

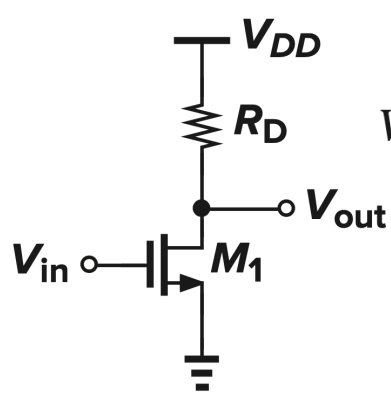
Analog IC design (EE-320), Lecture 5

Prof. Mahsa Shoaran

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

- **Assignment for EDADK document**, to be signed and uploaded via moodle, please complete the assignment **by Nov 6**
- **First TP session on Nov 11 in BC07-08 from 3:15pm to 6pm**
- **Homework 1 assignment** will be posted after lecture 6
- **Homework2 assignment** will be posted after TP3

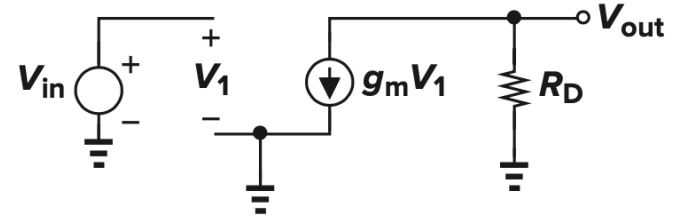
Review: Common-Source Amplifier



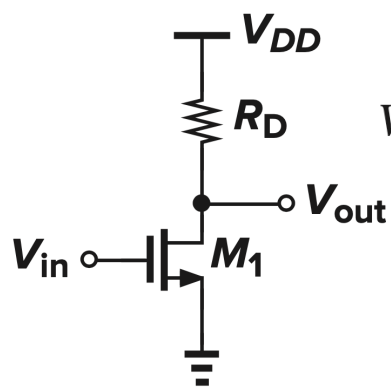
large-signal analysis:

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

small-signal analysis:



Review: Common-Source Amplifier



large-signal analysis:

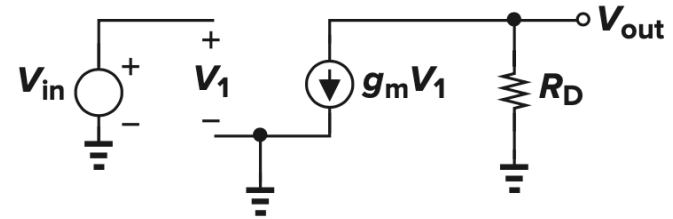
$$V_{out} = V_{DD} - R_D \frac{1}{2} \mu_n C_{ox} \frac{W}{L} (V_{in} - V_{TH})^2$$

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

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

$$= -g_m R_D$$

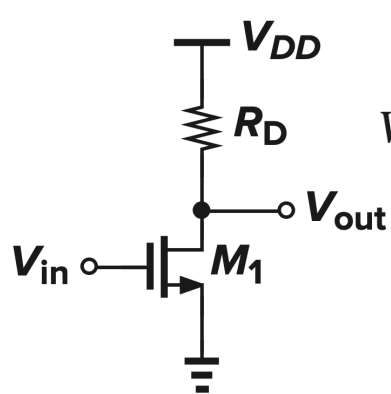
small-signal analysis:



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

$$A_v = -g_m R_D$$

Review: Common-Source Amplifier



large-signal analysis:

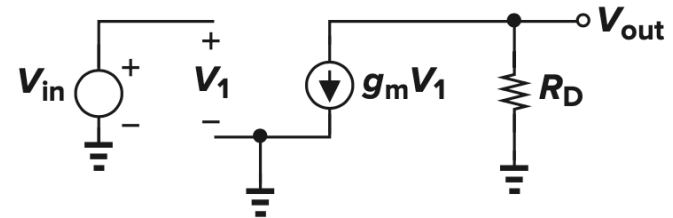
$$V_{out} = V_{DD} - R_D \frac{1}{2} \mu_n C_{ox} \frac{W}{L} (V_{in} - V_{TH})^2$$

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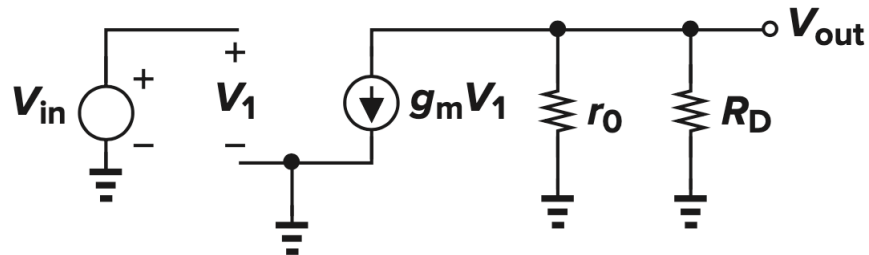
$$= -g_m R_D$$

small-signal analysis:



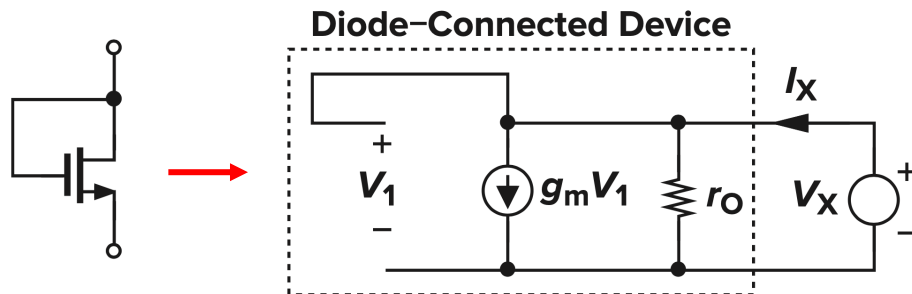
$$V_{out} = -g_m V_1 R_D = -g_m V_{in} R_D$$

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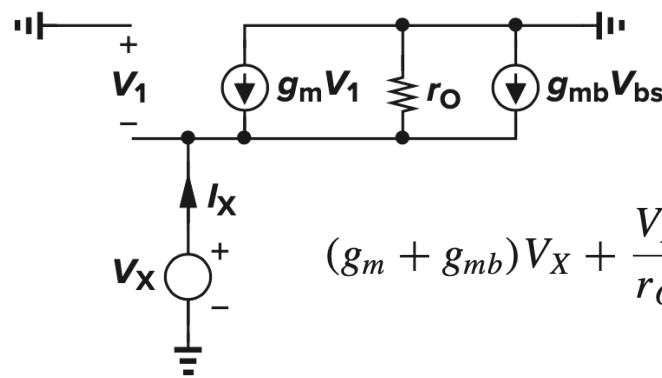
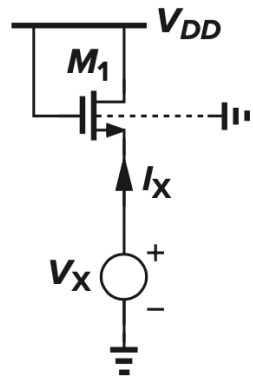
$$g_m V_1 (r_o \parallel R_D) = -V_{out}$$

$$V_{out} / V_{in} = -g_m (r_o \parallel R_D)$$



$$V_X / I_X = (1/g_m) \parallel r_o \approx 1/g_m$$

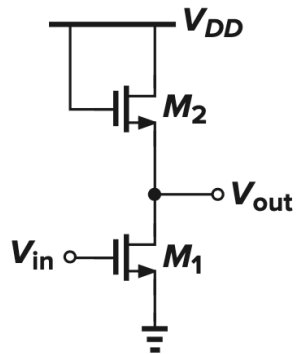
Review: Common-Source Amplifier



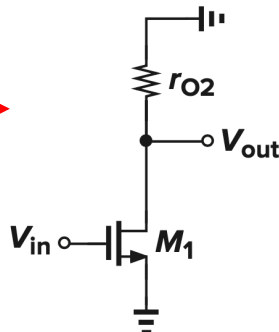
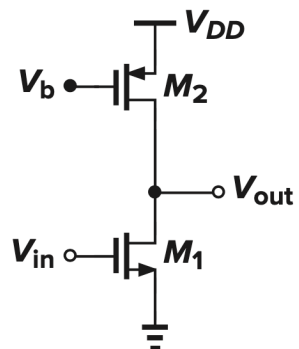
$$(g_m + g_{mb}) V_X + \frac{V_X}{r_O} = I_X$$



$$\begin{aligned} \frac{V_X}{I_X} &= \frac{1}{g_m + g_{mb} + r_O^{-1}} \\ &= \frac{1}{g_m + g_{mb}} \parallel r_O \\ &\approx \frac{1}{g_m + g_{mb}} \end{aligned}$$



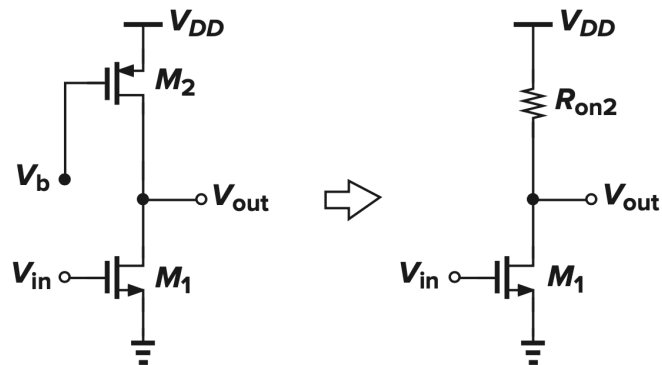
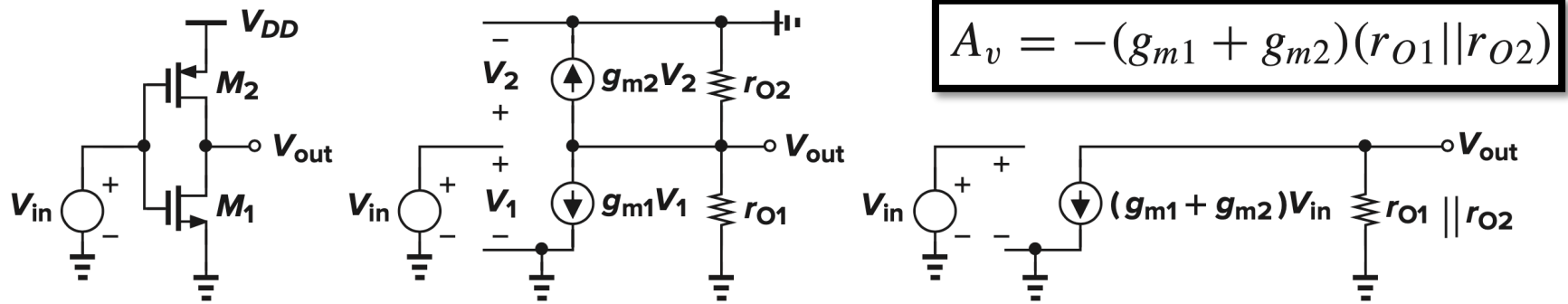
$$\begin{aligned} &= -g_{m1} \frac{1}{g_{m2} + g_{mb2}} \\ &= -\frac{g_{m1}}{g_{m2}} \frac{1}{1 + \eta} = -\sqrt{\frac{(W/L)_1}{(W/L)_2}} \frac{1}{1 + \eta} \end{aligned}$$



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

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

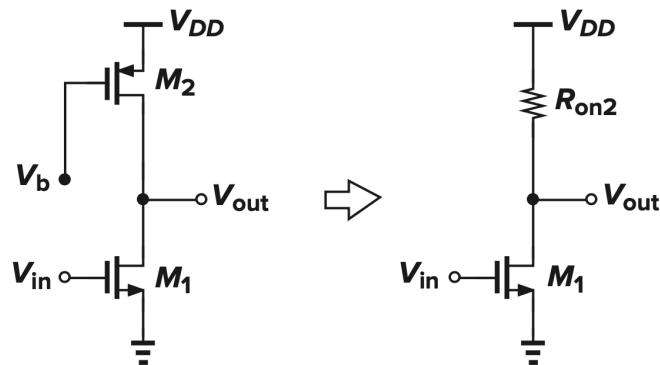
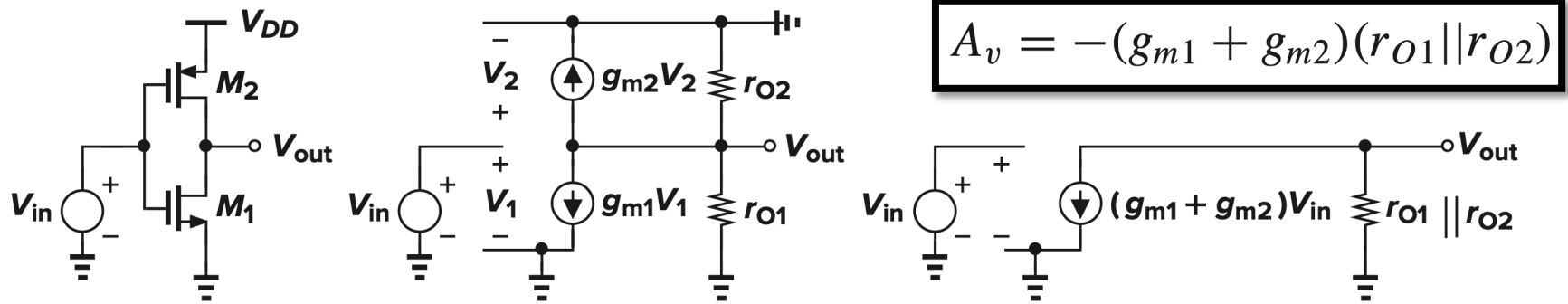
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$$A_v = -g_{m1} R_{on2}$$

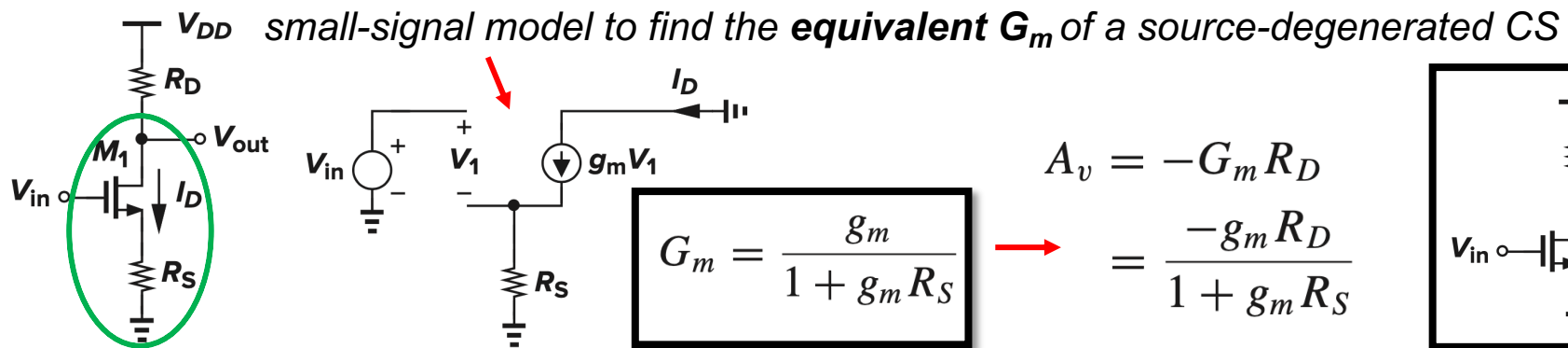
$$R_{on2} = \frac{1}{\mu_p C_{ox} (W/L)_2 (V_{DD} - V_b - |V_{THP}|)}$$

Review: Common-Source Amplifier



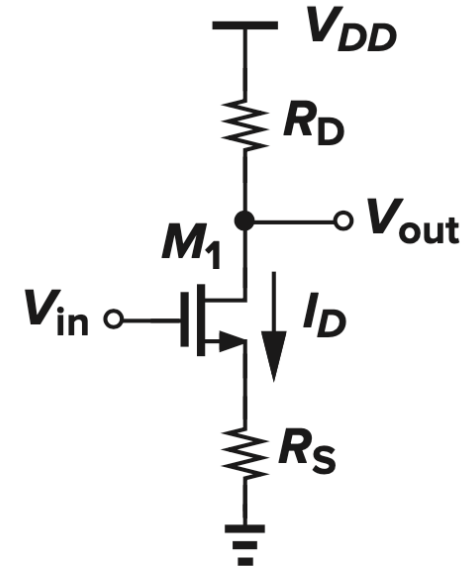
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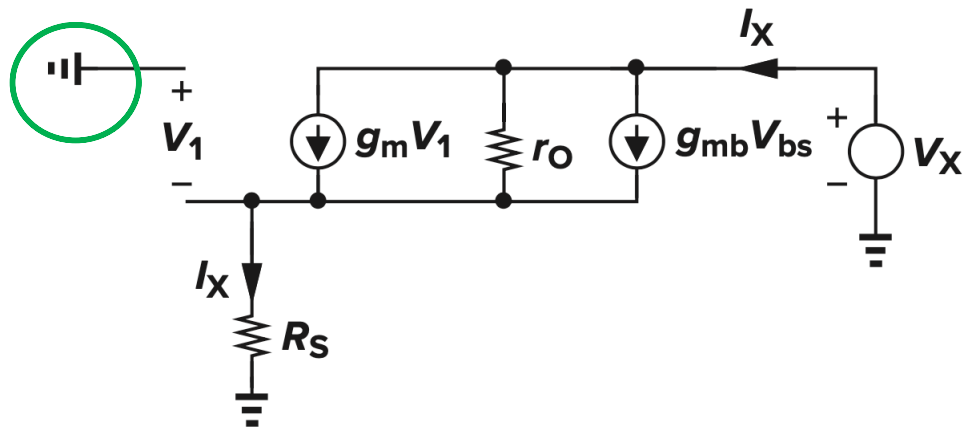
Output Resistance of a degenerated CS stage

- Source degeneration **increases** the output resistance



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- Source degeneration **increases** the output resistance



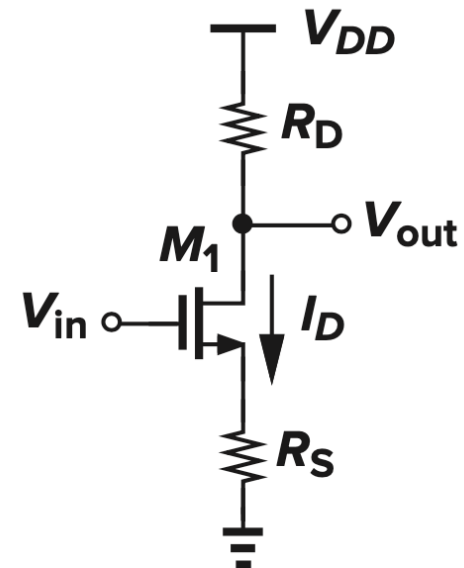
$$r_O[I_X + (g_m + g_{mb})R_S I_X] + I_X R_S = V_X$$

$$R_{out} = [1 + (g_m + g_{mb})R_S]r_O + R_S$$

$$= [1 + (g_m + g_{mb})r_O]R_S + r_O$$

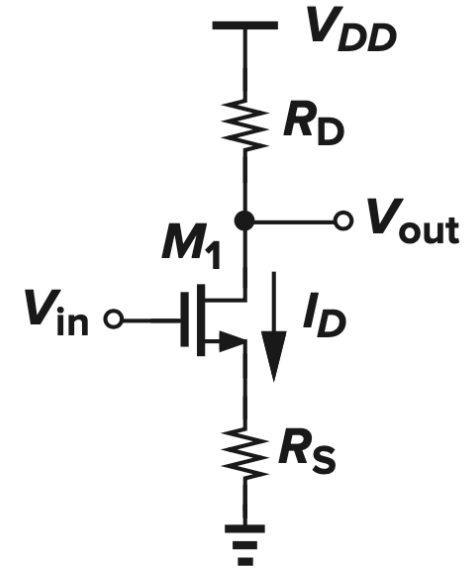
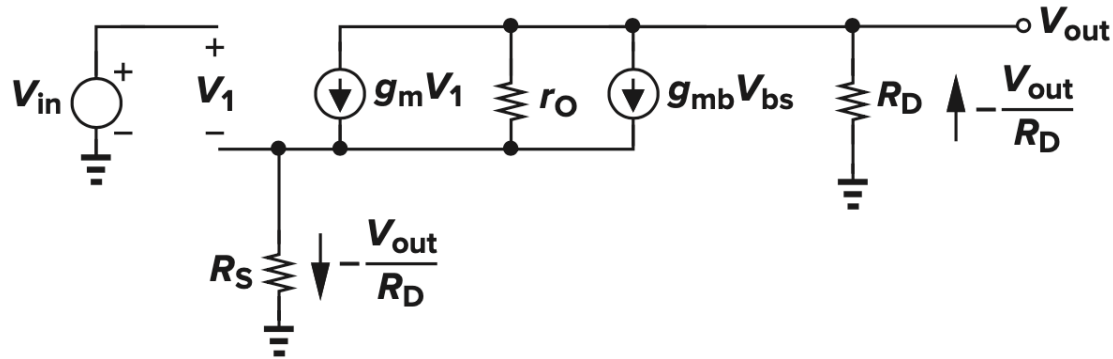
$$\approx (g_m + g_{mb})r_O R_S + r_O$$

$$= [1 + (g_m + g_{mb})R_S]r_O$$

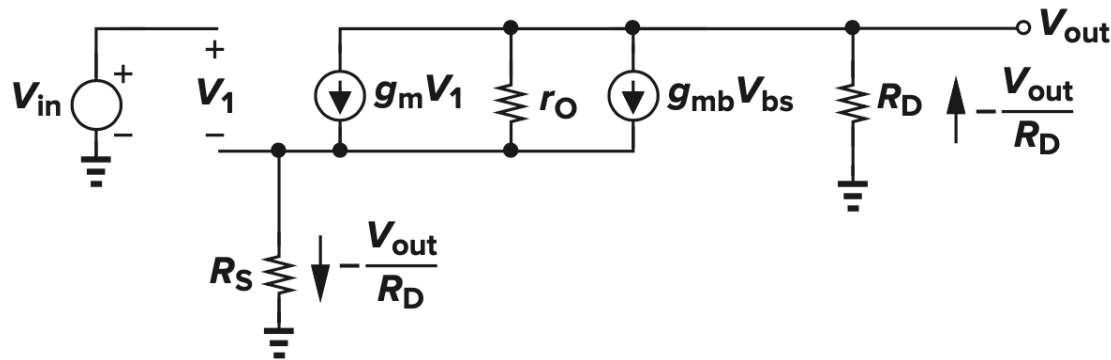


- The **overall output resistance** is the **parallel combination** of R_{out} and R_D

Gain of a degenerated CS stage



Gain of a degenerated CS stage



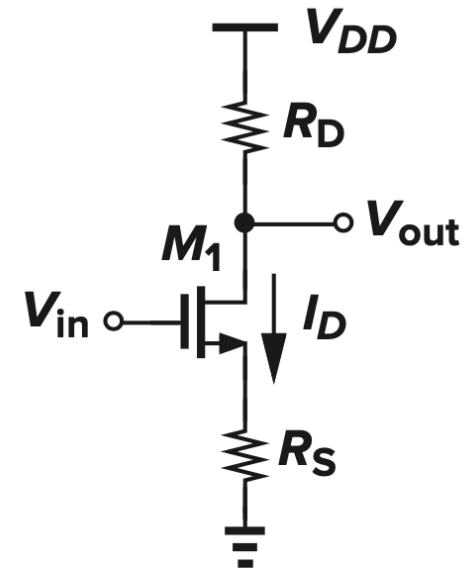
$$I_{ro} = -\frac{V_{out}}{R_D} - (g_m V_1 + g_{mb} V_{bs})$$

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

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

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

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

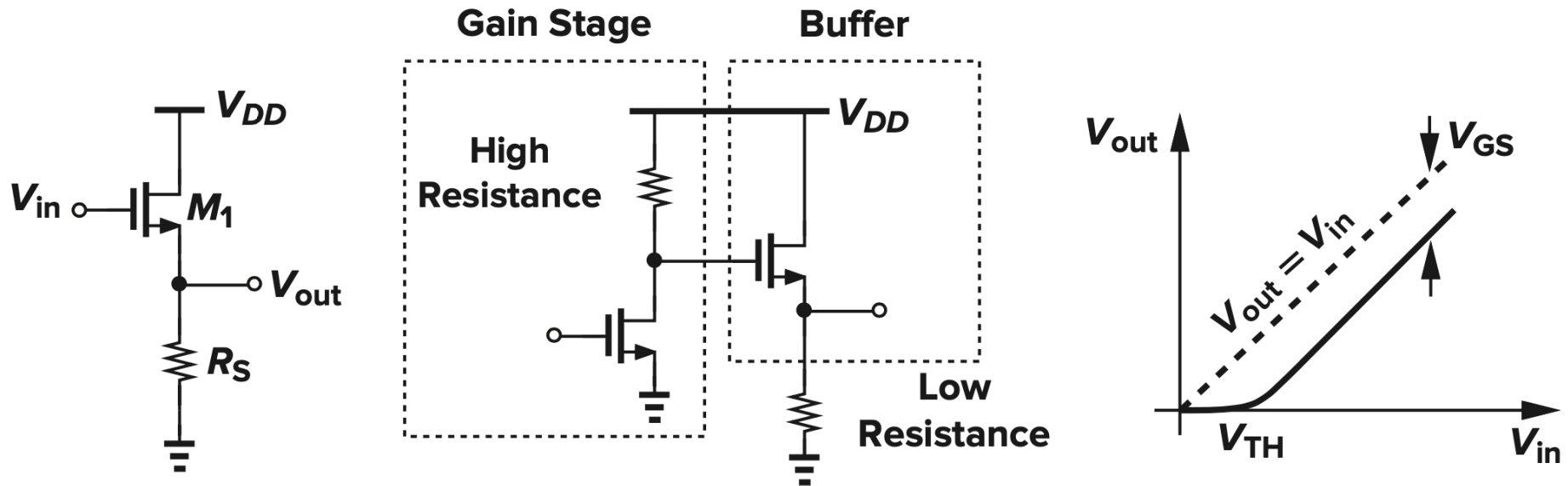


Source Follower stage

- 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**

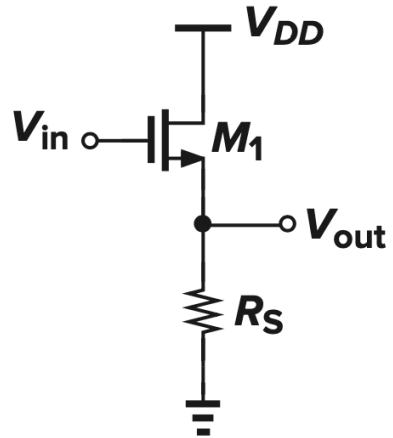
Source Follower stage

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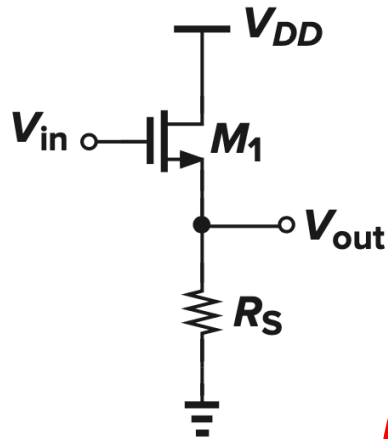


- It senses the signal at the gate, while presenting a **high input impedance**, and drives the load at the source, with a source potential “**following**” the gate voltage

Source Follower: large signal analysis



Source Follower: large signal analysis



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

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

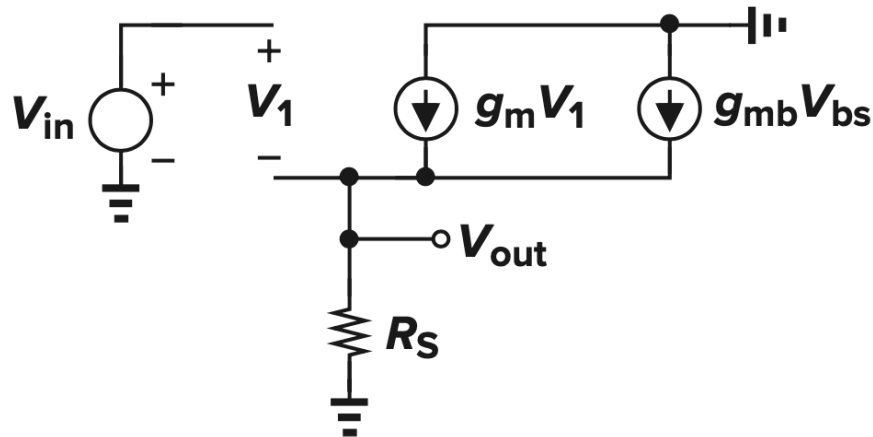
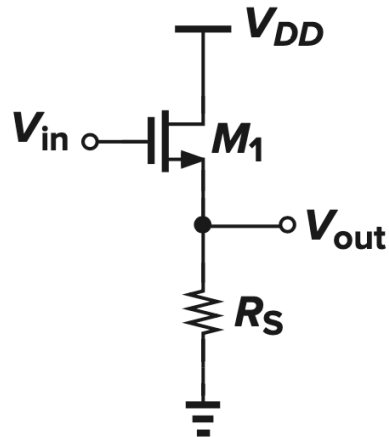
$$\boxed{\partial V_{TH} / \partial V_{in} = (\partial V_{TH} / \partial V_{SB})(\partial V_{SB} / \partial V_{in}) = \eta \partial V_{out} / \partial V_{in}}$$

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

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

Source Follower: small signal model

Small-signal equivalent of source follower:



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

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

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

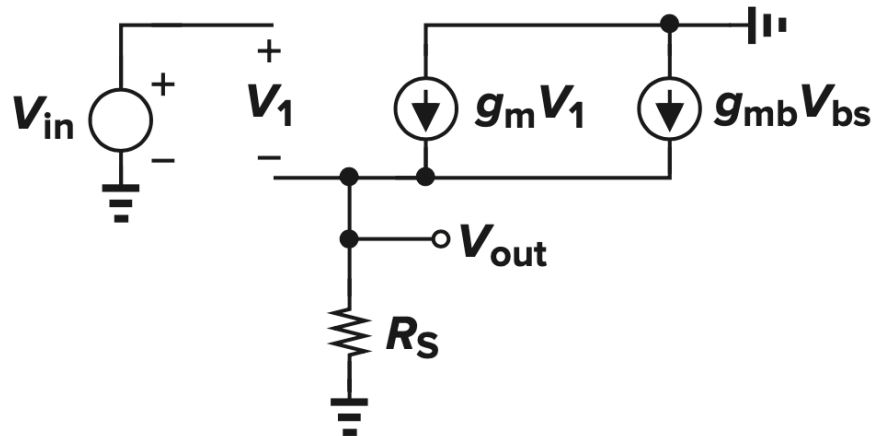
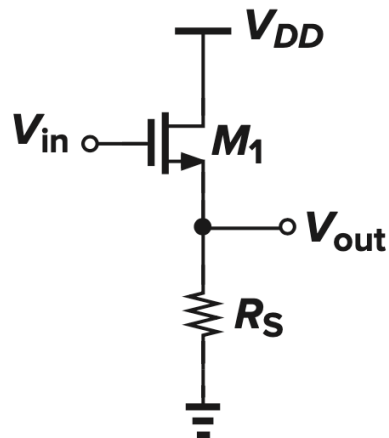
$$V_{out} / V_{in}$$



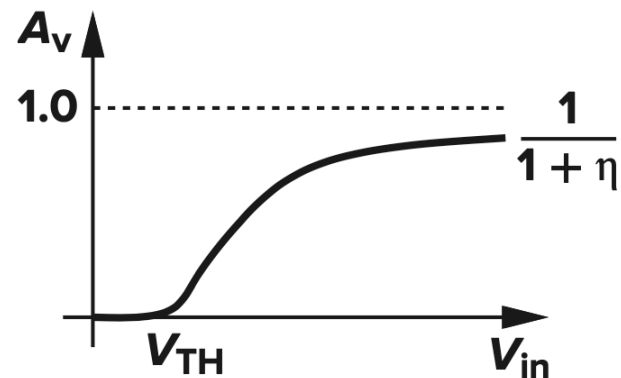
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Source Follower: small signal model

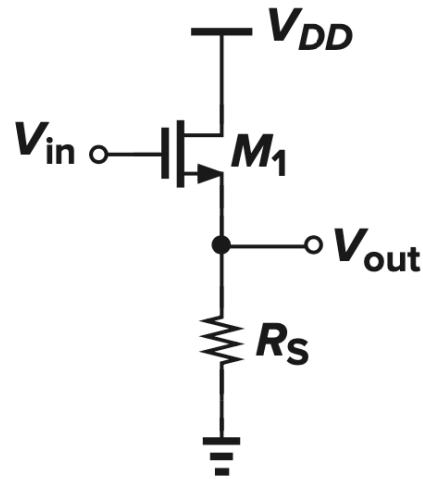
Small-signal equivalent of source follower:



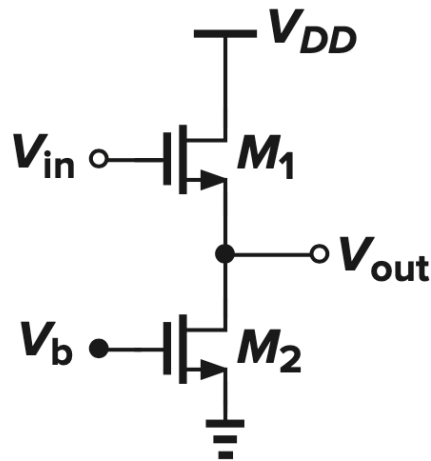
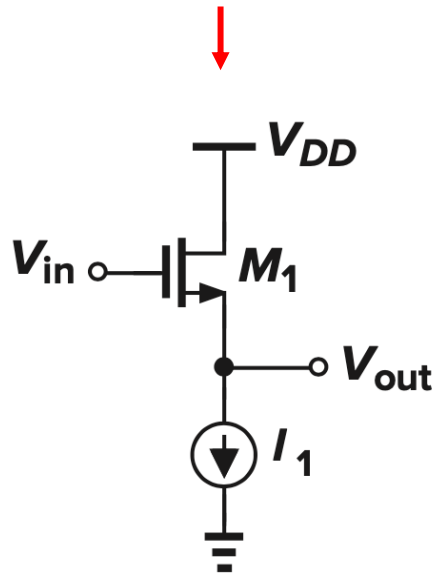
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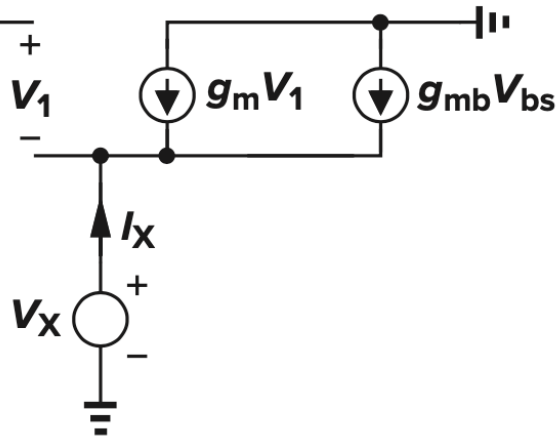
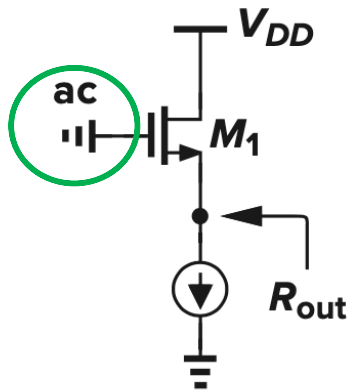
Source follower with a current source



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

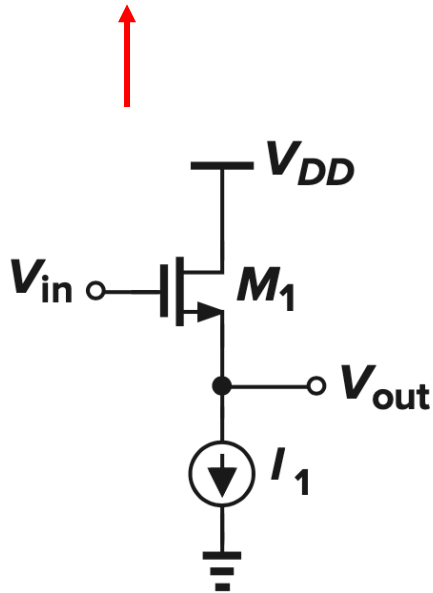


Output resistance of a Source Follower

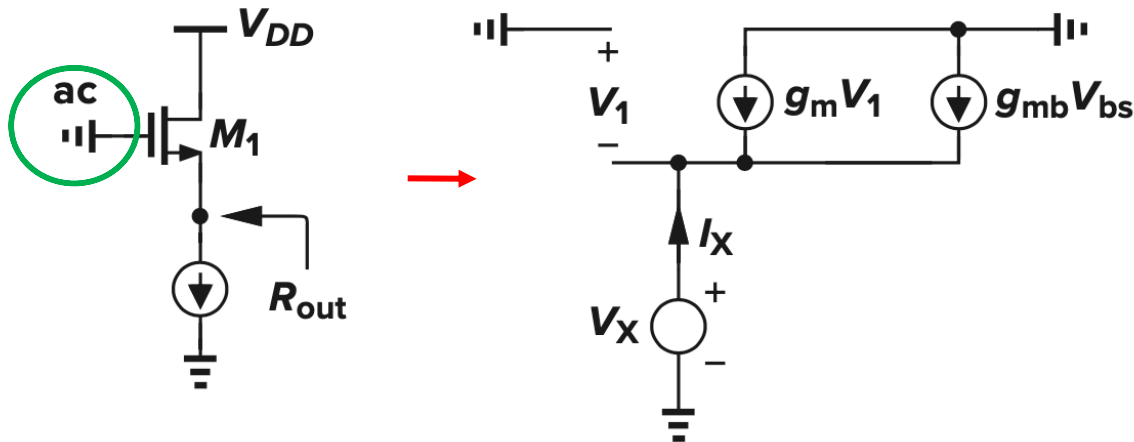


$$I_X - g_m V_X - g_{mb} V_X = 0$$

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

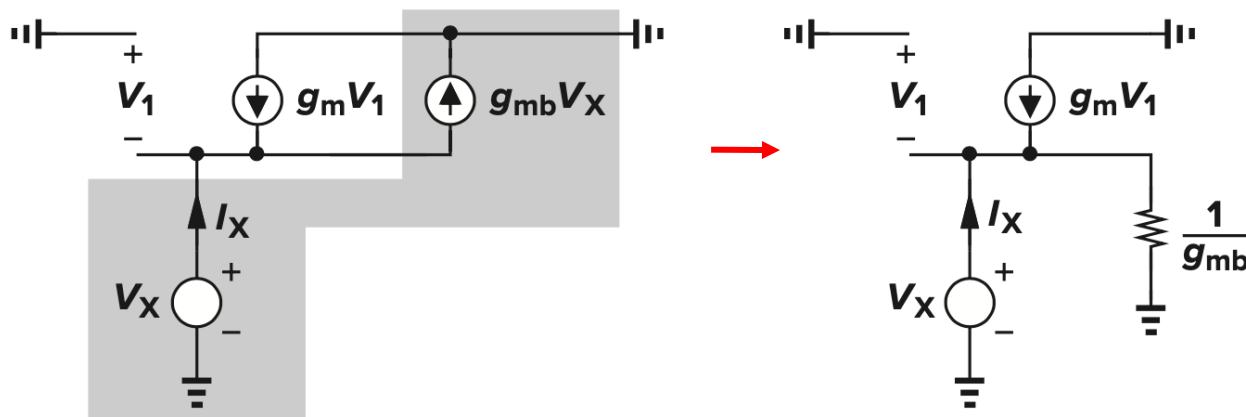


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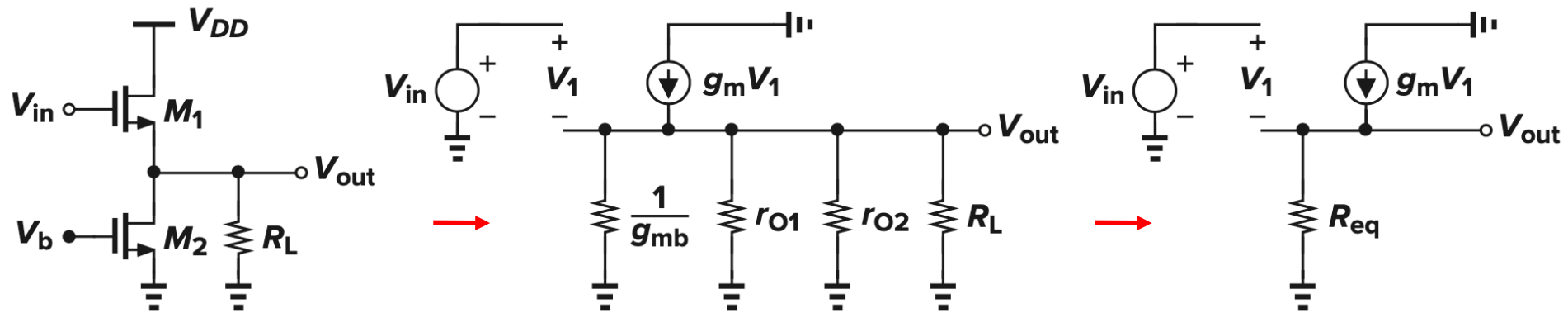


$$I_X - g_m V_X - g_{mb} V_X = 0$$

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



Source Follower with a finite load resistance



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

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