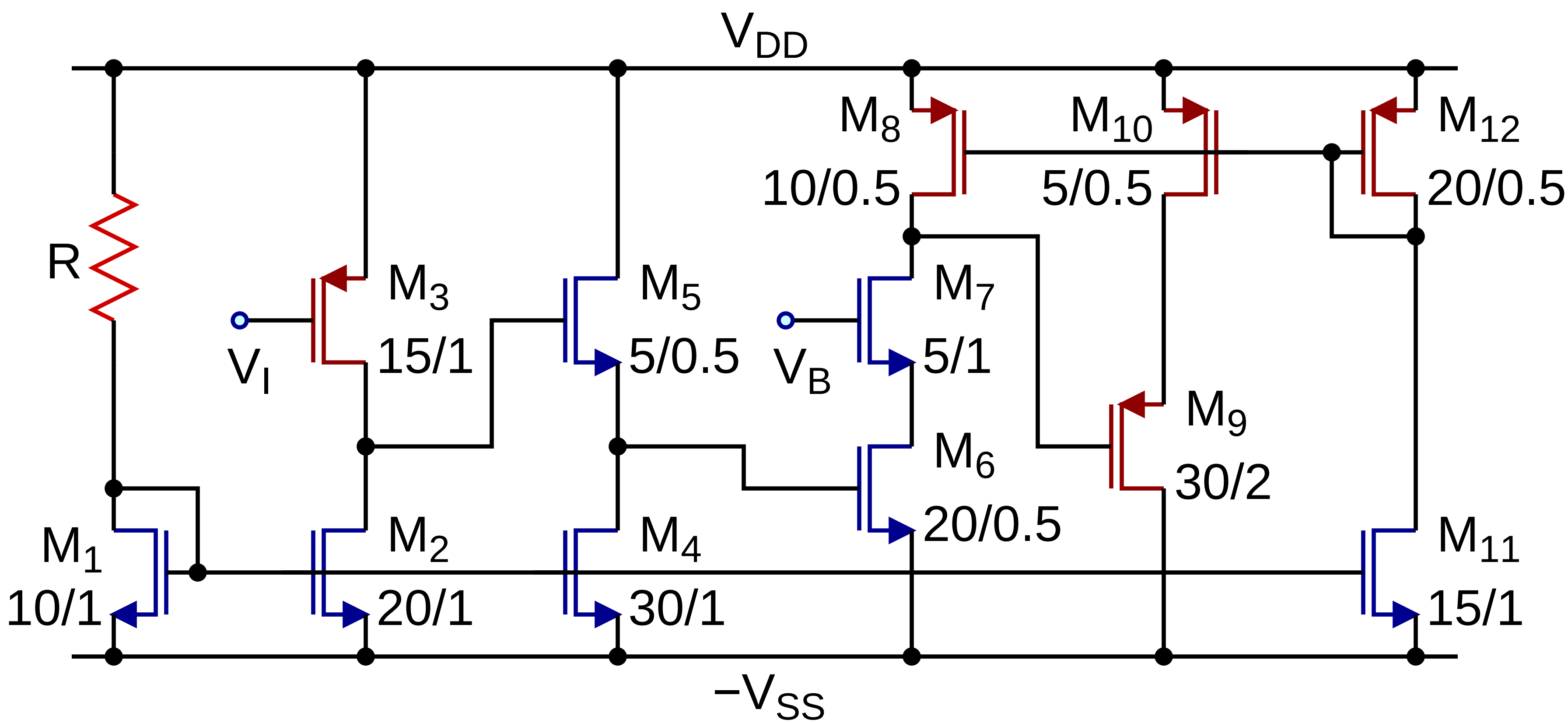
$$\left.\begin{array}{l} \mathbf{V_{DD} + V_{SS} = R_1 I_{D1} + V_{SG1}} \\ \mathbf{I_{D1} = \frac{k'_p}{2} \frac{10}{1} (V_{SG1} - |V_{tp}|)^2} \end{array}\right\} \Rightarrow \text{Find } \mathbf{I_{D1}}$$

<u>Assuming that all transistors are ACTIVE:</u>

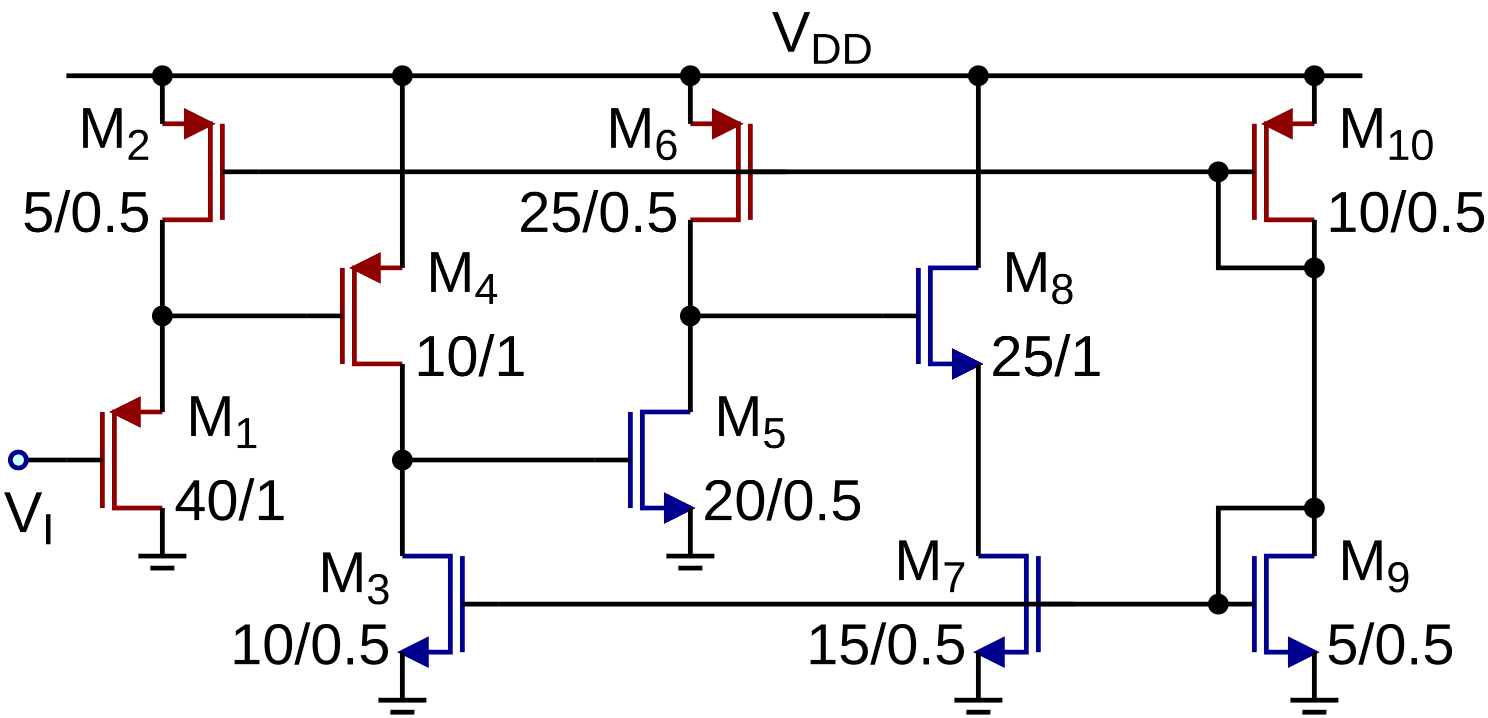
$$\mathbf{I_{D2} = 2I_{D1}} \qquad \mathbf{I_{D3} = \frac{I_{D1}}{5}} \qquad \mathbf{I_{D4} = \frac{I_{D1}}{2}}$$

$$\mathbf{I_{D5} = 4I_{D1}} \qquad \mathbf{I_{D6} = 3I_{D1}}$$

Current Mirror Biasing



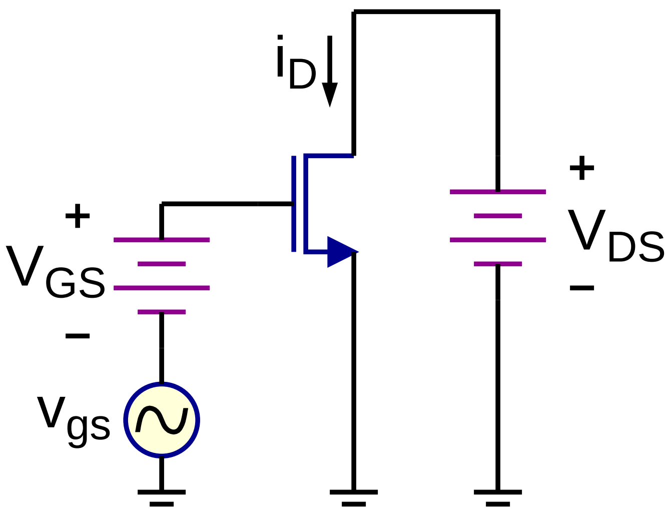
Current Mirror Biasing



MOSFET Small-Signal Operation

$$i_D = \frac{k'_n}{2}\frac{W}{L}(V_{GS} + v_{gs} - V_t)^2 = \frac{k'_n}{2}\frac{W}{L}(V_{ov} + v_{gs})^2$$

$$= \frac{k'_n}{2}\frac{W}{L}V_{ov}^2 + k'_n\frac{W}{L}V_{ov}v_{gs} + \frac{k'_n}{2}\frac{W}{L}v_{gs}^2$$



Assume $v_{gs} \ll 2V_{ov}$, then

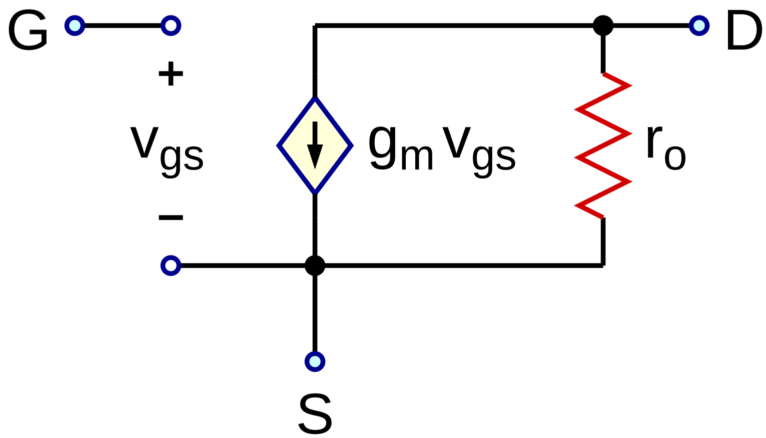
$$\begin{aligned} i_D &\approx I_D + k'_n\frac{W}{L}V_{ov}v_{gs} \\ &= I_D + g_m v_{gs} \\ &= I_D + i_d \end{aligned}$$

$$\boxed{g_m = k'_n\frac{W}{L}V_{ov}}$$

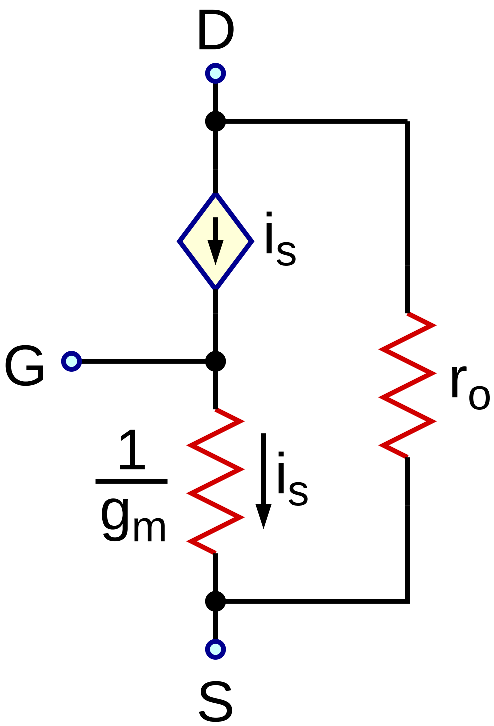
Small-Signal Model

$$g_m = k_n' \frac{W}{L} V_{ov} = \sqrt{2k_n' \frac{W}{L} I_D}$$

$$r_o = \frac{V_A}{I_D} = \frac{1}{\lambda_n I_D}$$



π model

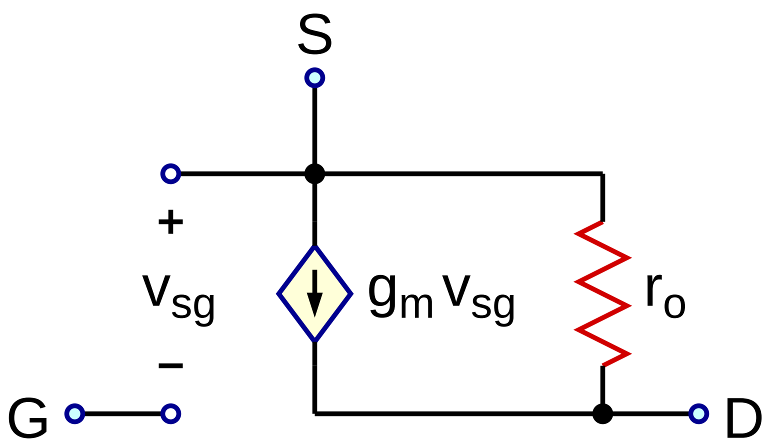


T model

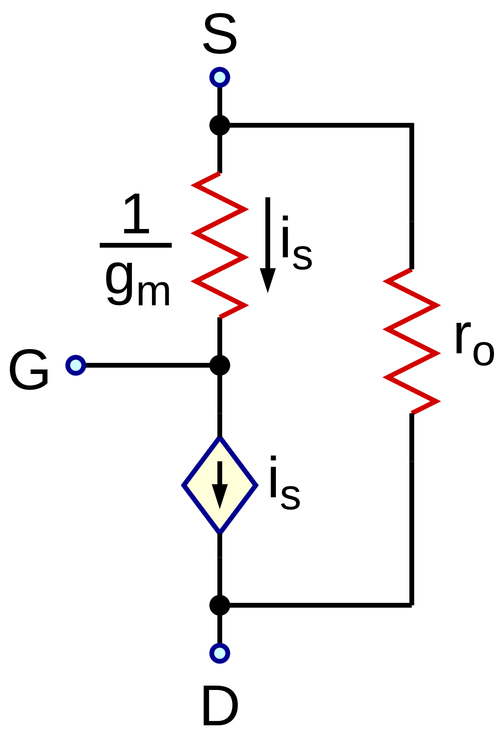
Small-Signal Model

$$g_m = k_p' \frac{W}{L} V_{ov} = \sqrt{2k_p' \frac{W}{L} I_D}$$

$$r_o = \frac{|V_A|}{I_D} = \frac{1}{|\lambda_p| I_D}$$



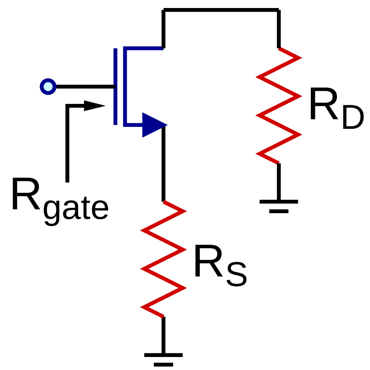
π model



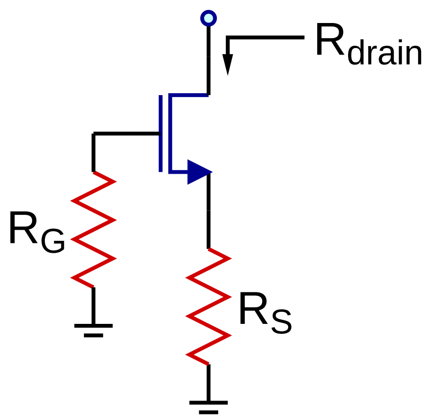
T model

MOS Node Resistances

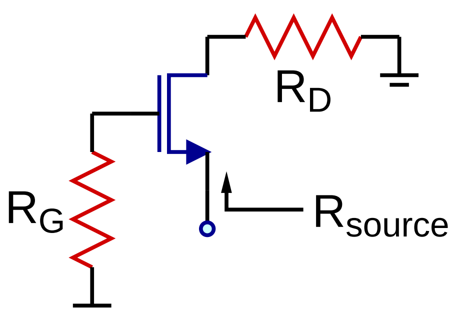
AC, $r_o = \infty$



$$R_{gate} = \infty$$

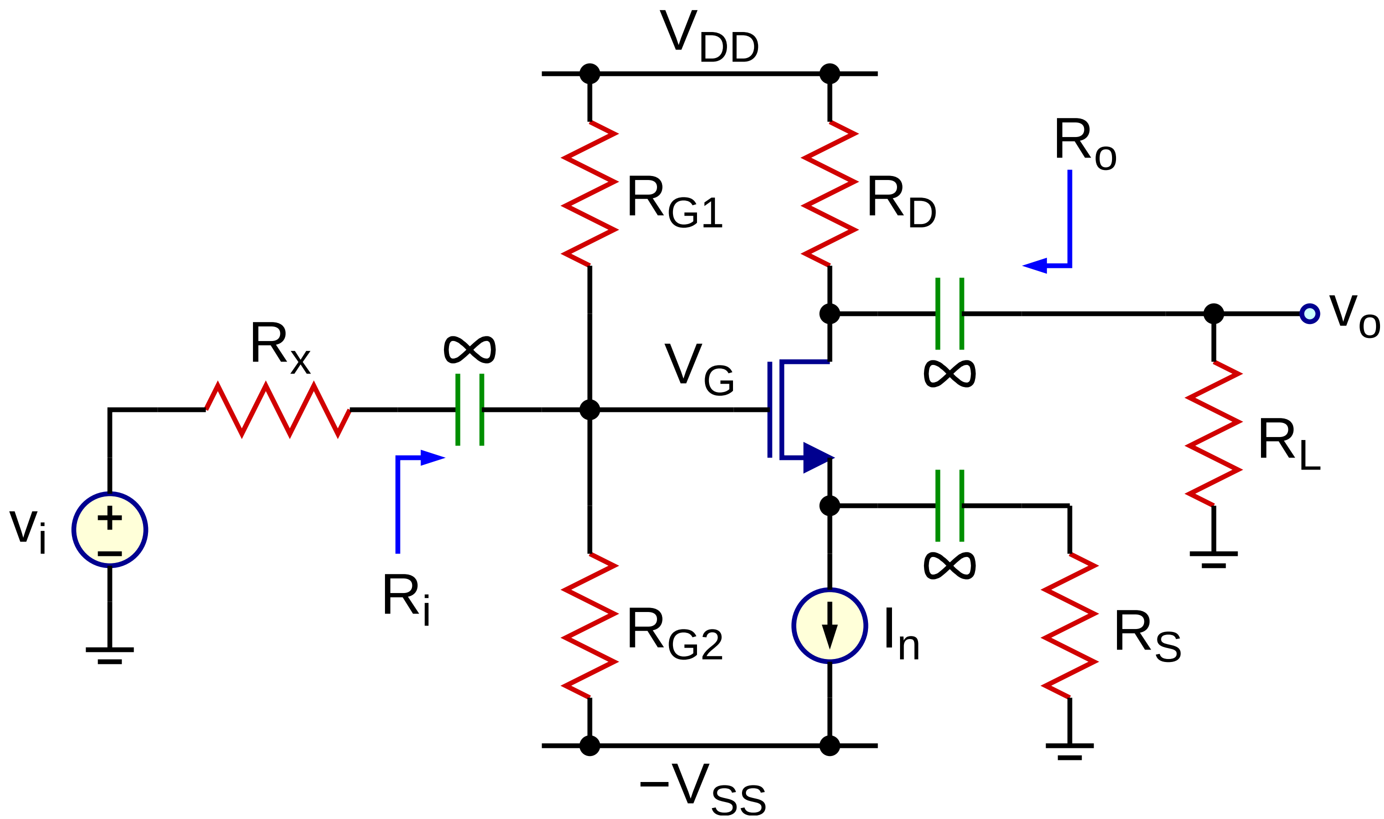


$$R_{drain} = \infty$$



$$R_{source} = \frac{1}{g_m}$$

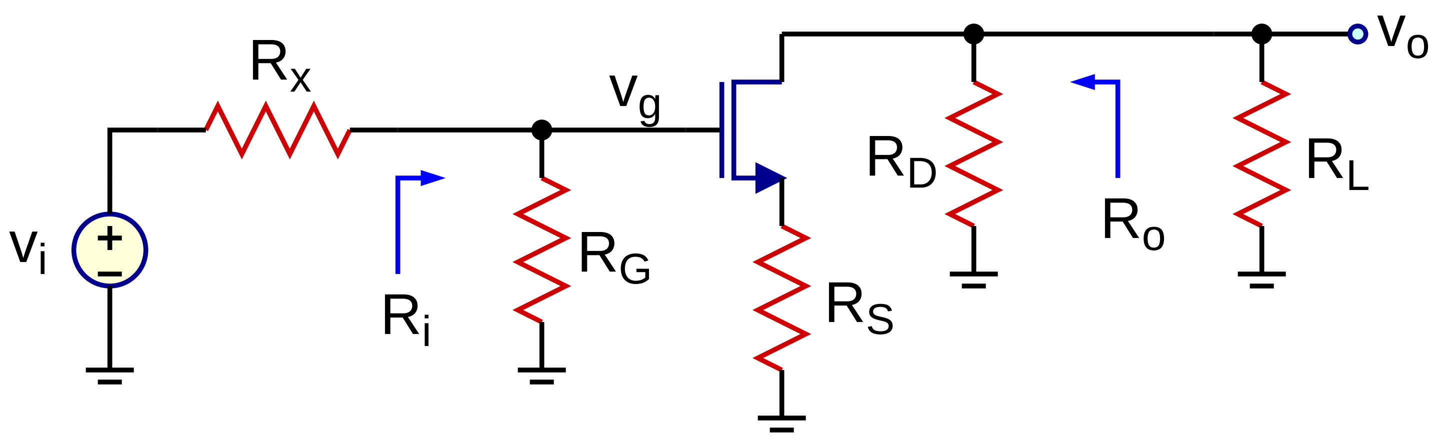
Common-Source Amplifier



$$I_D = I_n \quad , \quad V_G = -V_{SS} + \frac{R_{G2}}{R_{G1} + R_{G2}}(V_{DD} + V_{SS})$$

Common-Source Amplifier

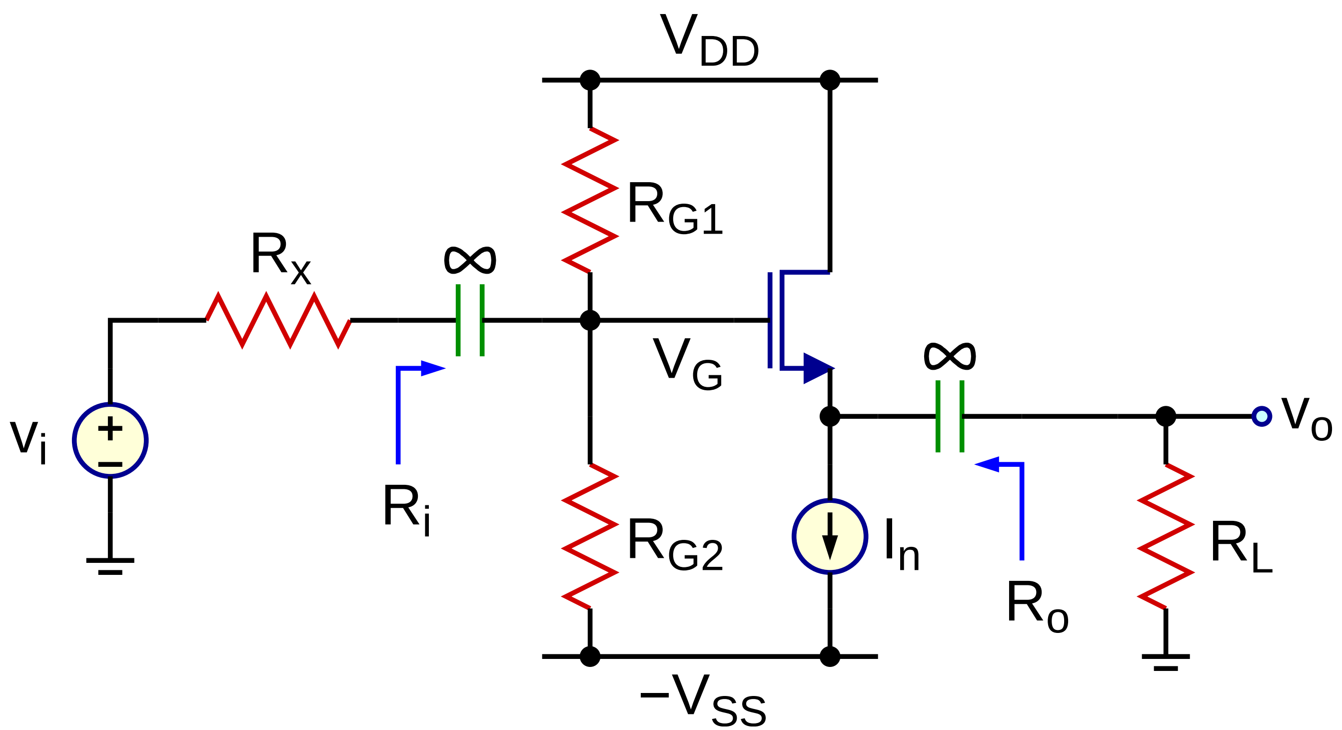
AC equivalent, $r_o = \infty$



$$R_i = R_G \parallel R_{gate} = R_{G1} \parallel R_{G2} \parallel R_{gate}$$

$$R_o = R_D \parallel R_{drain}$$

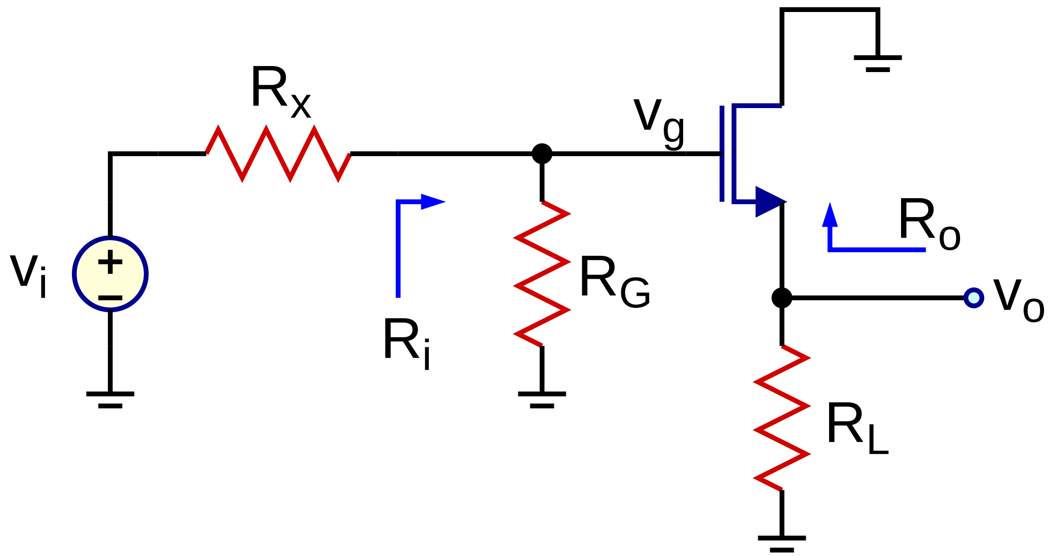
$$\frac{v_g}{v_i} = \frac{R_i}{R_x + R_i} \quad , \quad \frac{v_o}{v_g} = -\frac{R_D \parallel R_L}{\frac{1}{g_m} + R_S}$$



$$I_D = I_n \quad , \quad V_G = -V_{SS} + \frac{R_{G2}}{R_{G1} + R_{G2}}(V_{DD} + V_{SS})$$

Common-Drain Amplifier

AC equivalent, $\mathbf{r_o = \infty}$

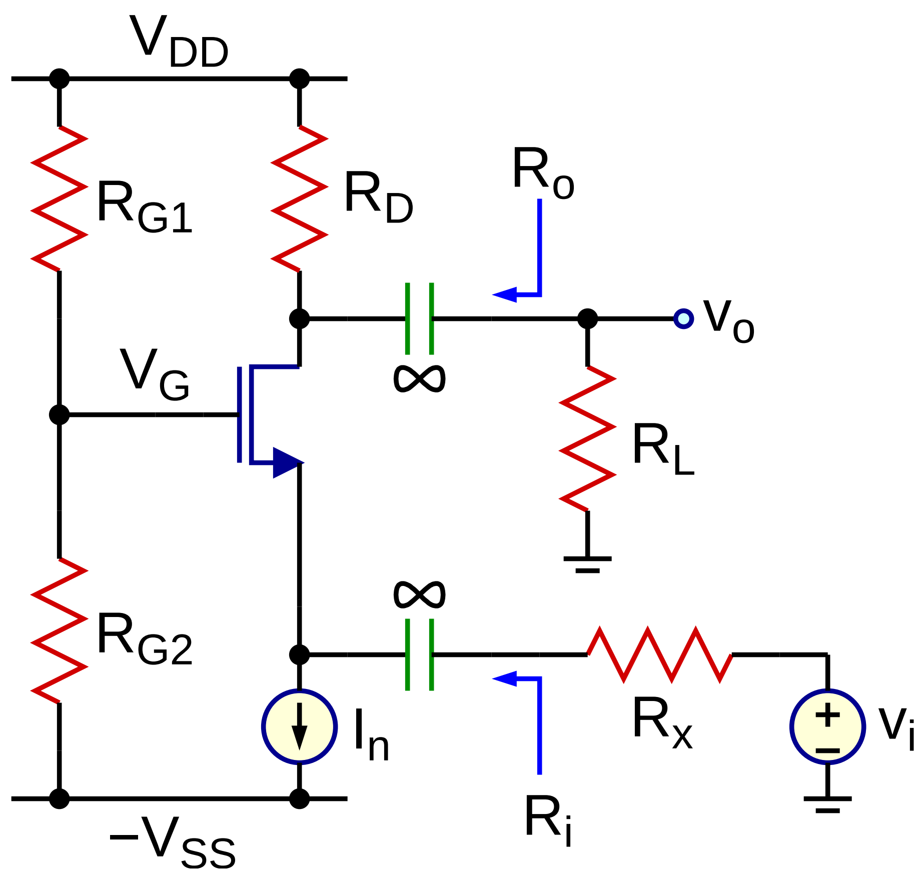


$$R_i = R_G \parallel R_{gate} = R_{G1} \parallel R_{G2} \parallel R_{gate}$$

$$R_o = R_{source}$$

$$\frac{v_g}{v_i} = \frac{R_i}{R_x + R_i} \quad , \quad \frac{v_o}{v_g} = \frac{R_L}{\frac{1}{g_m} + R_L}$$

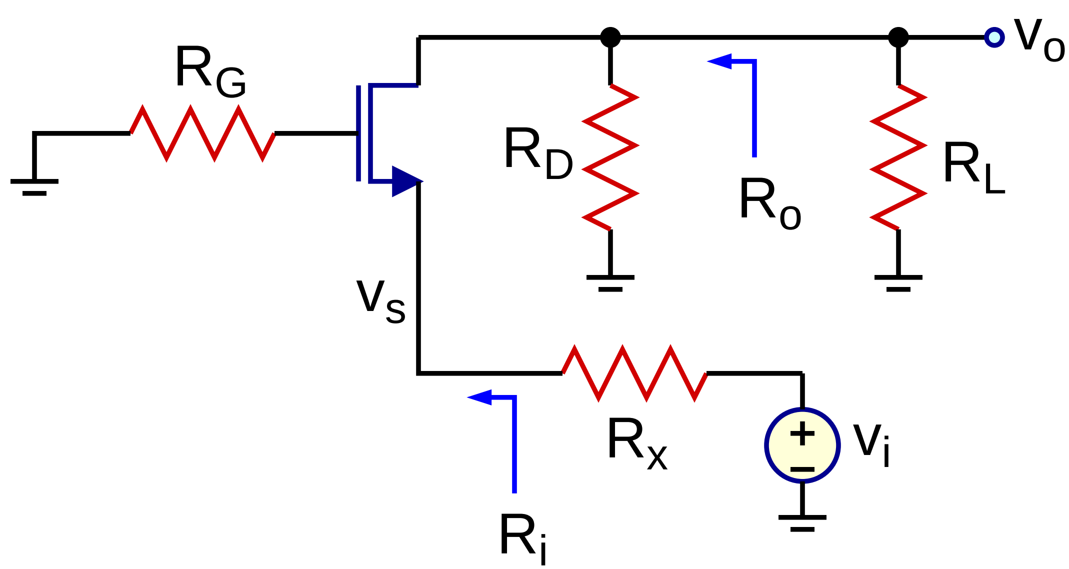
Common-Gate Amplifier



$$I_D = I_n \quad , \quad V_G = -V_{SS} + \frac{R_{G2}}{R_{G1} + R_{G2}}(V_{DD} + V_{SS})$$

Common-Gate Amplifier

AC equivalent, $\mathbf{r_o = \infty}$



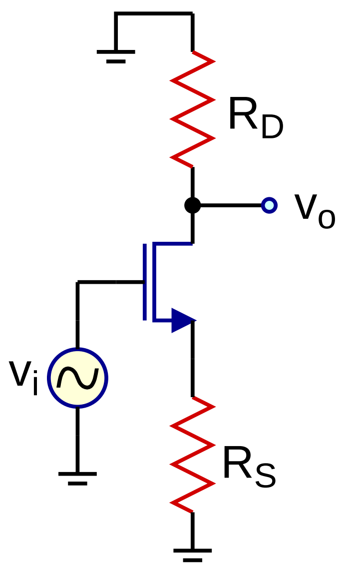
$$R_i = R_{source}$$

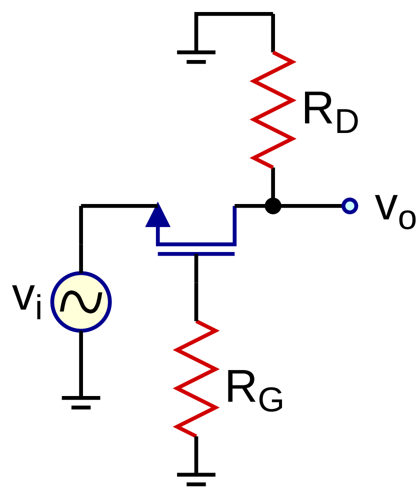
$$R_o = R_D \parallel R_{drain}$$

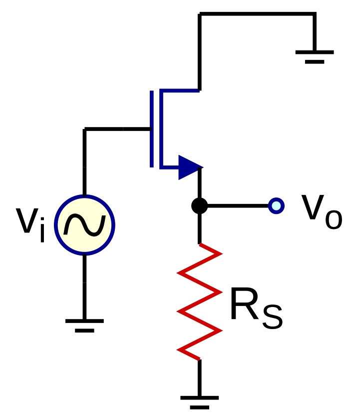
$$\frac{v_s}{v_i} = \frac{R_i}{R_x + R_i} \quad , \quad \frac{v_o}{v_s} = \frac{R_D \parallel R_L}{R_{source}}$$

MOSFET Amplifiers - Summary

AC, $r_o = \infty$







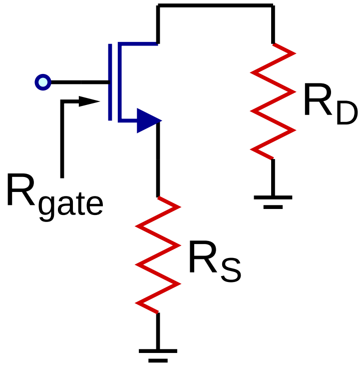
$$\frac{v_o}{v_i} = -\frac{R_D}{\frac{1}{g_m} + R_S}$$

$$\frac{v_o}{v_i} = \frac{R_D}{R_{source}}$$

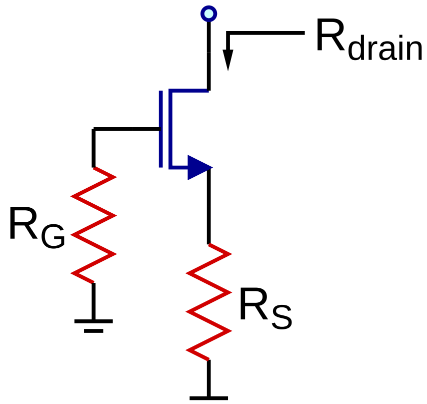
$$\frac{v_o}{v_i} = \frac{R_S}{\frac{1}{g_m} + R_S}$$

MOS Node Resistances

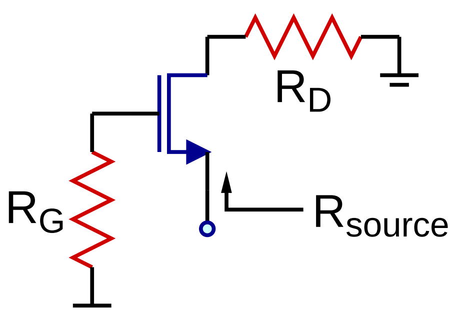
AC, r_o finite



$$R_{gate} = \infty$$

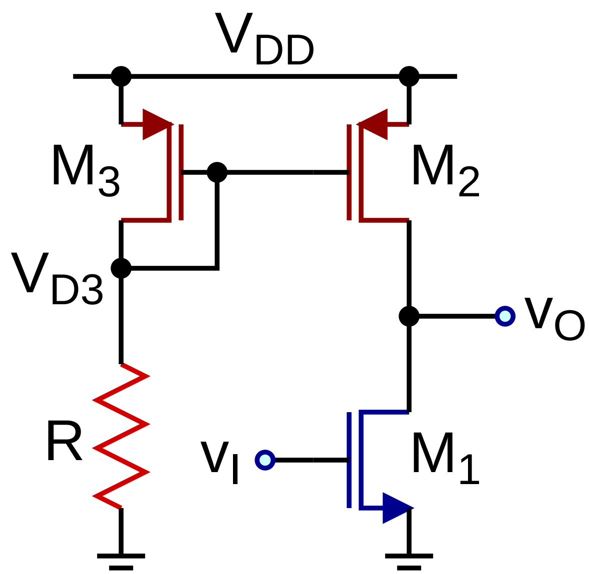


$$R_{drain} = g_m r_o R_S + r_o + R_S$$



$$R_{source} = \left(\frac{1}{g_m} \parallel r_o\right)\left(1 + \frac{R_D}{r_o}\right)$$

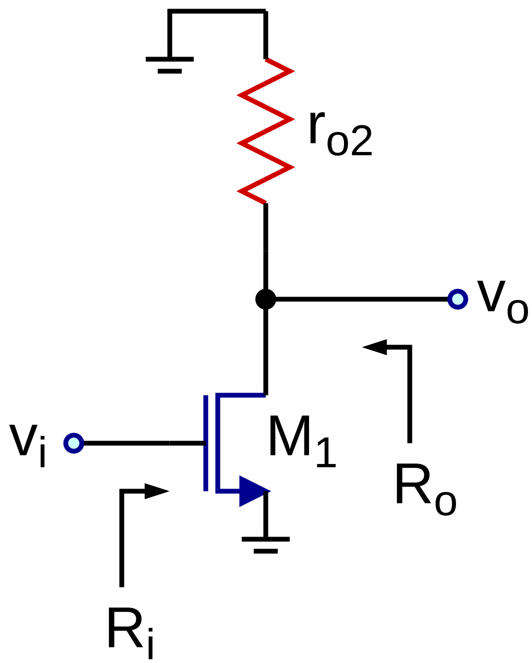
Common-Source Amplifier



$$I_{D3} = \frac{k_p'}{2}\left(\frac{W}{L}\right)_3 (V_{DD} - V_{D3} - |V_{tp}|)^2 = \frac{V_{D3}}{R}$$

$$\frac{I_{D2}}{I_{D3}} = \frac{\left(\frac{W}{L}\right)_2}{\left(\frac{W}{L}\right)_3} \quad , \quad I_{D1} = I_{D2}$$

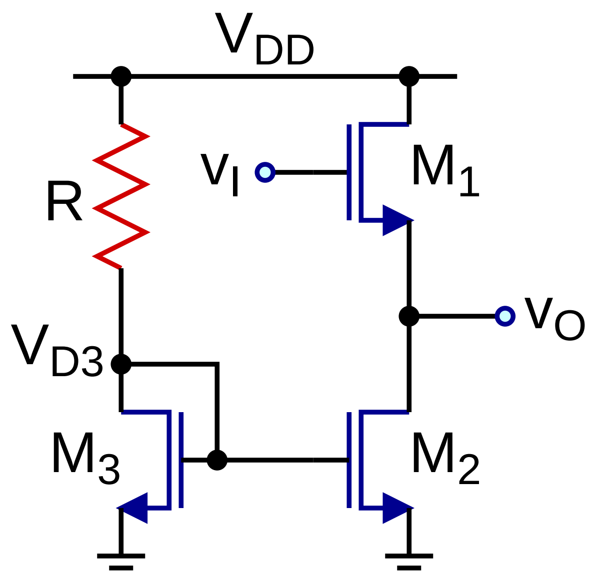
Common-Source Amplifier



$$\frac{v_o}{v_i} = -\frac{r_{o1} \parallel r_{o2}}{\frac{1}{g_{m1}}}$$

$$R_i = \infty$$

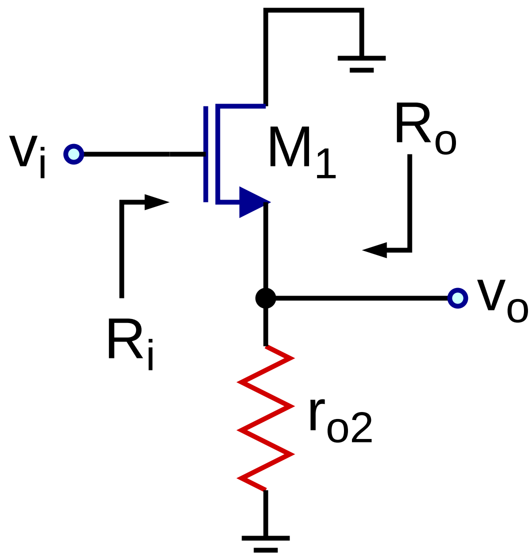
$$R_o = r_{o1} \parallel r_{o2}$$



$$I_{D3} = \frac{k_n'}{2}\left(\frac{W}{L}\right)_3 (V_{D3} - V_{tn})^2 = \frac{V_{DD} - V_{D3}}{R}$$

$$\frac{I_{D2}}{I_{D3}} = \frac{\left(\frac{W}{L}\right)_2}{\left(\frac{W}{L}\right)_3}, \quad I_{D1} = I_{D2}$$

Common-Drain Amplifier

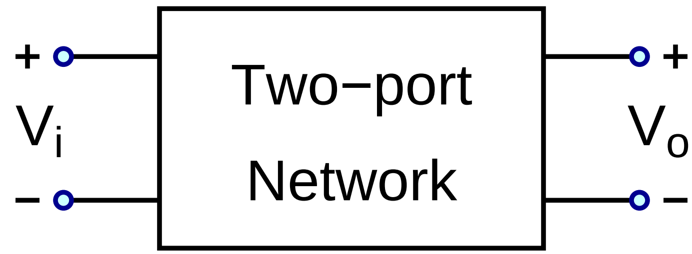


$$\frac{v_o}{v_i} = \frac{r_{o1} \parallel r_{o2}}{\frac{1}{g_{m1}} + (r_{o1} \parallel r_{o2})}$$

$$R_i = \infty$$

$$R_o = \frac{1}{g_{m1}} \parallel r_{o1} \parallel r_{o2}$$

Two-Port Modeling of Amplifiers



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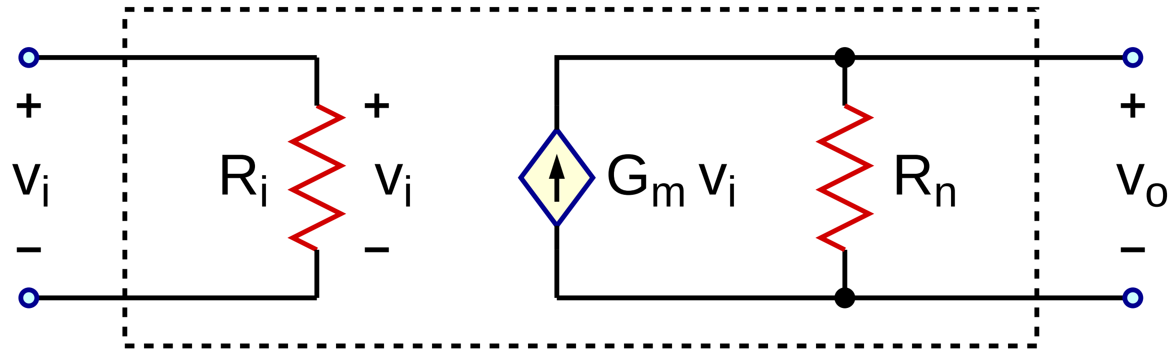
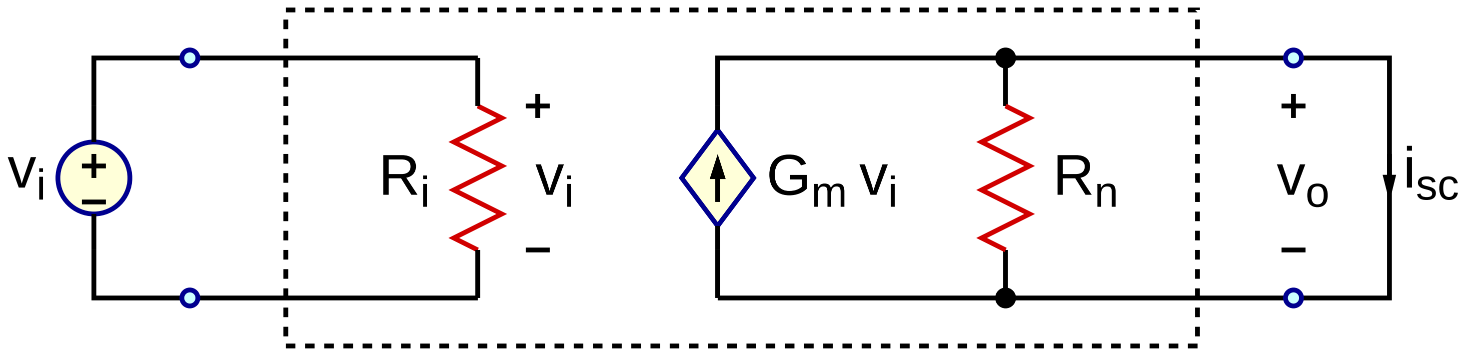
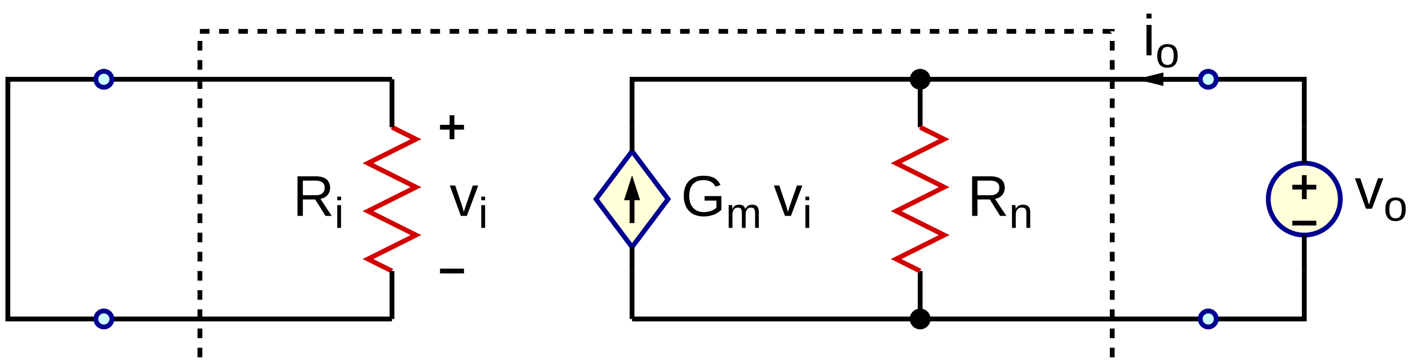


$$\frac{v_o}{v_i} = G_m R_n$$

Two-Port Modeling of Amplifiers

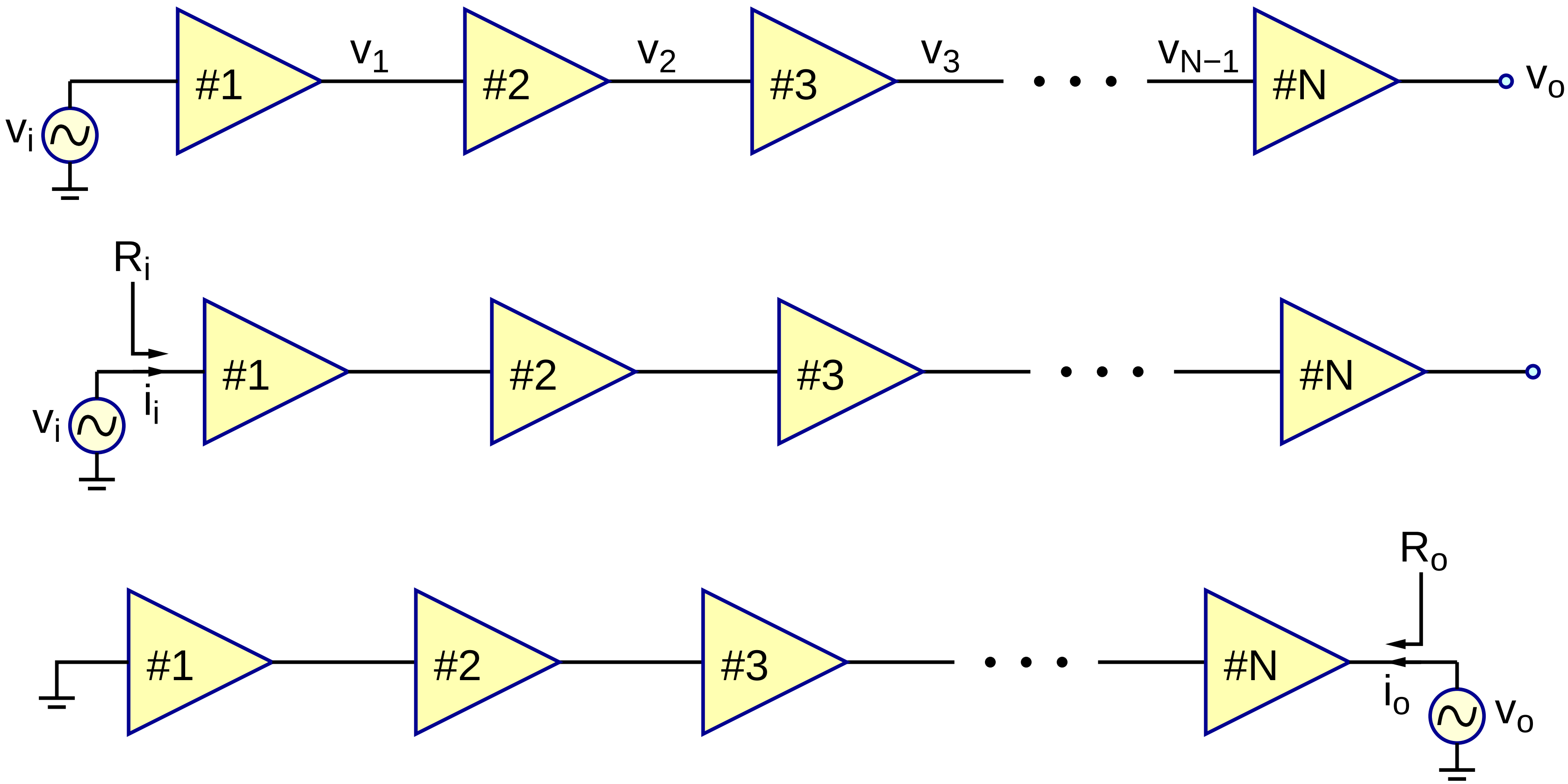


$$G_m = \left.\frac{i_{sc}}{v_i}\right|_{v_o=0}$$

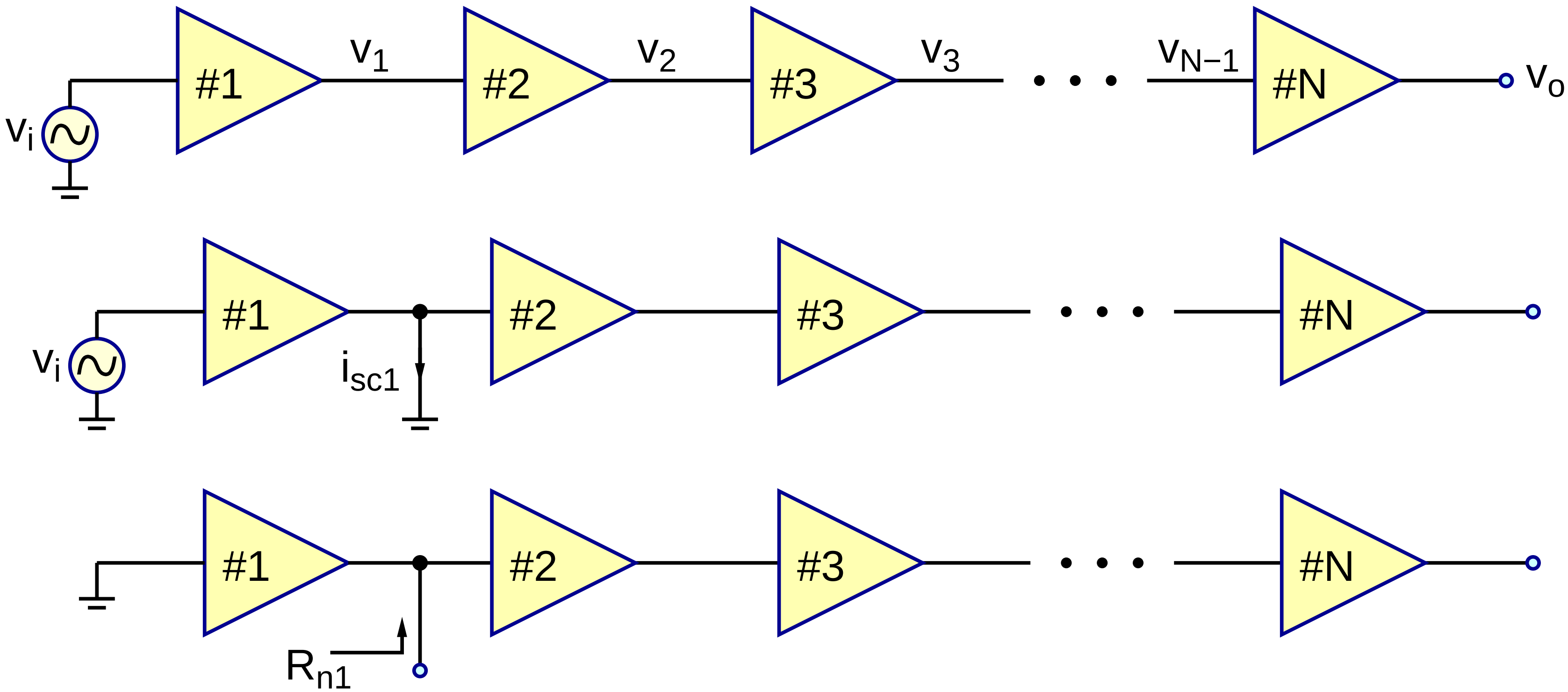


$$R_n = \left.\frac{v_o}{i_o}\right|_{v_i=0}$$

Two-Port Modeling of Amplifiers

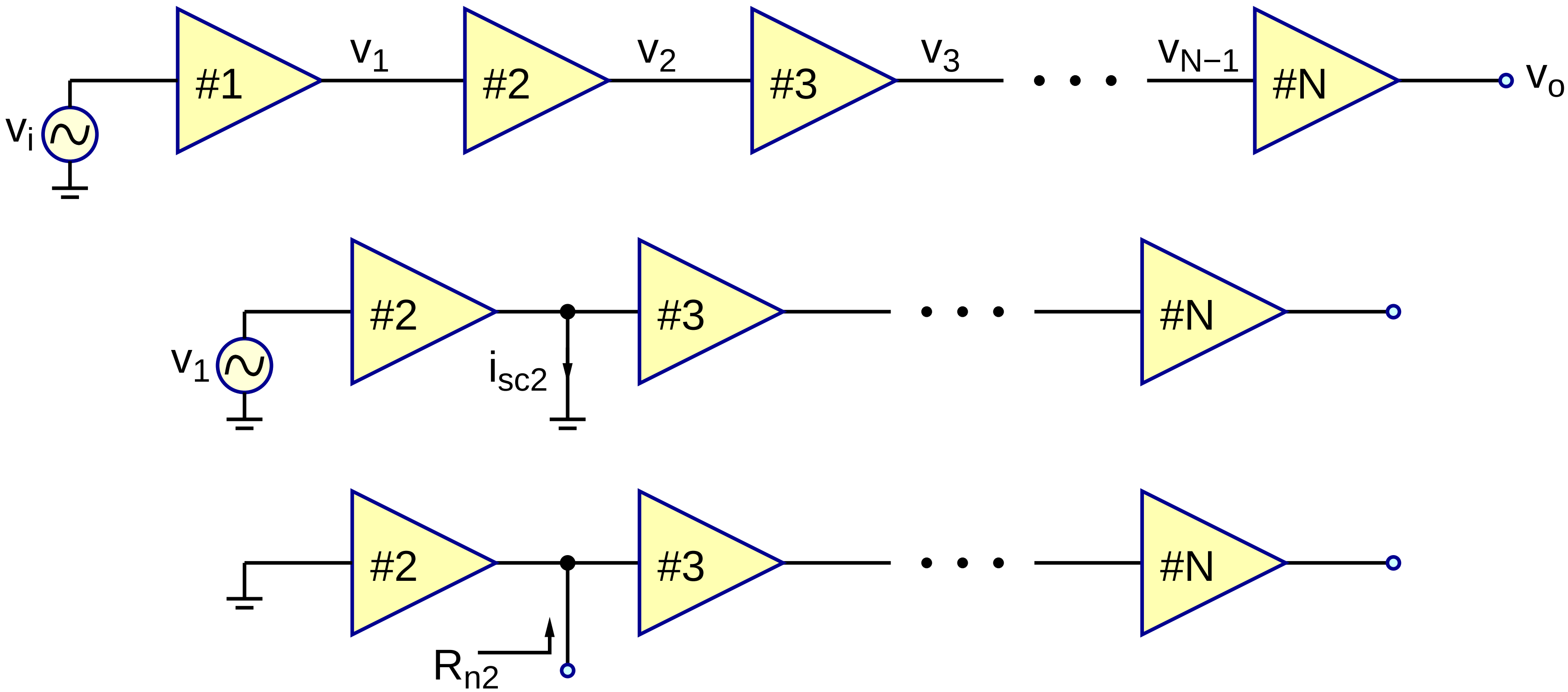


$$\frac{v_o}{v_i} = \frac{v_1}{v_i}\,\frac{v_2}{v_1}\cdots\frac{v_o}{v_{N-1}} \qquad R_i = \frac{v_i}{i_i} \qquad R_o = \frac{v_o}{i_o}$$



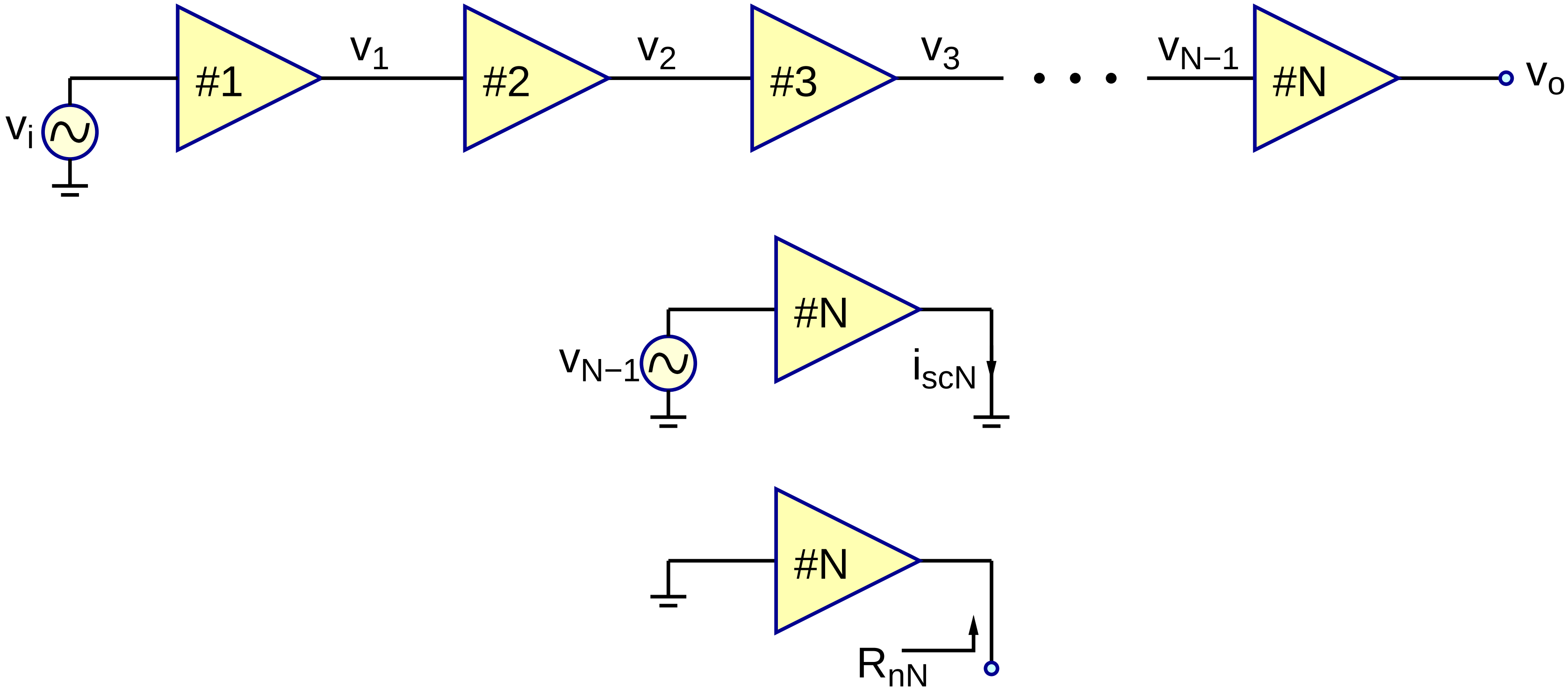
$$G_{m1} = \frac{i_{sc1}}{v_i} \qquad \frac{v_1}{v_i} = G_{m1} R_{n1}$$

Two-Port Modeling of Amplifiers



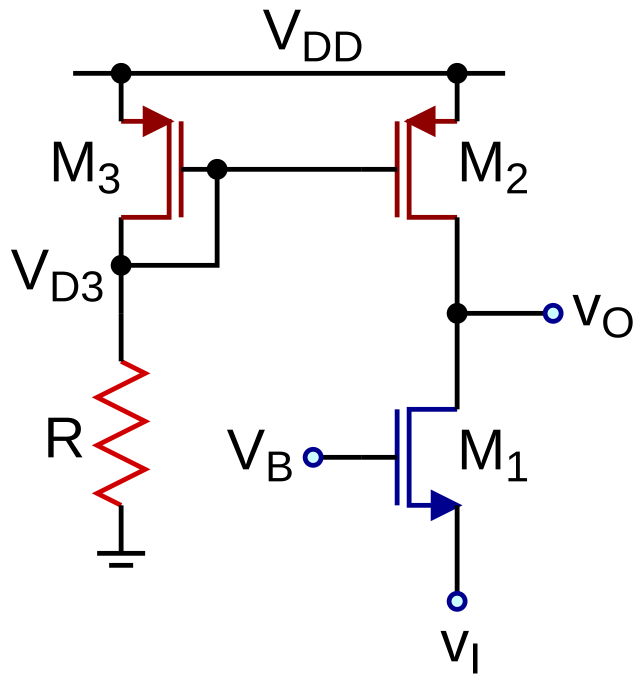
$$G_{m2} = \frac{i_{sc2}}{v_1} \qquad \frac{v_2}{v_1} = G_{m2} R_{n2}$$

Two-Port Modeling of Amplifiers



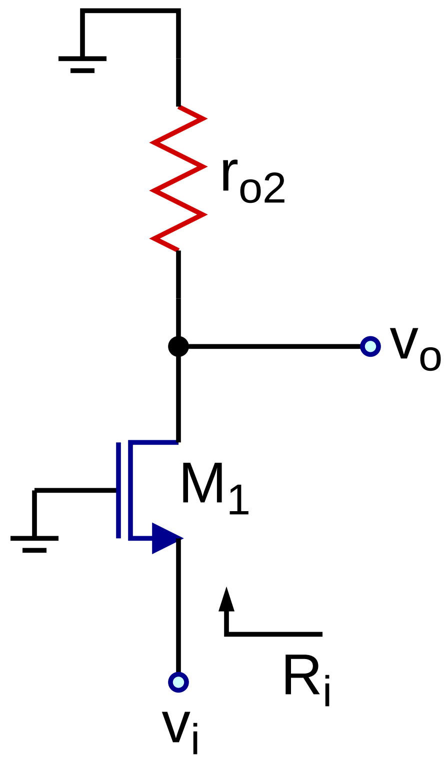
$$G_{mN} = \frac{i_{scN}}{v_{N-1}} \qquad \frac{v_o}{v_{N-1}} = G_{mN} R_{nN}$$

Common-Gate Amplifier



$$I_{D3} = \frac{k'_p}{2}\left(\frac{W}{L}\right)_3 (V_{DD} - V_{D3} - |V_{tp}|)^2 = \frac{V_{D3}}{R}$$

$$\frac{I_{D2}}{I_{D3}} = \frac{\left(\frac{W}{L}\right)_2}{\left(\frac{W}{L}\right)_3} \quad , \quad I_{D1} = I_{D2}$$



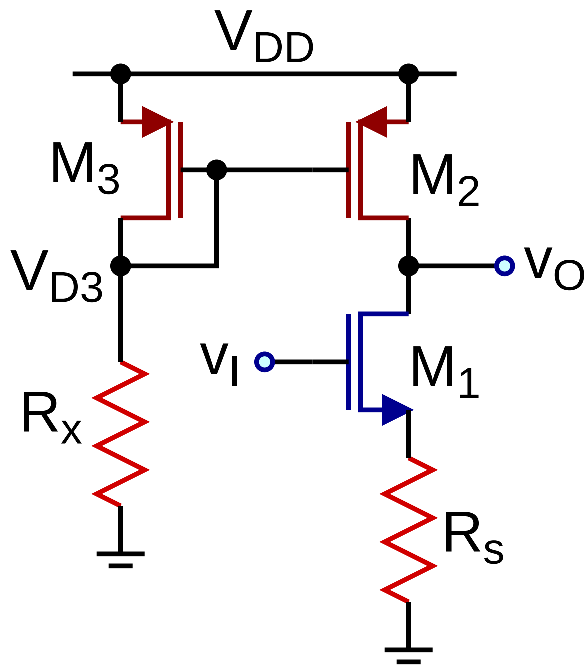
$$R_i = \left(\frac{1}{g_{m1}} \parallel r_{o1}\right)\left(1 + \frac{r_{o2}}{r_{o1}}\right)$$

$$G_m = g_{m1} + \frac{1}{r_{o1}}$$

$$R_n = r_{o1} \parallel r_{o2}$$

$$\frac{v_o}{v_i} = G_m R_n$$

Common-Source Amplifier - SD

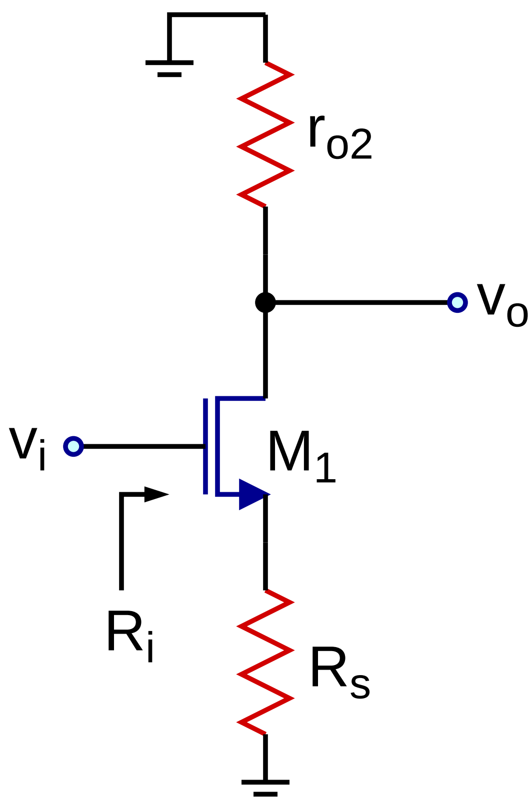


$$I_{D3} = \frac{k'_p}{2}\left(\frac{W}{L}\right)_3 (V_{DD} - V_{D3} - |V_{tp}|)^2 = \frac{V_{D3}}{R_x}$$

$$\frac{I_{D2}}{I_{D3}} = \frac{\left(\frac{W}{L}\right)_2}{\left(\frac{W}{L}\right)_3} \quad , \quad I_{D1} = I_{D2}$$

Common-Source Amplifier - SD

AC equivalent



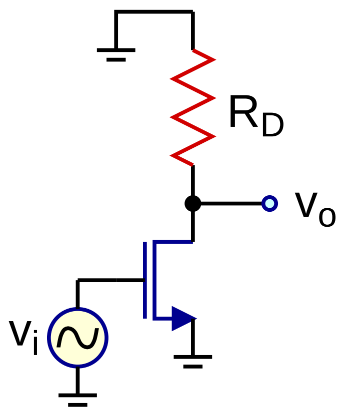
$$R_i = \infty$$

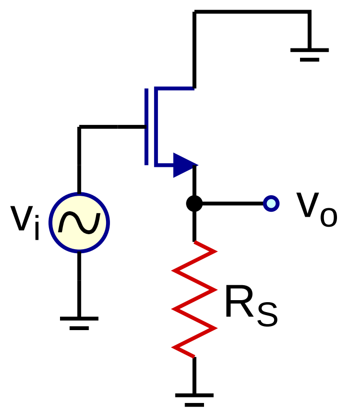
$$G_m = \frac{-g_{m1}}{1 + g_{m1}R_s + (R_s/r_{o1})}$$

$$R_n = r_{o2} \parallel (R_s + r_{o1} + g_{m1}R_s r_{o1})$$

$$\frac{v_o}{v_i} = G_m R_n$$

MOSFET Amplifiers- Summary

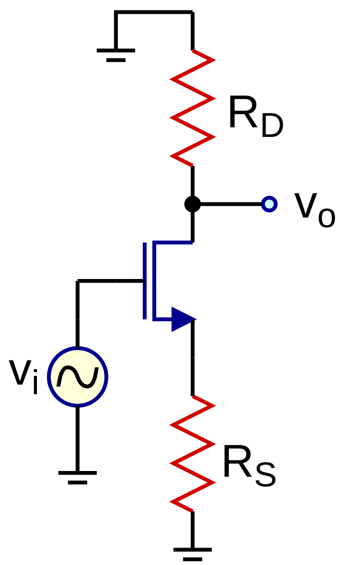


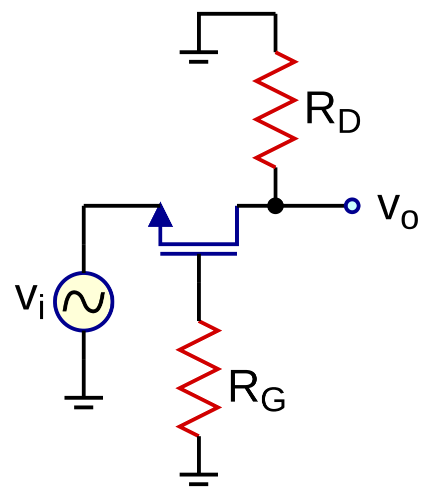


$$\frac{v_o}{v_i} = -\frac{R_D \parallel r_o}{\frac{1}{g_m}}$$

$$\frac{v_o}{v_i} = \frac{R_S \parallel r_o}{\frac{1}{g_m} + (R_S \parallel r_o)}$$

MOSFET Amplifiers - Summary





$$G_m = \frac{-g_m}{1 + g_m R_S + \frac{R_S}{r_o}}$$

$$R_n = R_D \parallel (g_m r_o R_S + r_o + R_S)$$

$$\frac{v_o}{v_i} = G_m R_n$$

$$G_m = g_m + \frac{1}{r_o}$$

$$R_n = R_D \parallel r_o$$

$$\frac{v_o}{v_i} = G_m R_n$$