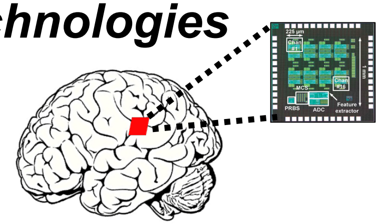
Integrated Neurotechnologies Laboratory

EPFL

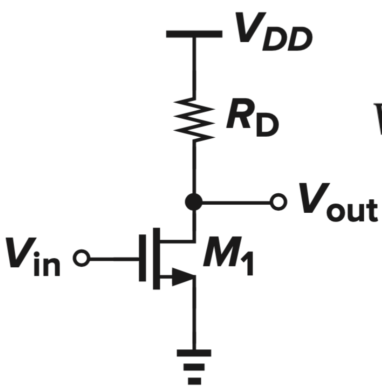


Analog IC design (EE-320), Lecture 5

Prof. Mahsa Shoaran

Institute of Electrical and Micro Engineering, School of Engineering, EPFL

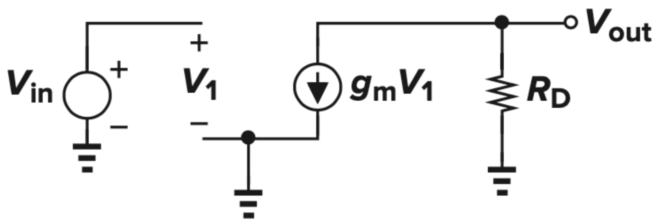
Review: Common-Source Amplifier



large-signal analysis:

$$V_{out} = V_{DD} - R_D \frac{1}{2} \mu_n C_{ox} \frac{W}{L} (V_{in} - V_{TH})^2$$

small-signal analysis:



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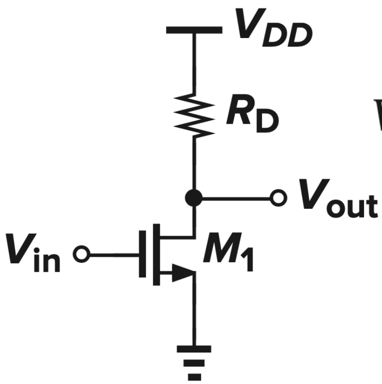

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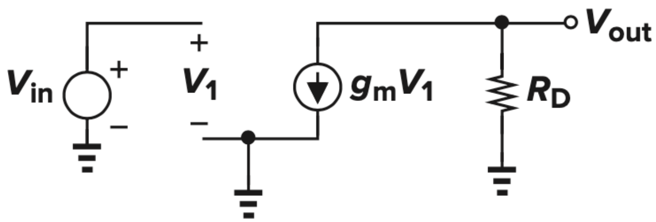
$$V_{out} = V_{DD} - R_D \frac{1}{2} \mu_n C_{ox} \frac{W}{L} (V_{in} - V_{TH})^2$$

$$A_v = \frac{\partial V_{out}}{\partial V_{in}}$$

$$= -R_D \mu_n C_{ox} \frac{W}{L} (V_{in} - V_{TH})$$

$$= -g_m R_D$$

small-signal analysis:



$$V_{out} = -g_m V_1 R_D = -g_m V_{in} R_D$$

$$A_v = -g_m R_D$$

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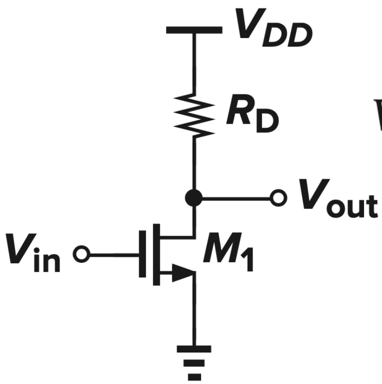

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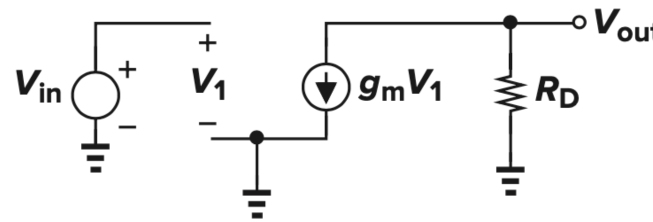

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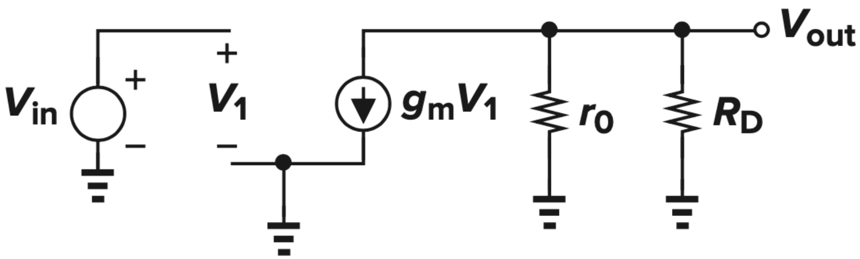
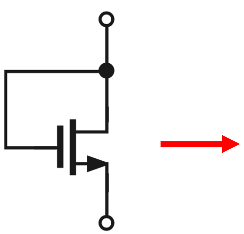
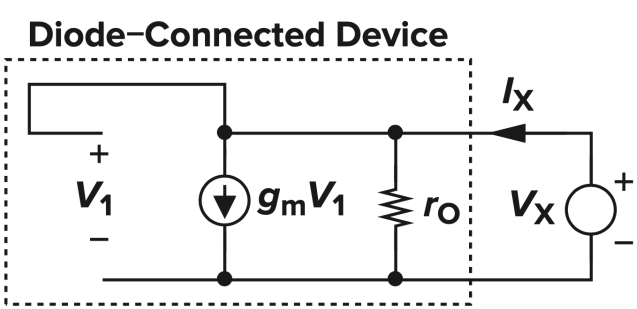


$$g_m V_1 (r_O \| R_D) = -V_{out}$$

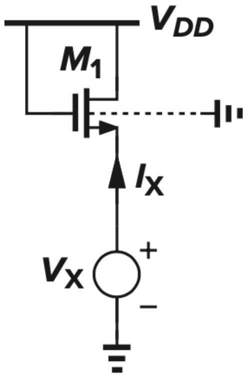
$$V_{out}/V_{in} = -g_m (r_O \| R_D)$$

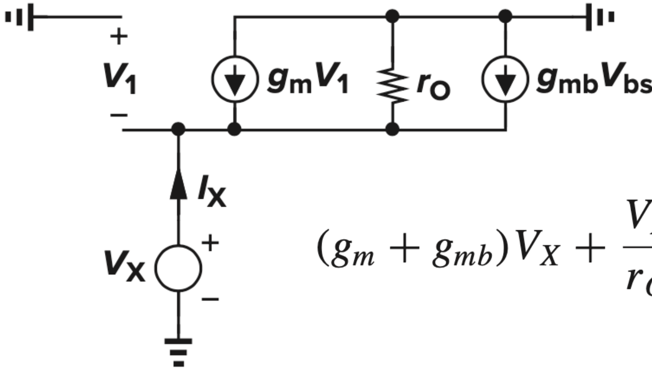




$$V_X/I_X = (1/g_m)\|r_O \approx 1/g_m$$

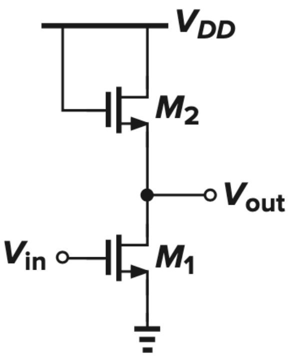
Review: Common-Source Amplifier





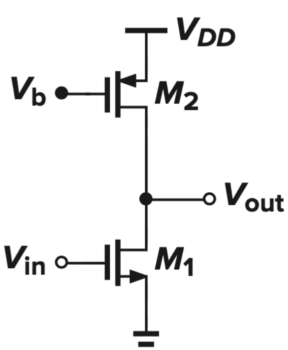
$$(g_m + g_{mb})V_X + \frac{V_X}{r_O} = I_X$$

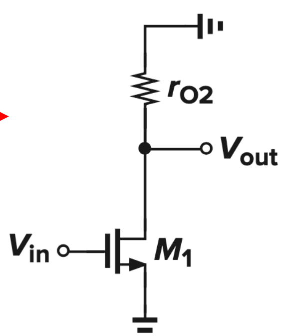
$$\frac{V_X}{I_X} = \frac{1}{g_m + g_{mb} + r_O^{-1}} = \frac{1}{g_m + g_{mb}} \| r_O \approx \frac{1}{g_m + g_{mb}}$$



$$= -g_{m1} \frac{1}{g_{m2} + g_{mb2}}$$

$$= -\frac{g_{m1}}{g_{m2}} \frac{1}{1+\eta} = -\sqrt{\frac{(W/L)_1}{(W/L)_2}} \frac{1}{1+\eta}$$

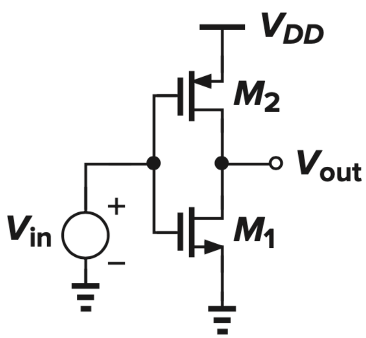


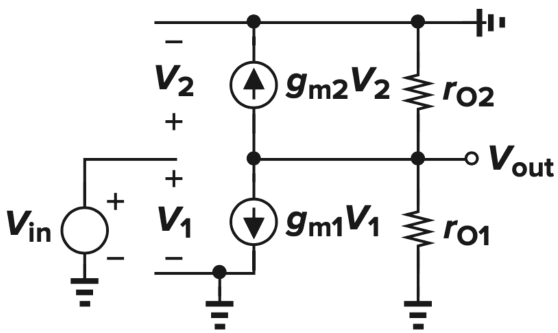


$$A_v = -g_{m1}(r_{O1} \| r_{O2})$$

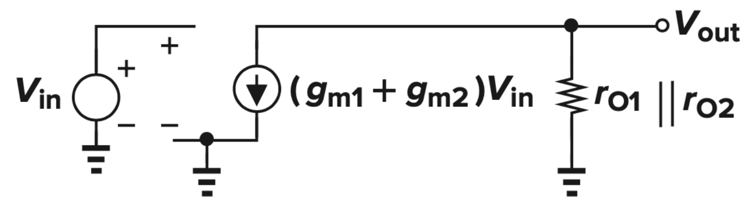
$$|V_{DS2,min}| = |V_{GS2} - V_{TH2}|$$

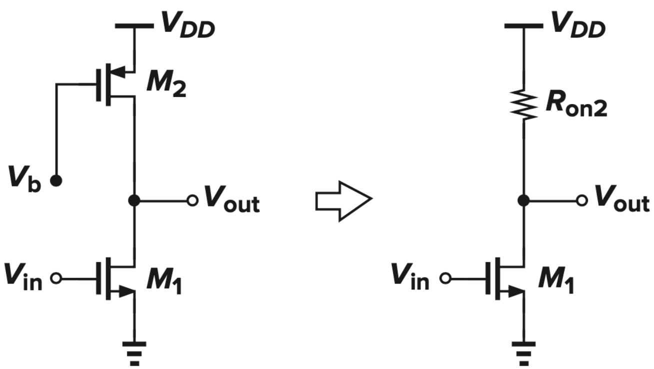
Review: Common-Source Amplifier





$$A_v = -(g_{m1} + g_{m2})(r_{O1}||r_{O2})$$

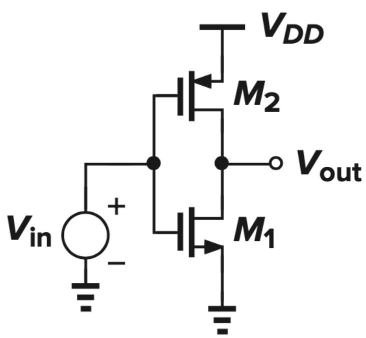


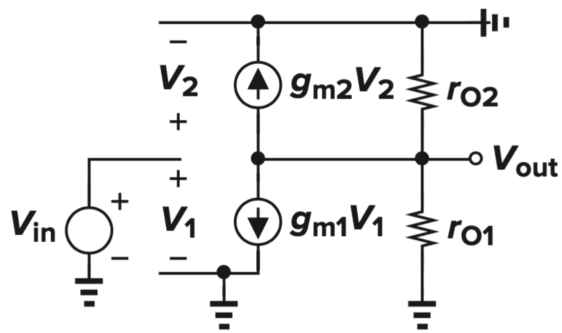


$$A_v = -g_{m1} R_{on2}$$

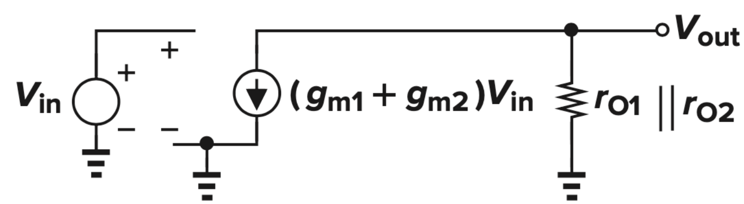
$$R_{on2} = \frac{1}{\mu_p C_{ox}(W/L)_2(V_{DD} - V_b - |V_{THP}|)}$$

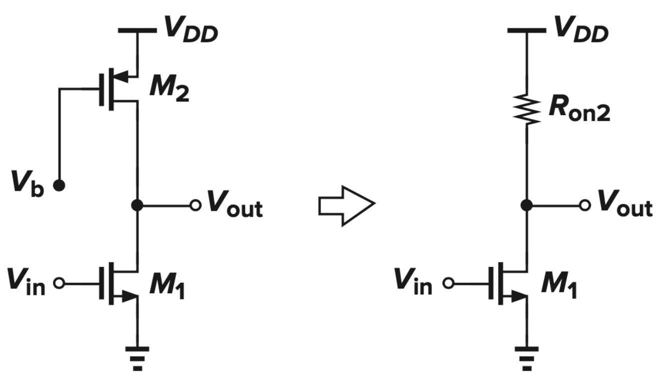
Review: Common-Source Amplifier





$$A_v = -(g_{m1} + g_{m2})(r_{O1} || r_{O2})$$





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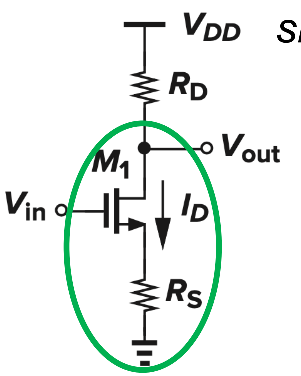
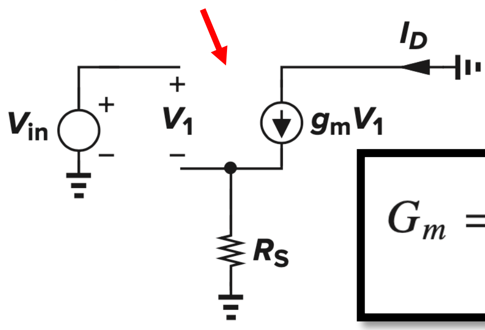
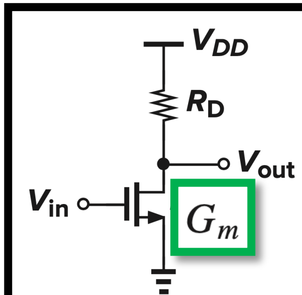


small-signal model to find the ***equivalent*** $\boldsymbol{G_m}$ *of a source-degenerated CS*



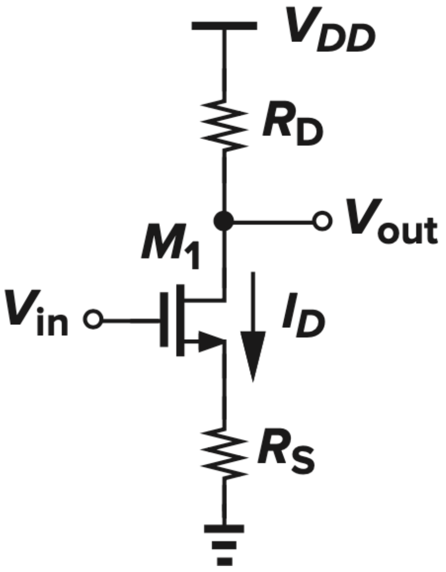
$$G_m = \frac{g_m}{1 + g_m R_S}$$

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



Output Resistance of a degenerated CS stage

- Source degeneration **increases** the output resistance



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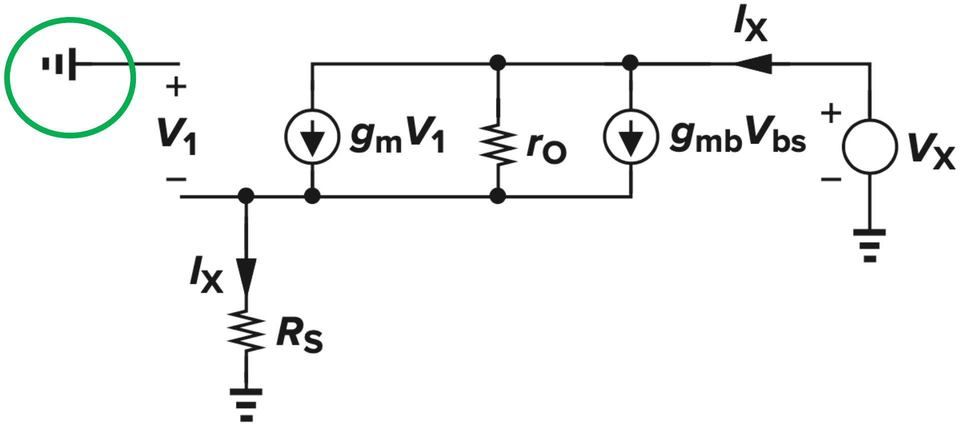
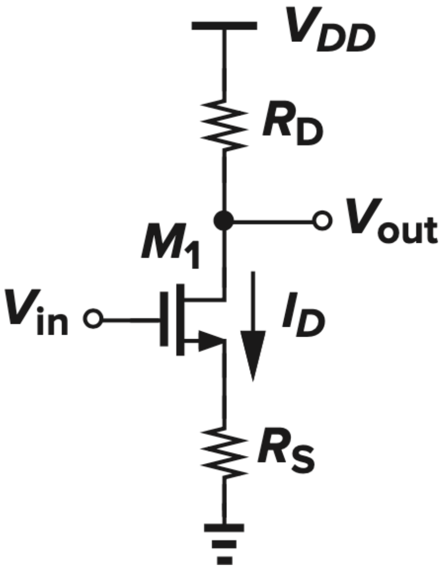


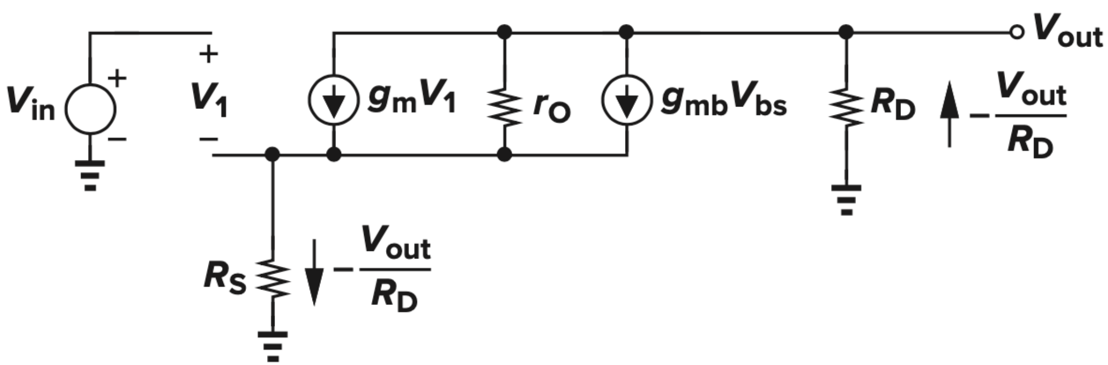


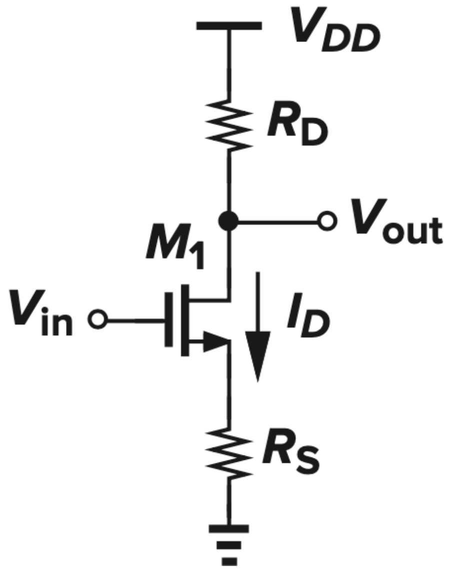
$$r_O[I_X + (g_m + g_{mb})R_S I_X] + I_X R_S = V_X$$

$$\begin{aligned} R_{out} &= [1 + (g_m + g_{mb})R_S]r_O + R_S \\ &= [1 + (g_m + g_{mb})r_O]R_S + r_O \\ &\approx (g_m + g_{mb})r_O R_S + r_O \\ &= [1 + (g_m + g_{mb})R_S]r_O \end{aligned}$$

- The **overall output resistance** is the **parallel combination** of R_{out} and R_D

Gain of a degenerated CS stage





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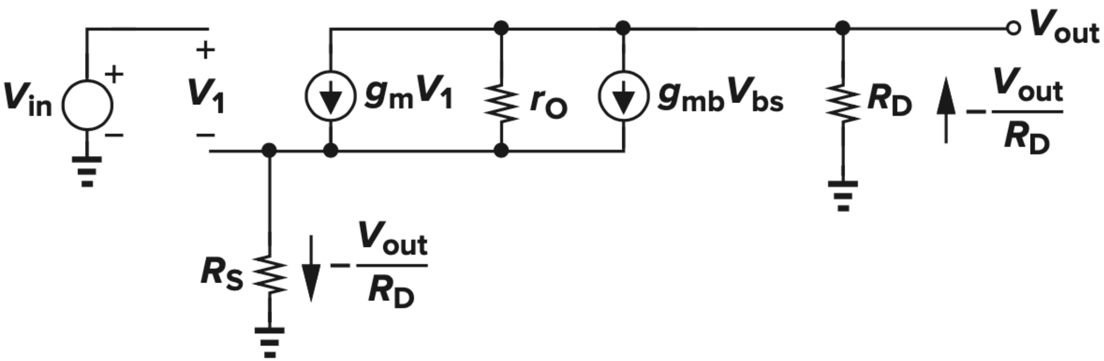

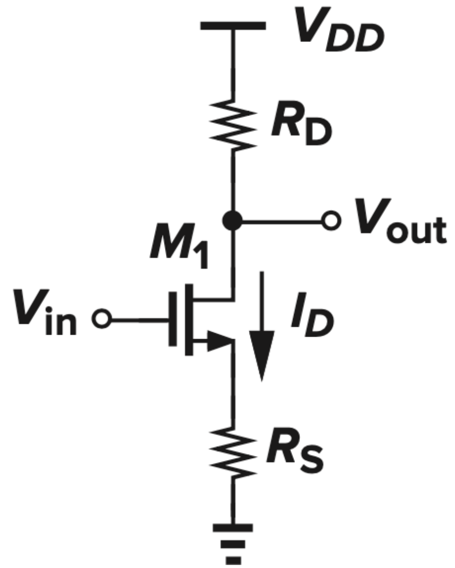

$$I_{ro} = -\frac{V_{out}}{R_D} - (g_m V_1 + g_{mb} V_{bs})$$

$$= -\frac{V_{out}}{R_D} - \left[g_m \left(V_{in} + V_{out} \frac{R_S}{R_D} \right) + g_{mb} V_{out} \frac{R_S}{R_D} \right]$$

$$V_{out} = I_{ro} r_O - \frac{V_{out}}{R_D} R_S$$

$$= -\frac{V_{out}}{R_D} r_O - \left[g_m \left(V_{in} + V_{out} \frac{R_S}{R_D} \right) + g_{mb} V_{out} \frac{R_S}{R_D} \right] r_O - V_{out} \frac{R_S}{R_D}$$

$$\boxed{\frac{V_{out}}{V_{in}} = \frac{-g_m r_O R_D}{R_D + R_S + r_O + (g_m + g_{mb}) R_S r_O}}$$

Source Follower stage

- To achieve a high voltage gain, the load impedance must be large
- If such a stage is to drive a **low-impedance** load, then a “**buffer**” must be placed after the amplifier **to avoid gain reduction**

- A **source follower** (or “**common-drain**” stage) can operate as a **voltage buffer**

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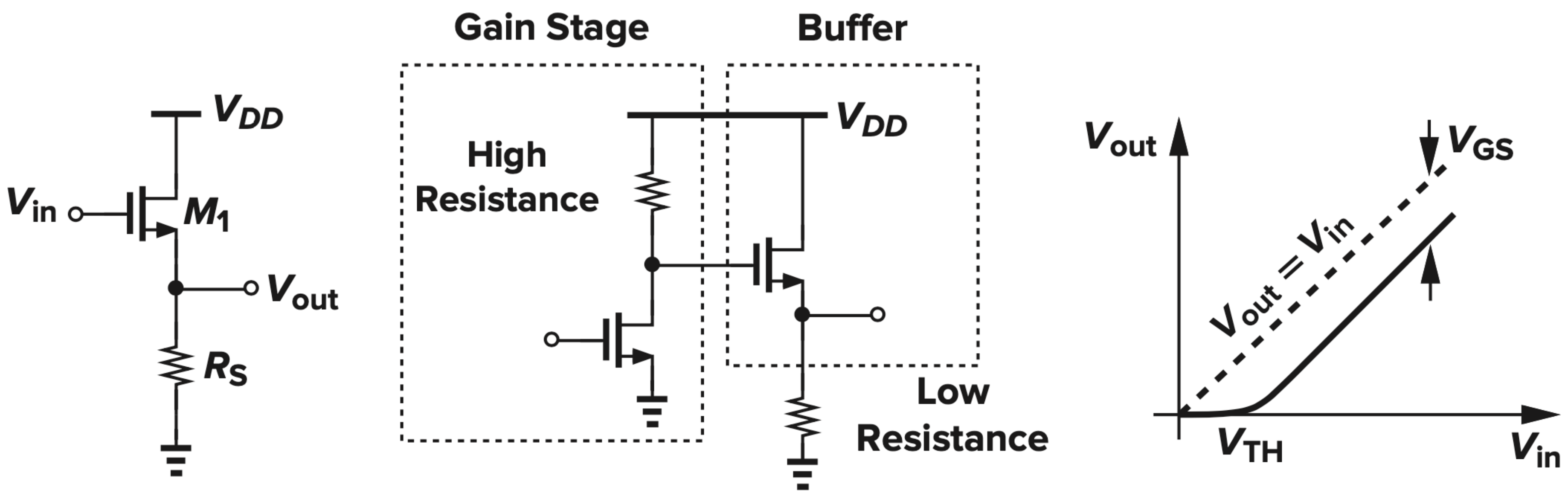
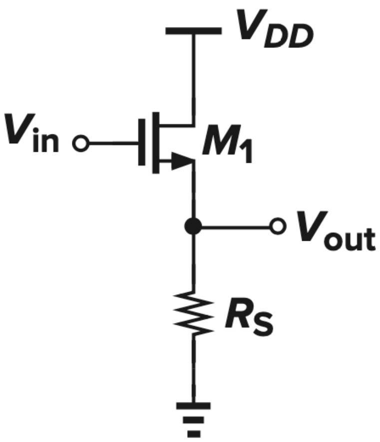


- It senses the signal at the gate, while presenting a **high input impedance**, and drives the load at the source, with a source potential "**following**" the gate voltage

Source Follower: large signal analysis



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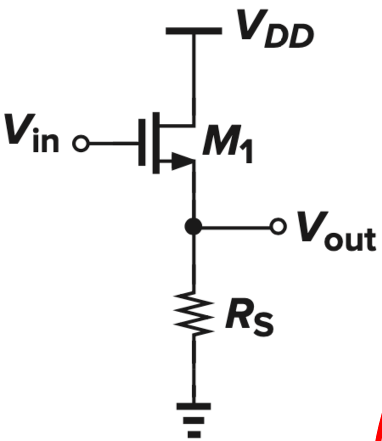


$$\frac{1}{2}\mu_n C_{ox}\frac{W}{L}(V_{in}-V_{TH}-V_{out})^2 R_S = V_{out}$$

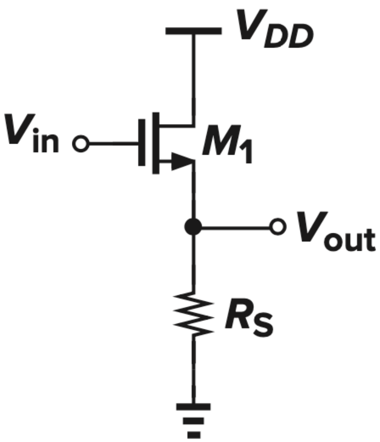
$$\frac{1}{2}\mu_n C_{ox}\frac{W}{L}2(V_{in}-V_{TH}-V_{out})\left(1-\frac{\partial V_{TH}}{\partial V_{in}}-\frac{\partial V_{out}}{\partial V_{in}}\right)R_S = \frac{\partial V_{out}}{\partial V_{in}}$$

$$\partial V_{TH}/\partial V_{in} = (\partial V_{TH}/\partial V_{SB})(\partial V_{SB}/\partial V_{in}) = \eta \partial V_{out}/\partial V_{in}$$

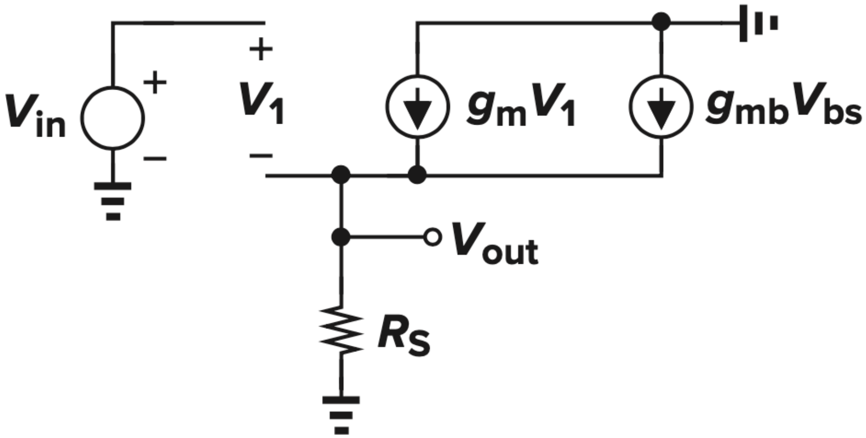
$$\frac{\partial V_{out}}{\partial V_{in}} = \frac{\mu_n C_{ox}\frac{W}{L}(V_{in}-V_{TH}-V_{out})R_S}{1+\mu_n C_{ox}\frac{W}{L}(V_{in}-V_{TH}-V_{out})R_S(1+\eta)}$$

$$A_v = \frac{g_m R_S}{1+(g_m+g_{mb})R_S}$$

Source Follower: small signal model



Small-signal equivalent of source follower:



$$V_{in} - V_1 = V_{out}$$

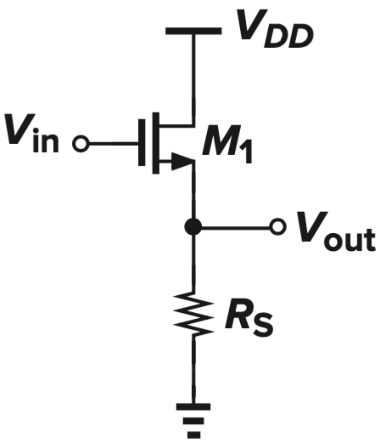
$$V_{bs} = -V_{out}$$

$$g_m V_1 - g_{mb} V_{out} = V_{out} / R_S$$

V_{out}/V_{in} →

$$A_v = \frac{g_m R_S}{1 + (g_m + g_{mb}) R_S}$$

Source Follower: small signal model



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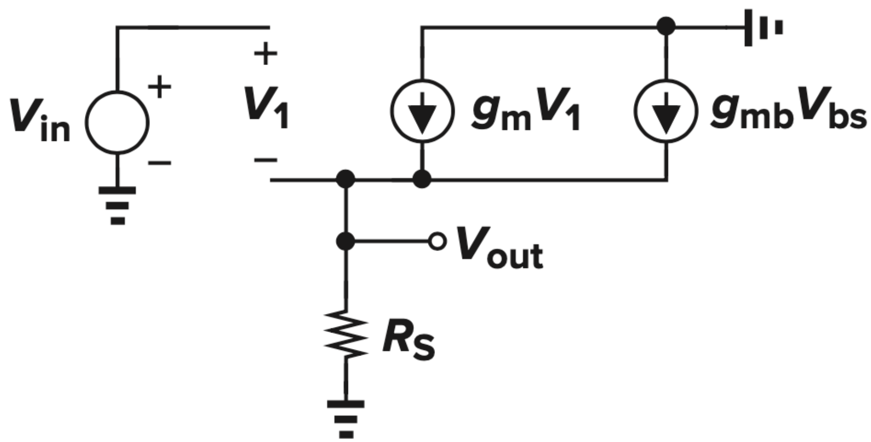
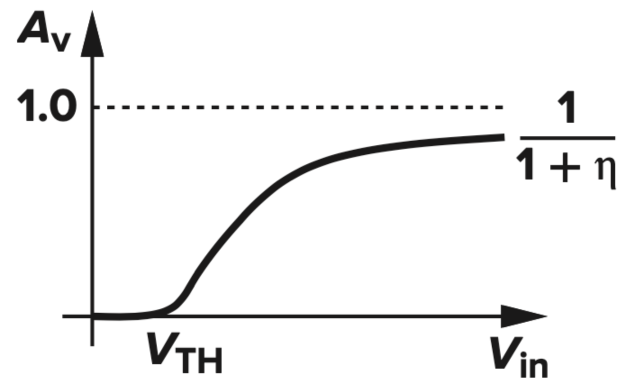
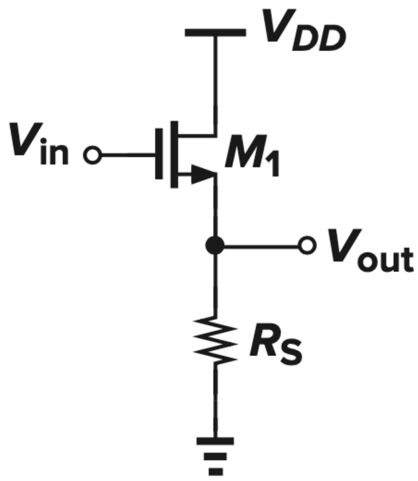


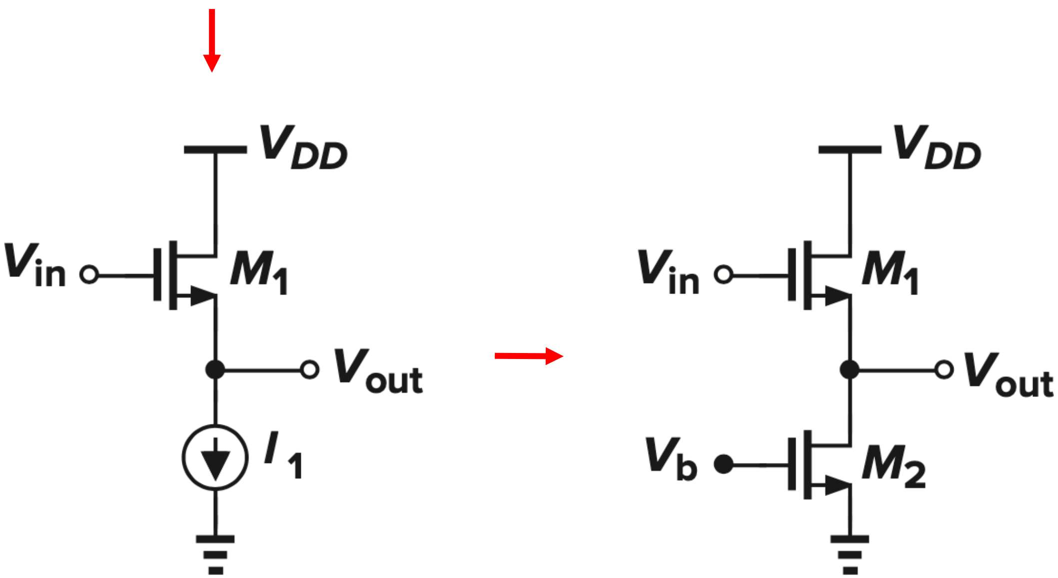
$$A_v = \frac{g_m R_S}{1 + (g_m + g_{mb}) R_S}$$



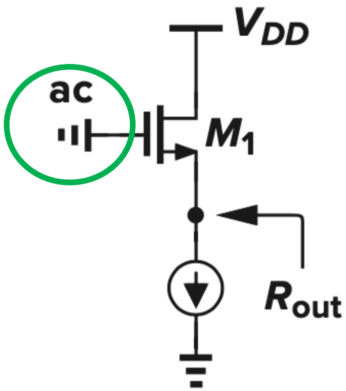
Source follower with a current source

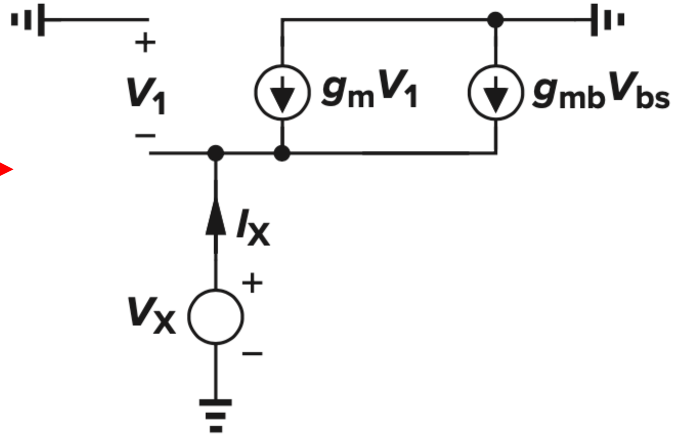


$$\frac{1}{2}\mu_n C_{ox}\frac{W}{L}(V_{in} - V_{TH} - V_{out})^2 R_S = V_{out}$$



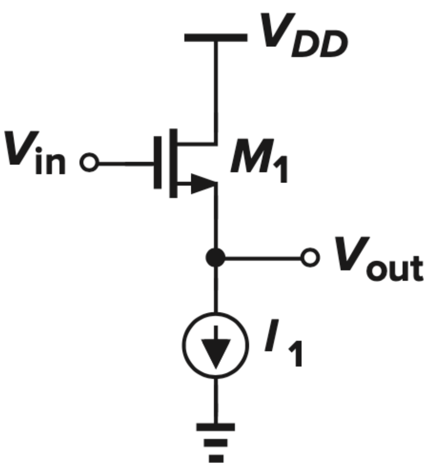
Output resistance of a Source Follower



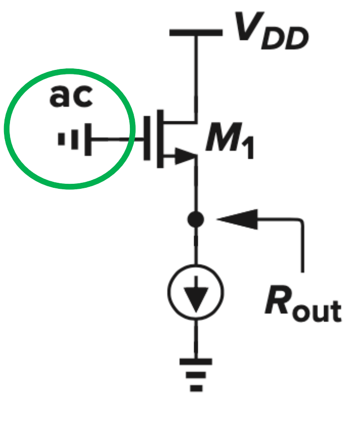


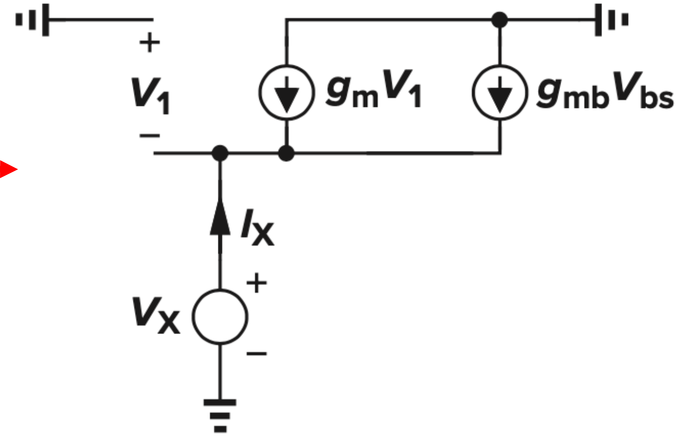
$$I_X - g_m V_X - g_{mb} V_X = 0$$

$$R_{out} = \frac{1}{g_m + g_{mb}}$$



Output resistance of a Source Follower





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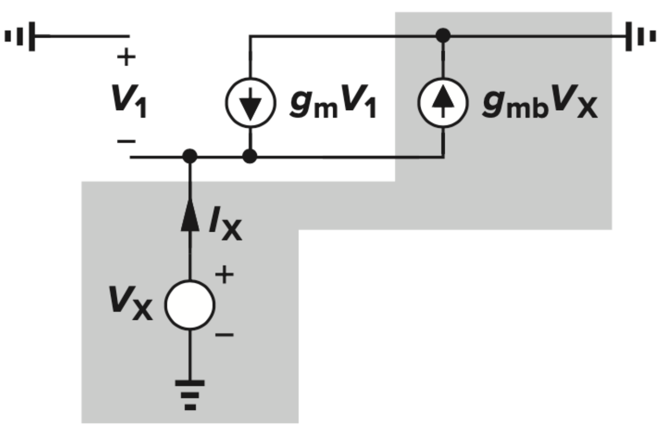
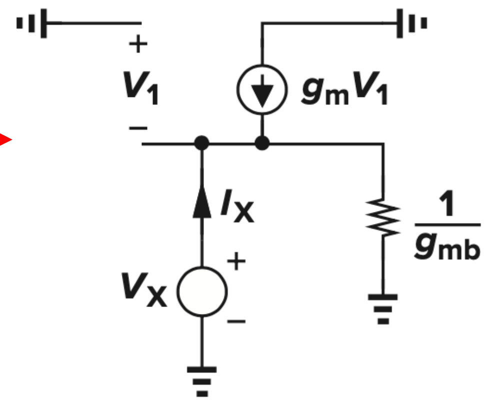
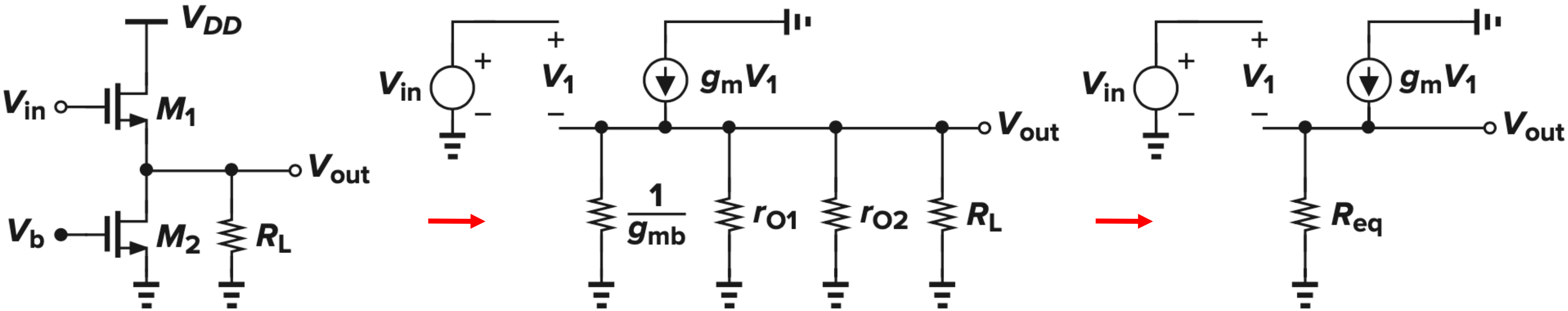




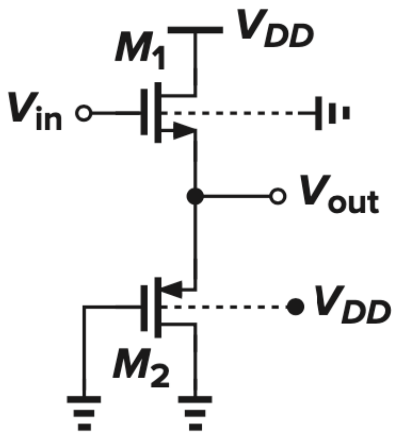
Source Follower with a finite load resistance



$$A_v = \frac{R_{eq}}{R_{eq} + \dfrac{1}{g_m}}$$

$$R_{eq} = (1/g_{mb})||r_{O1}||r_{O2}||R_L$$

Example: Calculate the voltage gain



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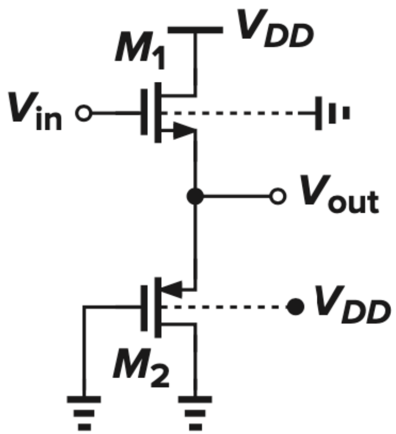


$$A_v = \frac{\dfrac{1}{g_{m2}+g_{mb2}} \| r_{O2} \| r_{O1} \| \dfrac{1}{g_{mb1}}}{\dfrac{1}{g_{m2}+g_{mb2}} \| r_{O2} \| r_{O1} \| \dfrac{1}{g_{mb1}} + \dfrac{1}{g_{m1}}}$$

PMOS Source Follower with no body effect

- Source follower drawbacks:
  - **nonlinearity**
  - **voltage headroom limitation**

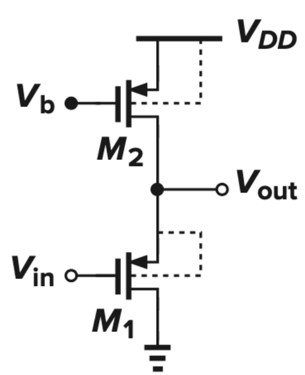
- Even if biased by an ideal current source, some nonlinearity exists due to the **nonlinear** dependence of V_{TH} upon the **source** potential

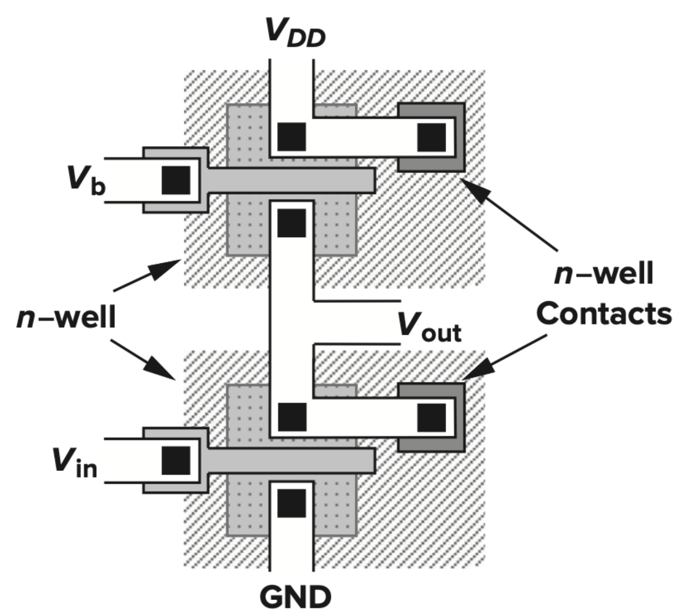
PMOS Source Follower with no body effect

- Source follower drawbacks:
  - **nonlinearity**
  - **voltage headroom limitation**

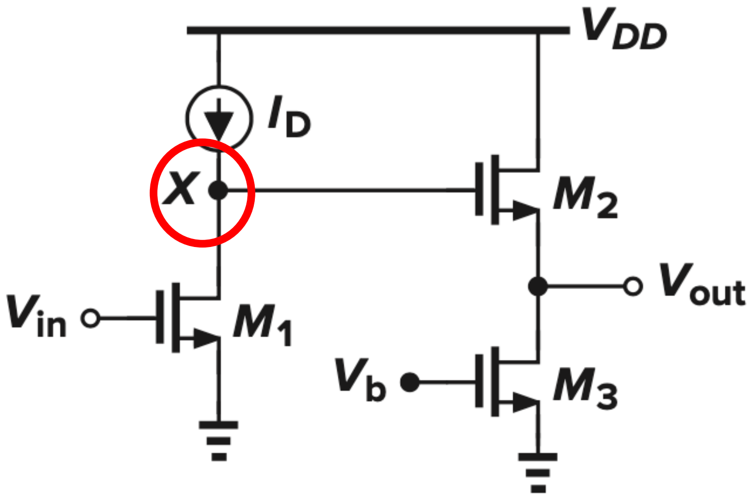
- Even if biased by an ideal current source, some nonlinearity exists due to the **nonlinear** dependence of $\boldsymbol{V_{TH}}$ upon the **source** potential

- The nonlinearity due to body effect can be eliminated if the bulk is tied to source





Source Follower: a level shifter



$$V_{GS1} - V_{TH1} \rightarrow V_{GS2} + (V_{GS3} - V_{TH3})$$

- Source followers shift the dc level by V_{GS}, thereby consuming voltage headroom and limiting the swings
- One application of source followers is in performing **voltage-level shift**