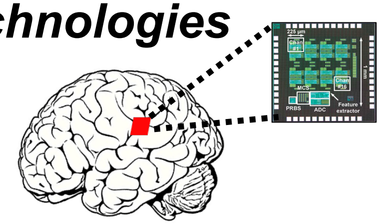
Integrated Neurotechnologies Laboratory

EPFL



Analog IC design (EE-320), Lecture 6

Prof. Mahsa Shoaran

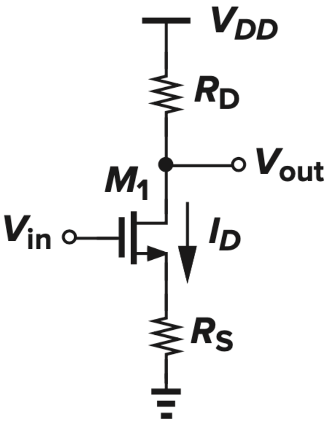
Institute of Electrical and Micro Engineering, School of Engineering, EPFL

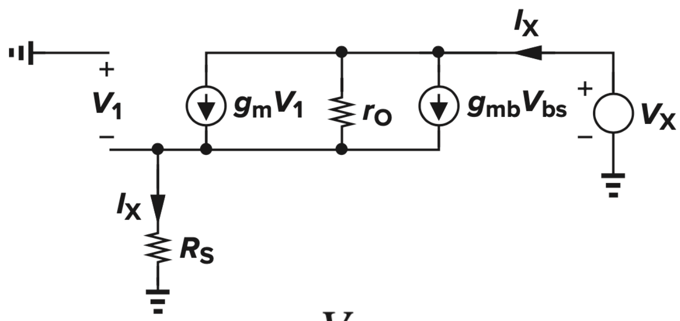
Homework 1, TP Schedule

- **Homework 1 assignment** will be posted this week
- 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**

Week	Subject by week – EE-320: Analog IC design – Fall 2024	Suggested Chapters
Week 1: **09/09** – 15/09	**Introduction, organization, review of BJT and MOS transistors** + Exercise1	Ch 1, Ch 2.1-2.4, Slides on Moodle
Week 2: **16/09** – 22/09	**Holiday - No class**	
Week 3: **23/09** – 29/09	**MOS large and small-signal models, regimes of operations** + Exercise2	Ch 2.1-2.4
Week 4: **30/09** – 06/10	**MOS parasitic effects, layout basic, single-stage amplifiers** + Exercise3	Ch 2.1-2.4, Ch 3.1
Week 5: **07/10** – 13/10	**Single-stage amplifiers** + Exercise4	Ch 3.1-3.7
Week 6: **14/10** – 20/10	**Single-stage amplifiers** + Exercise5	Ch 3.1-3.7
Week 7: **21/10** – 27/10	**Holiday – No class**	
Week 8: **28/10** – 03/11	**Single-stage amplifiers + Cascode** + Exercise6 + **Homework1**	Ch 4.1-4.4
Week 9: **04/11** – 10/11	**Differential amplifiers** + Exercise7	Ch 4.1-4.4
Week 10: **11/11** – 17/11	**TP1** Practical exercise session on Cadence	Tutorial on Moodle
Week 11: **18/11** – 24/11	**TP2** Practical exercise session on Cadence	Tutorial on Moodle
Week 12: **25/11** – 01/12	**TP3** Practical exercise session on Cadence + **Homework2**	Tutorial on Moodle
Week 13: **02/12** – 08/12	**TP4** Practical exercise session on Cadence	Tutorial on Moodle
Week 14: **09/12** – 15/12	**Differential amplifiers, current mirrors** + Exercise8	Ch 4.1-4.4, Ch 5.1-5.3
Week 15: **16/12** – 22/12	**Current mirrors** + Exercise9	Ch 5.1-5.3

Review: Common-Source

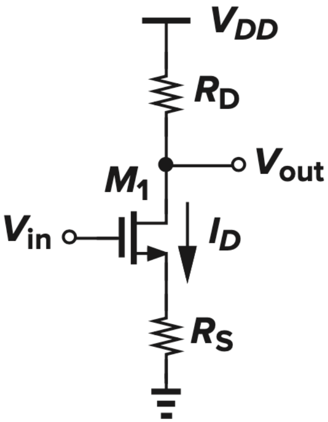


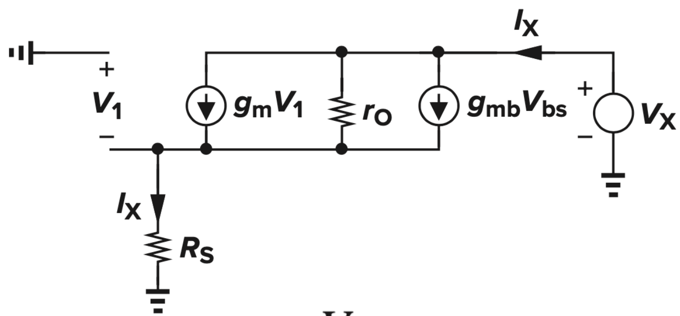


$$R_{out} = [1 + (g_m + g_{mb})R_S]r_O + R_S$$
$$= [1 + (g_m + g_{mb})r_O]R_S + r_O$$

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

Review: Common-Source, Source-Follower





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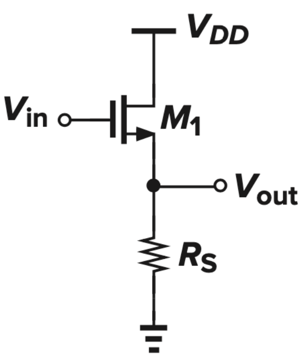
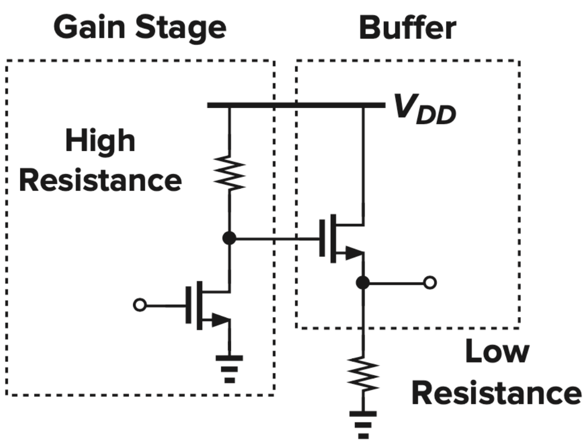
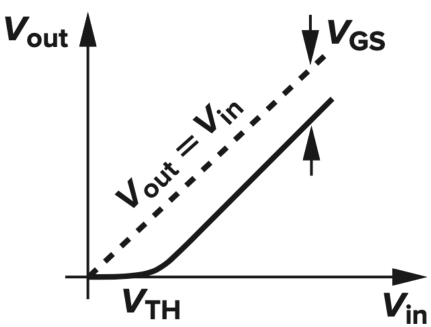
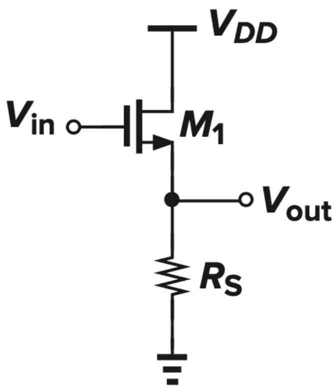
Source follower: common-drain or **voltage buffer**

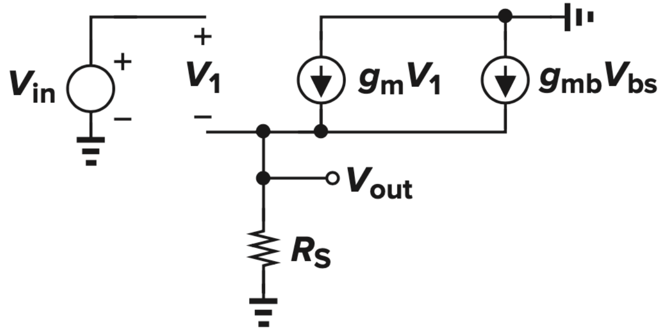




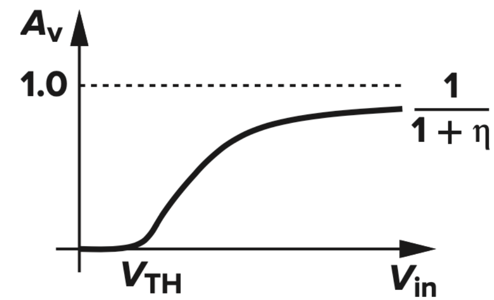


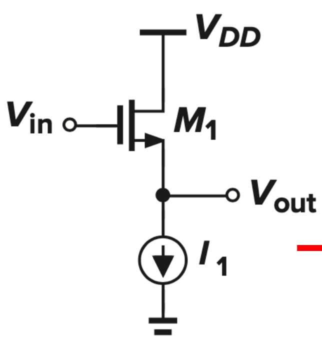
Review: Source-Follower

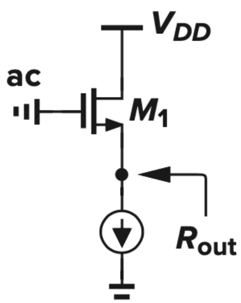


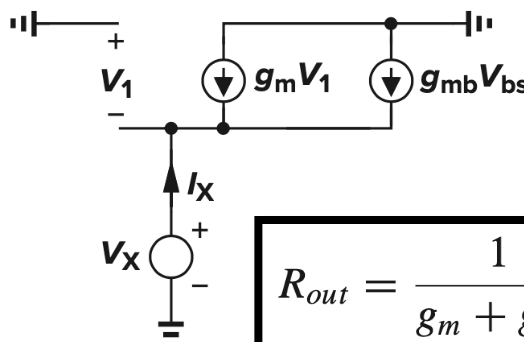


$$A_v = \frac{g_m R_S}{1 + (g_m + g_{mb}) R_S}$$

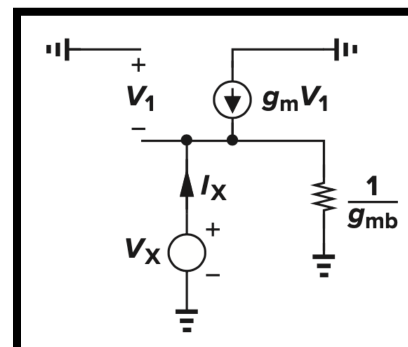




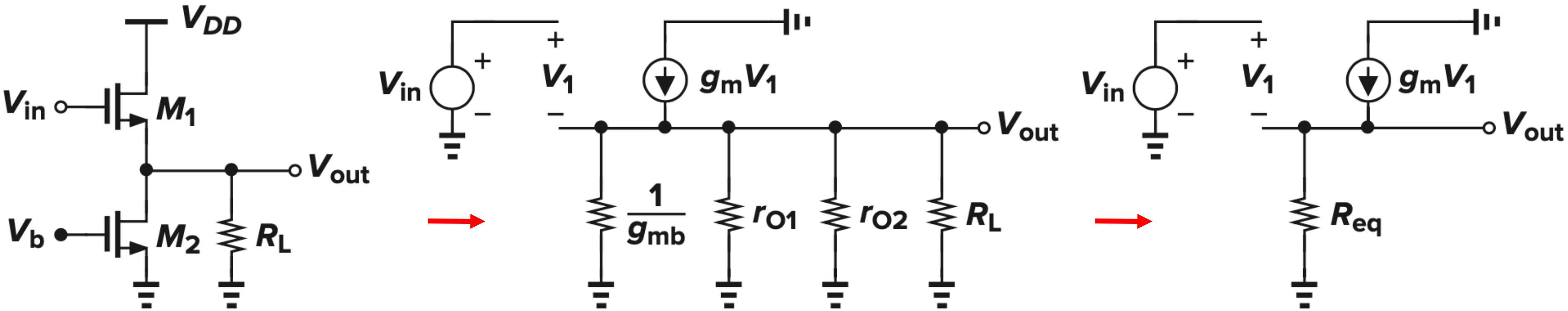




$$\boxed{R_{out} = \frac{1}{g_m + g_{mb}}}$$



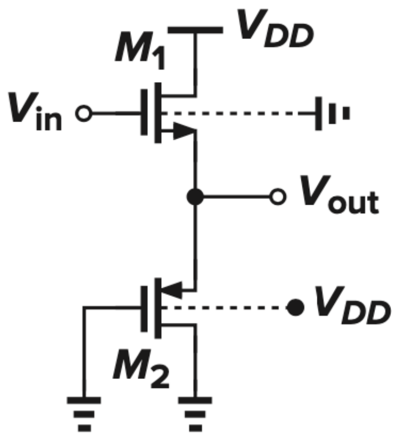
Review: Source Follower with a finite load resistance



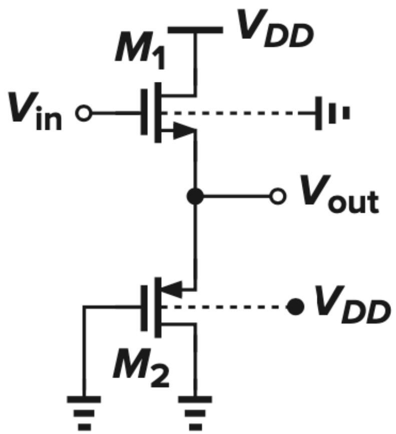
$$A_v = \frac{R_{eq}}{R_{eq} + \dfrac{1}{g_m}}$$

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

Example: Calculate the voltage gain



Example: Calculate the voltage gain



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

PMOS Source Follower with no body effect

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

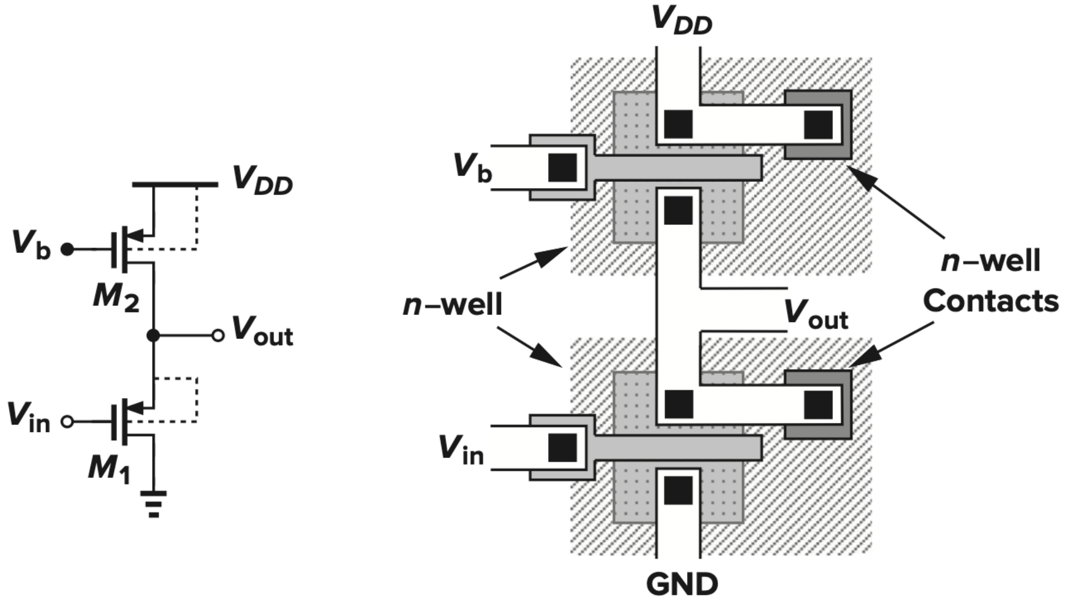
- Even if biased by an ideal current source, some nonlinearity exists due to the **nonlinear** dependence of $\boldsymbol{V_{TH}}$ upon the **source** potential

PMOS Source Follower with no body effect

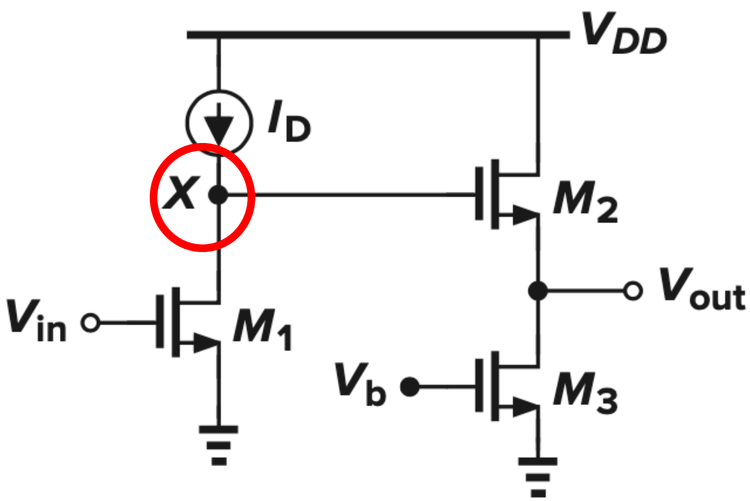
- Source follower drawbacks:
  - **nonlinearity**
  - **voltage headroom limitation**

- Even if biased by an ideal current source, some nonlinearity exists due to the **nonlinear** dependence of 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

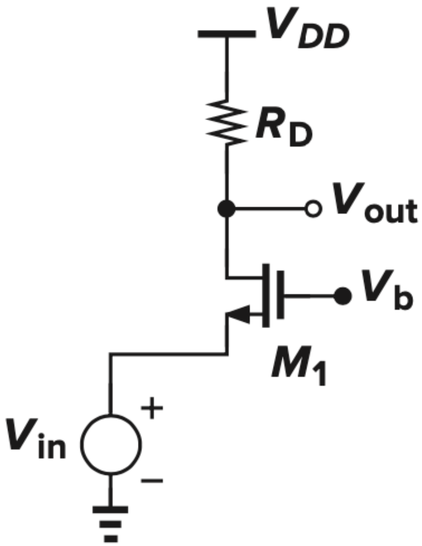


$$V_{GS1} - V_{TH1} \quad \rightarrow \quad V_{GS2} + (V_{GS3} - V_{TH3})$$

- 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**

Common-Gate Stage

- A common-gate (CG) stage senses the input at the **source** and produces the output at the **drain**



Common-Gate Stage

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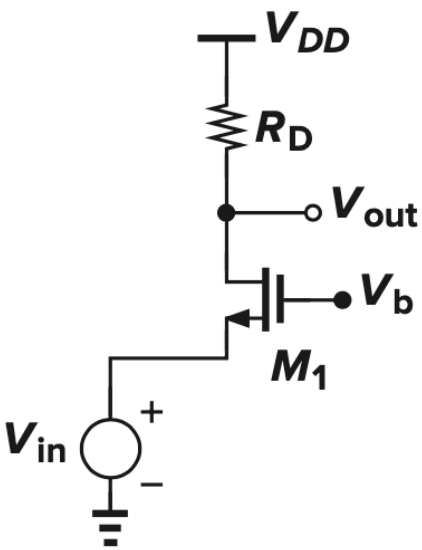
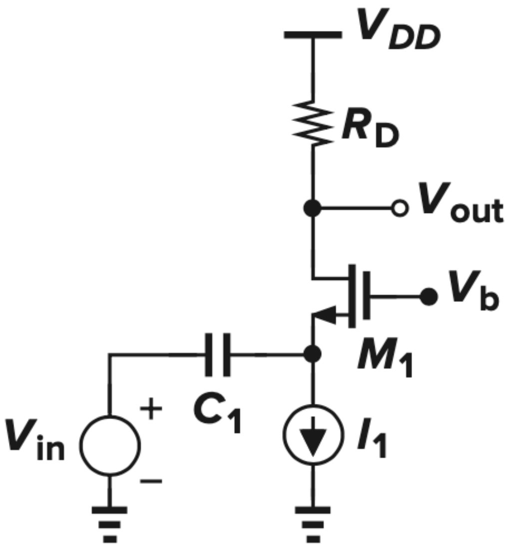
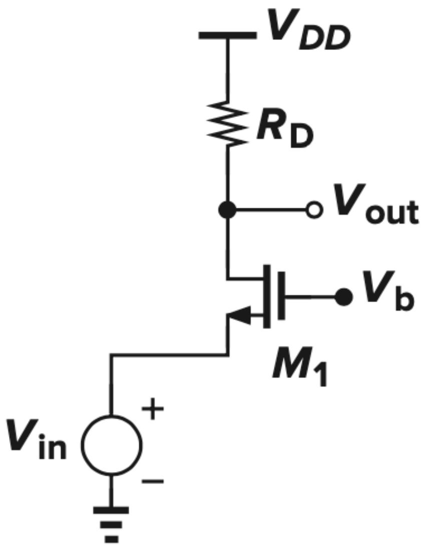




Common-Gate Stage: large signal analysis



in saturation

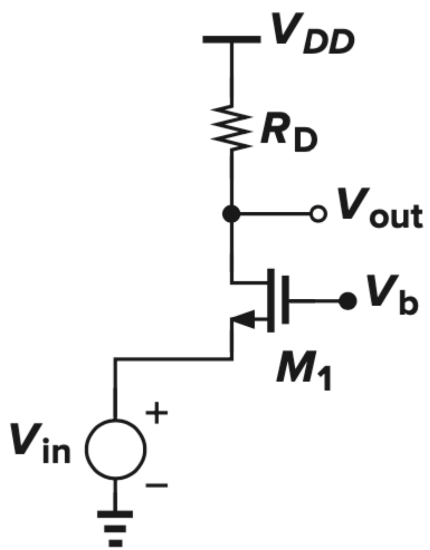
$$I_D = \frac{1}{2}\mu_n C_{ox}\frac{W}{L}(V_b - V_{in} - V_{TH})^2$$

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

driving M_1 into the triode region if:

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

Common-Gate Stage: large signal analysis



in saturation

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

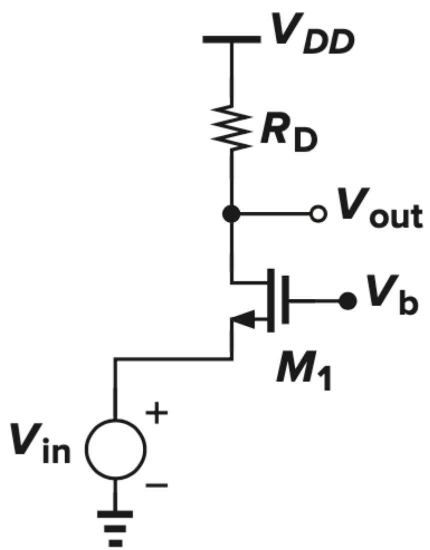
$$\frac{\partial V_{out}}{\partial V_{in}} = -\mu_n C_{ox}\frac{W}{L}(V_b - V_{in} - V_{TH})\left(-1 - \frac{\partial V_{TH}}{\partial V_{in}}\right) R_D$$

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

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

$$\boxed{= g_m(1+\eta)R_D}$$

Common-Gate Stage: large signal analysis



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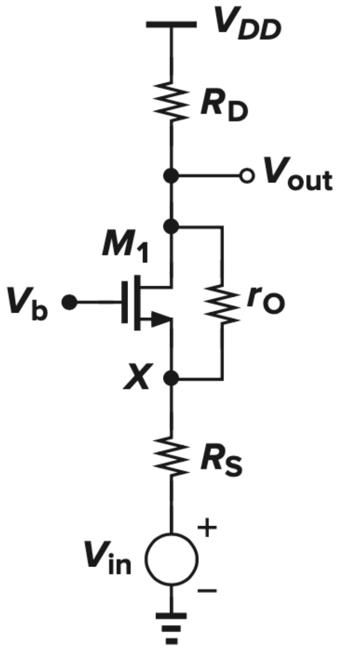
$$= \mu_n C_{ox}\frac{W}{L} R_D (V_b - V_{in} - V_{TH})(1+\eta)$$

$$\boxed{= g_m(1+\eta)R_D}$$

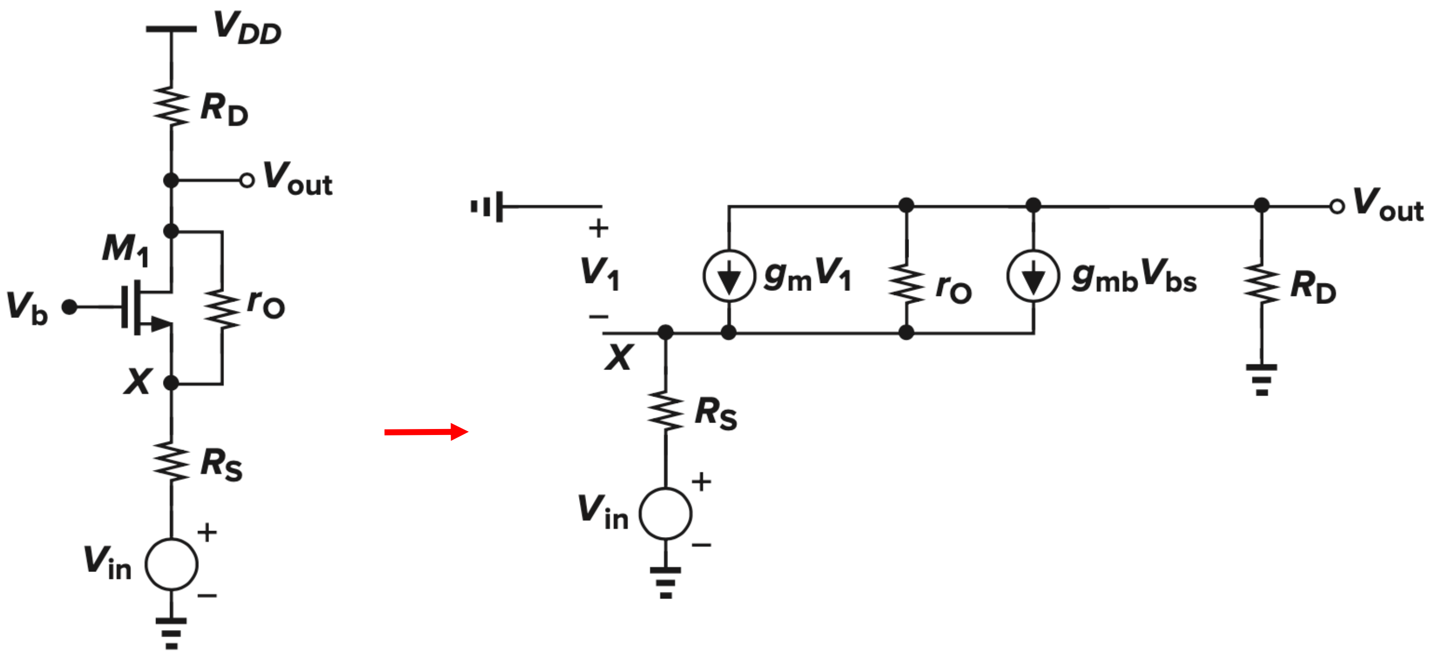
- for $\lambda = 0$, the **input impedance** (seen at the source of M_1): $\boxed{1/(g_m + g_{mb})}$

$$\boxed{1/[g_m(1+\eta)]}$$

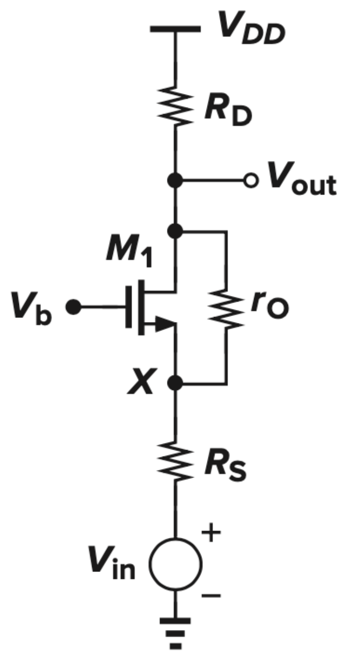
Common-Gate Stage: general case

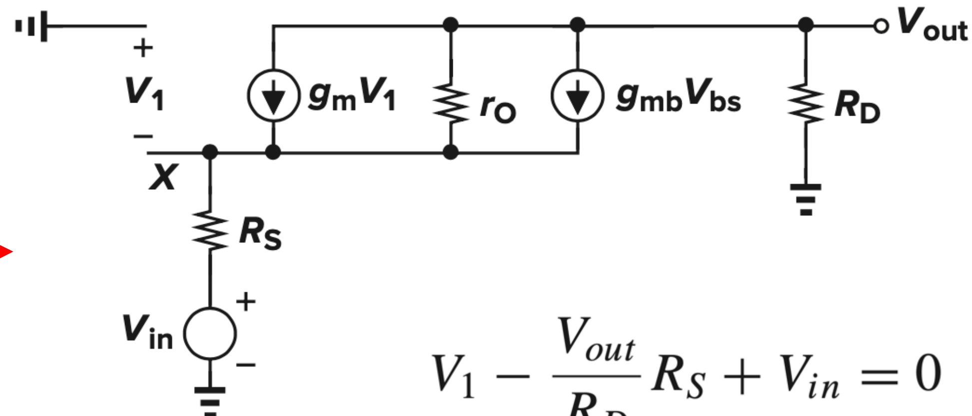


Common-Gate Stage: general case



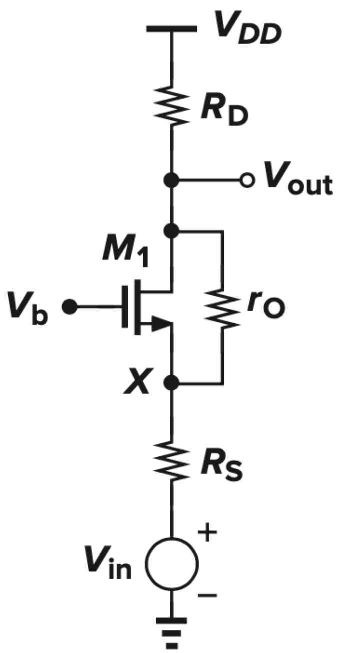
Common-Gate Stage: general case

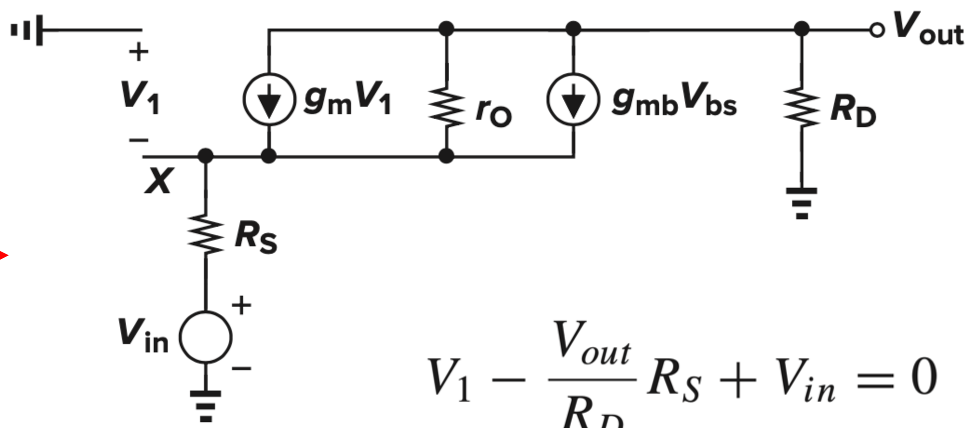




$$V_1 - \frac{V_{out}}{R_D} R_S + V_{in} = 0$$

Common-Gate Stage: general case

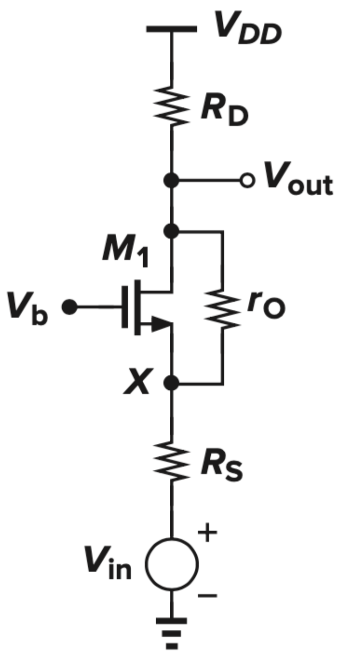


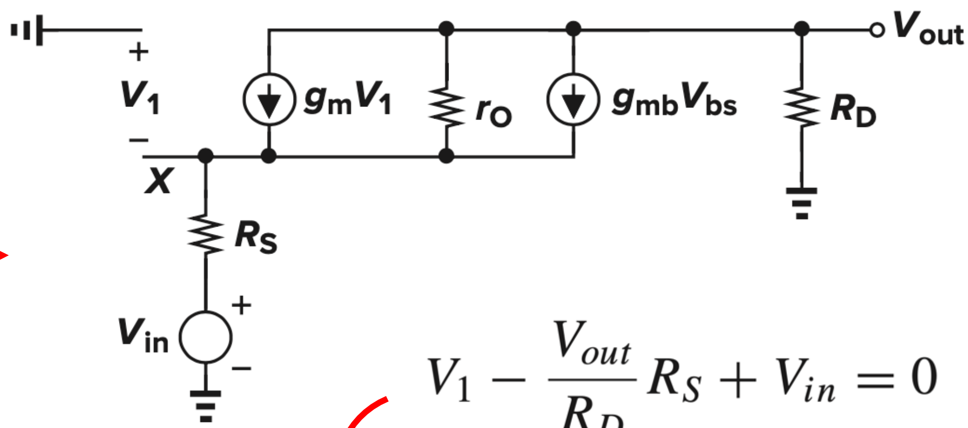


$$V_1 - \frac{V_{out}}{R_D} R_S + V_{in} = 0$$

$$r_O \left(\frac{-V_{out}}{R_D} - g_m V_1 - g_{mb} V_1 \right) - \frac{V_{out}}{R_D} R_S + V_{in} = V_{out}$$

Common-Gate Stage: general case





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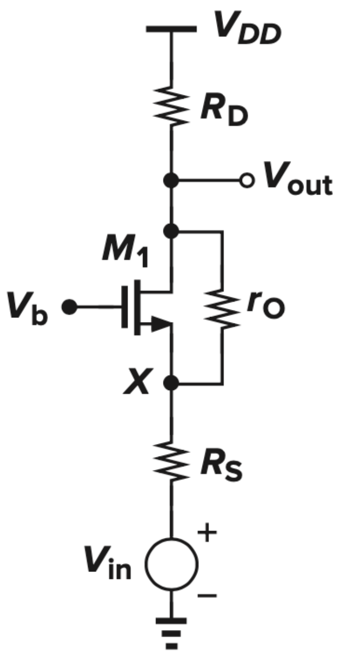
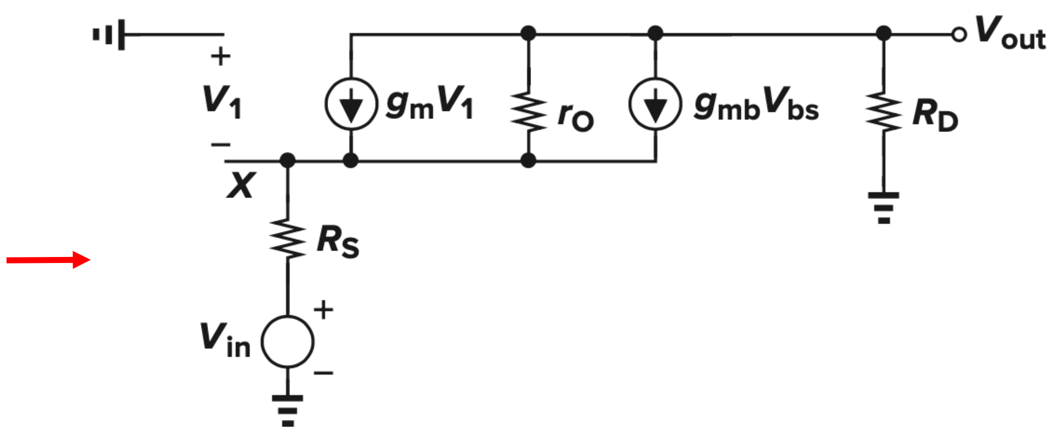
$$r_O \left(\frac{-V_{out}}{R_D} - g_m V_1 - g_{mb} V_1 \right) - \frac{V_{out}}{R_D} R_S + V_{in} = V_{out}$$

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

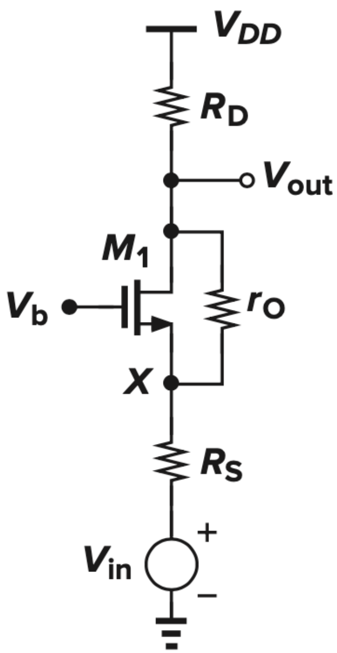
Common-Gate Stage: general case

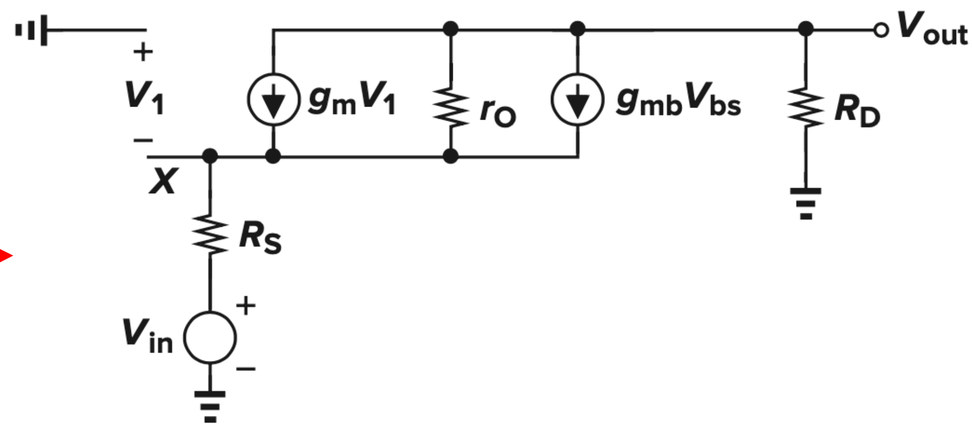




$$\frac{V_{out}}{V_{in}} = \frac{(g_m + g_{mb})r_O + 1}{r_O + (g_m + g_{mb})r_O R_S + R_S + R_D} R_D$$

Common-Gate Stage: general case



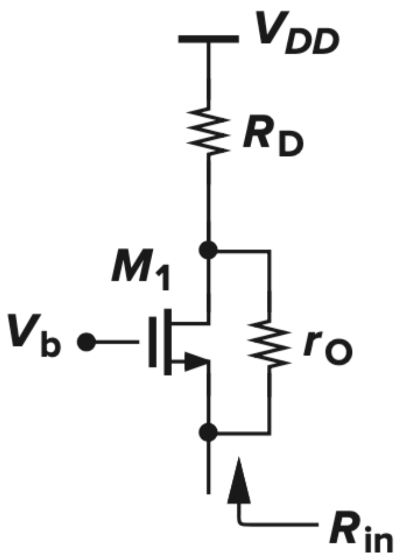


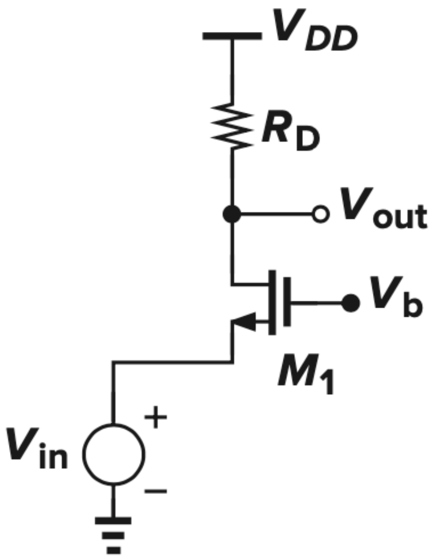
$$\frac{V_{out}}{V_{in}} = \frac{(g_m + g_{mb})r_O + 1}{r_O + (g_m + g_{mb})r_O R_S + R_S + R_D} R_D$$

Gain of a degenerated CS stage

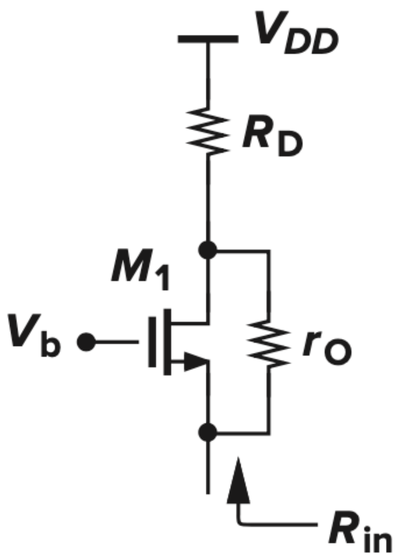
$$\boxed{\frac{V_{out}}{V_{in}} = \frac{-g_m r_O R_D}{R_D + R_S + r_O + (g_m + g_{mb}) R_S r_O}}$$

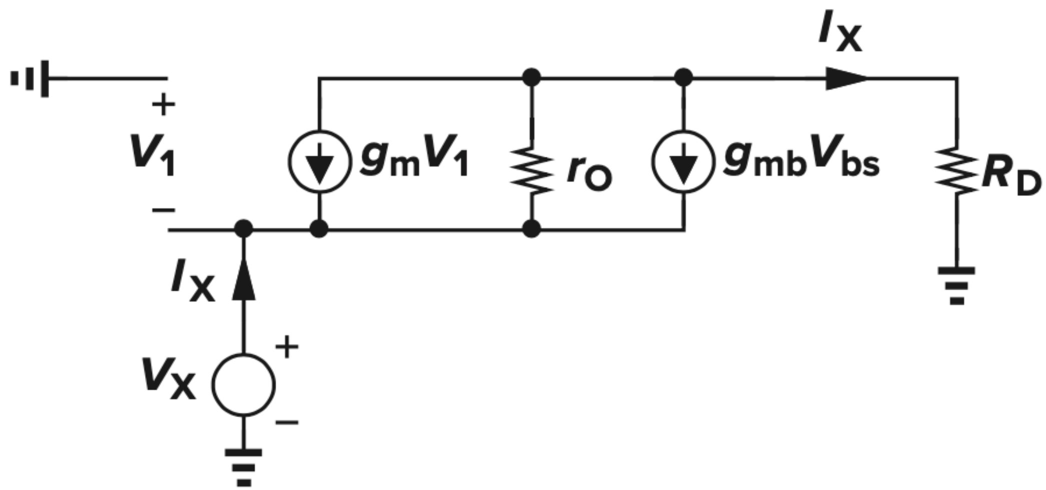
Input resistance of a CG stage





Input resistance of a CG stage



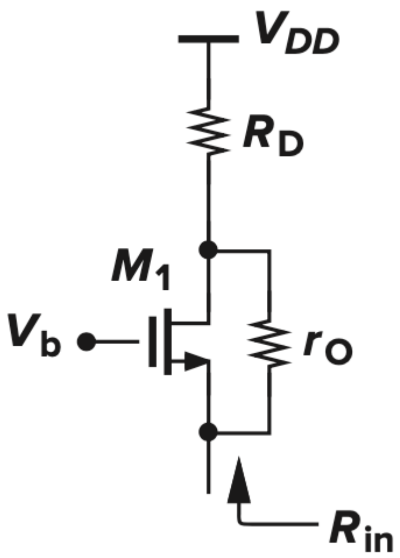


$$R_D I_X + r_O[I_X - (g_m + g_{mb})V_X] = V_X$$

$$\frac{V_X}{I_X} = \frac{R_D + r_O}{1 + (g_m + g_{mb})r_O}$$

$$\approx \frac{R_D}{(g_m + g_{mb})r_O} + \frac{1}{g_m + g_{mb}}$$

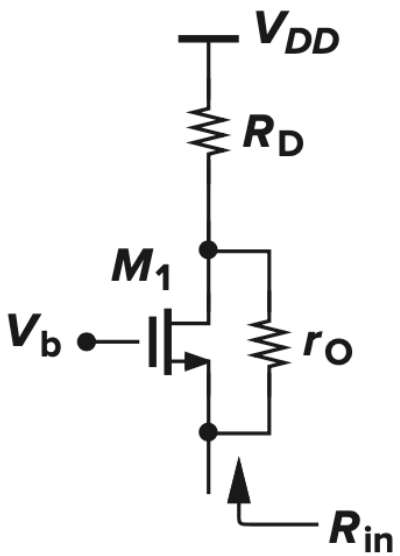
Input resistance of a CG stage



$$\frac{V_X}{I_X} = \frac{R_D + r_O}{1 + (g_m + g_{mb})r_O}$$
$$\approx \frac{R_D}{(g_m + g_{mb})r_O} + \frac{1}{g_m + g_{mb}}$$

✓ the **drain impedance** is **divided** by $(g_m + g_{mb})r_O$ when seen at the **source**

Input resistance of a CG stage



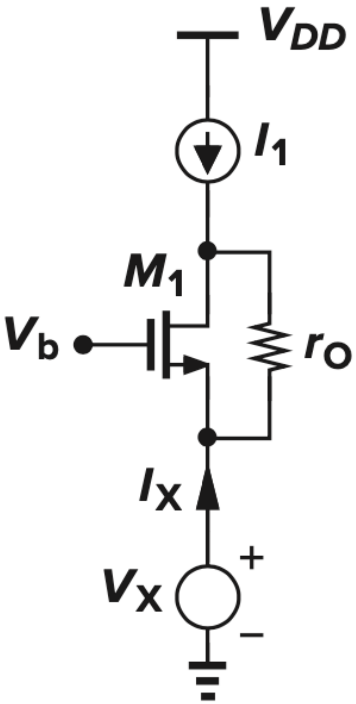
$$\frac{V_X}{I_X} = \frac{R_D + r_O}{1 + (g_m + g_{mb})r_O}$$
$$\approx \frac{R_D}{(g_m + g_{mb})r_O} + \frac{1}{g_m + g_{mb}}$$

✓ the **drain impedance** is **divided** by $(g_m + g_{mb})r_O$ when seen at the **source**

$R_D = 0$ →

$$\frac{V_X}{I_X} = \frac{r_O}{1 + (g_m + g_{mb})r_O}$$
$$= \frac{1}{\frac{1}{r_O} + g_m + g_{mb}}$$

Input resistance of a CG stage

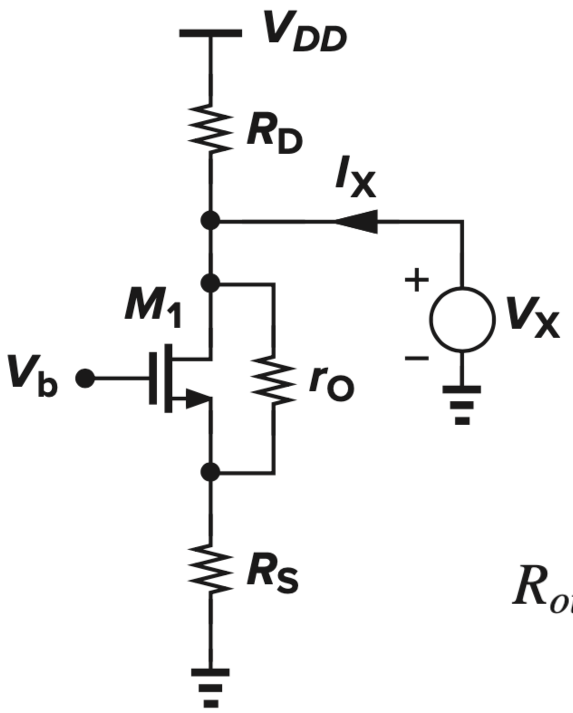


$$\frac{V_X}{I_X} = \frac{R_D + r_O}{1 + (g_m + g_{mb})r_O}$$

$$\approx \frac{R_D}{(g_m + g_{mb})r_O} + \frac{1}{g_m + g_{mb}}$$

the input impedance approaches infinity

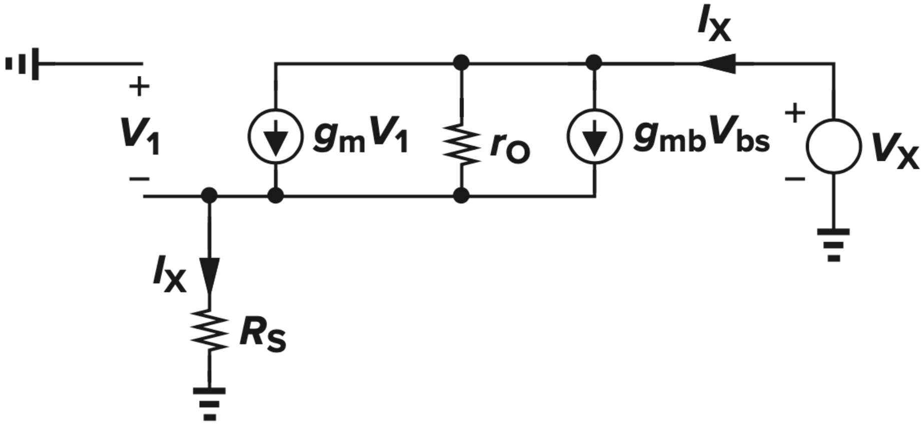
Output resistance of a CG stage

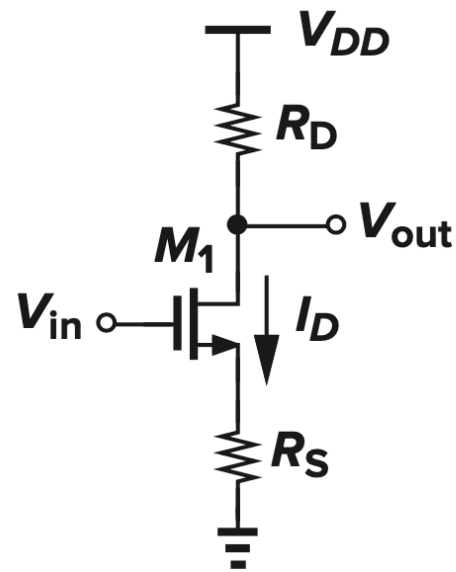


$$R_{out} = \{[1 + (g_m + g_{mb})r_O]R_S + r_O\} \| R_D$$

Recall: Output resistance of a degenerated CS

- Source degeneration **increases** the output resistance



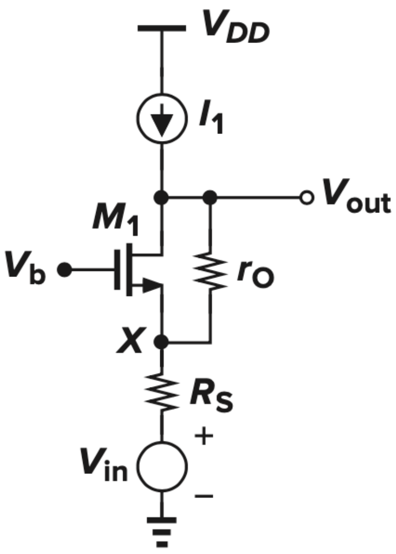


$$r_O[I_X + (g_m + g_{mb})R_S I_X] + I_X R_S = V_X$$

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

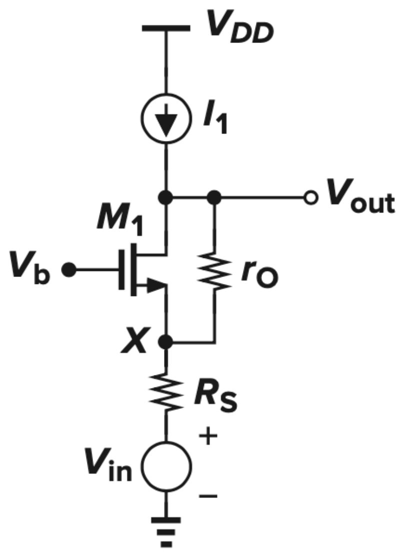
- **The overall output resistance is the parallel combination of R_{out} and R_D**

Example: Calculate the voltage gain



- A common-gate stage with a **current-source load**

Example: Calculate the voltage gain



- A common-gate stage with a current-source load

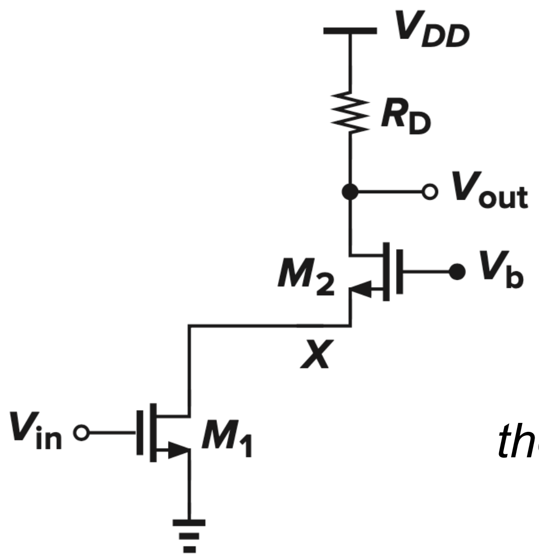
$$\frac{V_{out}}{V_{in}} = \frac{(g_m + g_{mb})r_O + 1}{r_O + (g_m + g_{mb})r_O R_S + R_S + R_D} R_D$$

$R_D \rightarrow \infty$

$$A_v = (g_m + g_{mb})r_O + 1$$

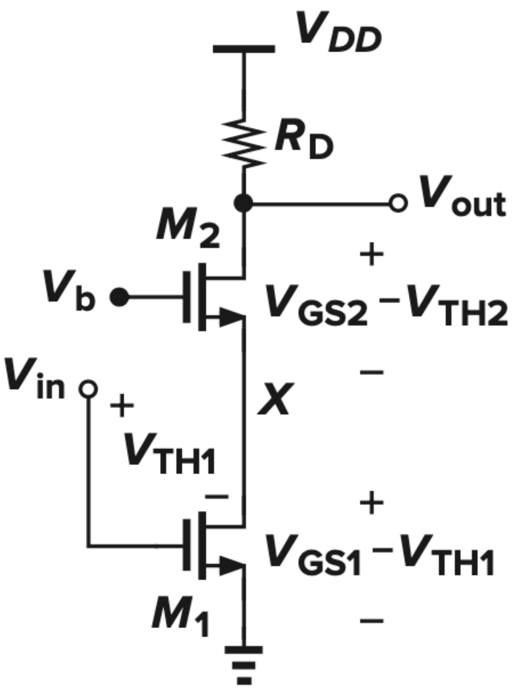
Cascode stage

- The cascade of a **CS stage and a CG stage** is called a “cascode” topology, providing many useful properties.



the “telescopic” cascode

Cascode: bias condition



$$V_b - V_{GS2} \geq V_{in} - V_{TH1}$$

$$V_{out} \geq V_b - V_{TH2}$$

$$\downarrow$$

$$V_{out} \geq V_{in} - V_{TH1} + V_{GS2} - V_{TH2}$$

$$= (V_{GS1} - V_{TH1}) + (V_{GS2} - V_{TH2})$$

✓ the minimum output level for both transistors to operate in saturation is equal to the overdrive voltage of M_1 plus that of M_2

Cascode: large-signal behavior