Mikroelektronische Schaltungen und Systeme

Single Stage Amplifiers

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Mikroelektronische Schaltungen und Systeme

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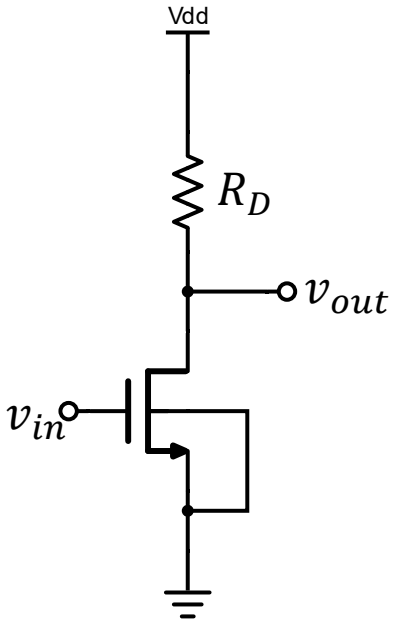
Common-Source Amplifier

Letter Convention

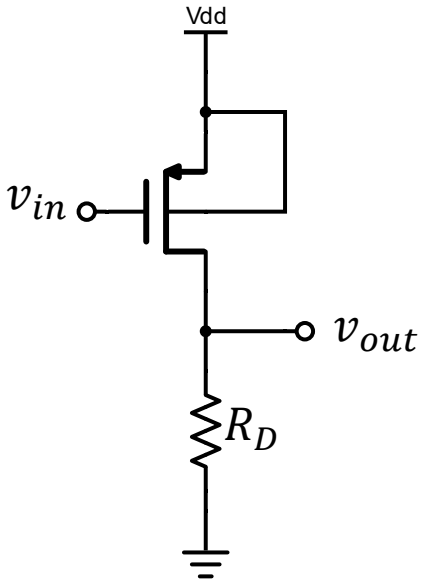
- DC Signals (Upper case): V_{GS}, V_B, I_D
- AC Signals (Lower case): v_{gs}, v_x, i_x

Common-Source Stage with Resistive Load

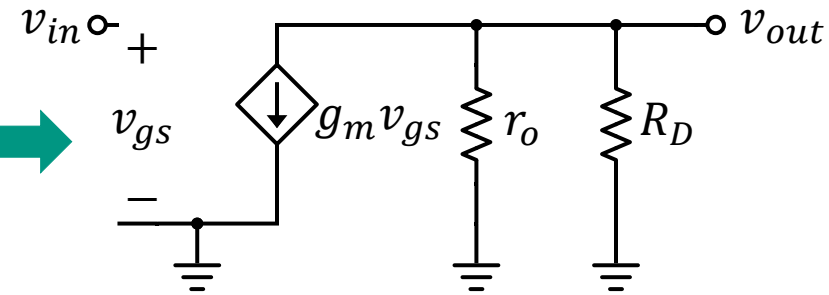
- The common-source amplifier is the most fundamental amplifier block, which was introduced in the ES course.



- *CS NMOS*



- *CS PMOS*



- *Small-signal model*

- The midband gain:

$$A_v = \frac{v_{out}}{v_{in}} = -g_m(r_o \parallel R_D) \approx -g_m R_D$$

- Input & output resistances:

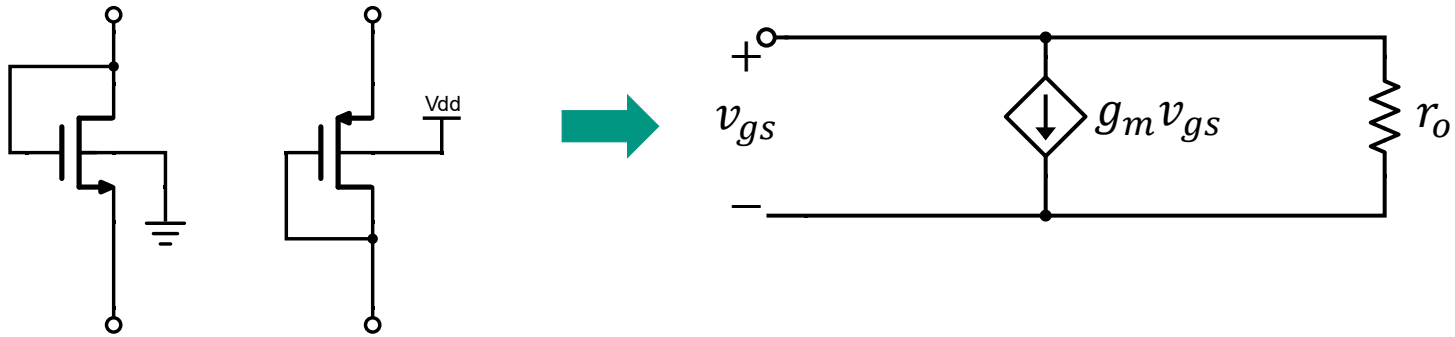
$$R_{in} \to \infty$$

$$R_{out} = (r_o \parallel R_D)$$

CS Stage with Diode-Connected Load

Diode Connected Device

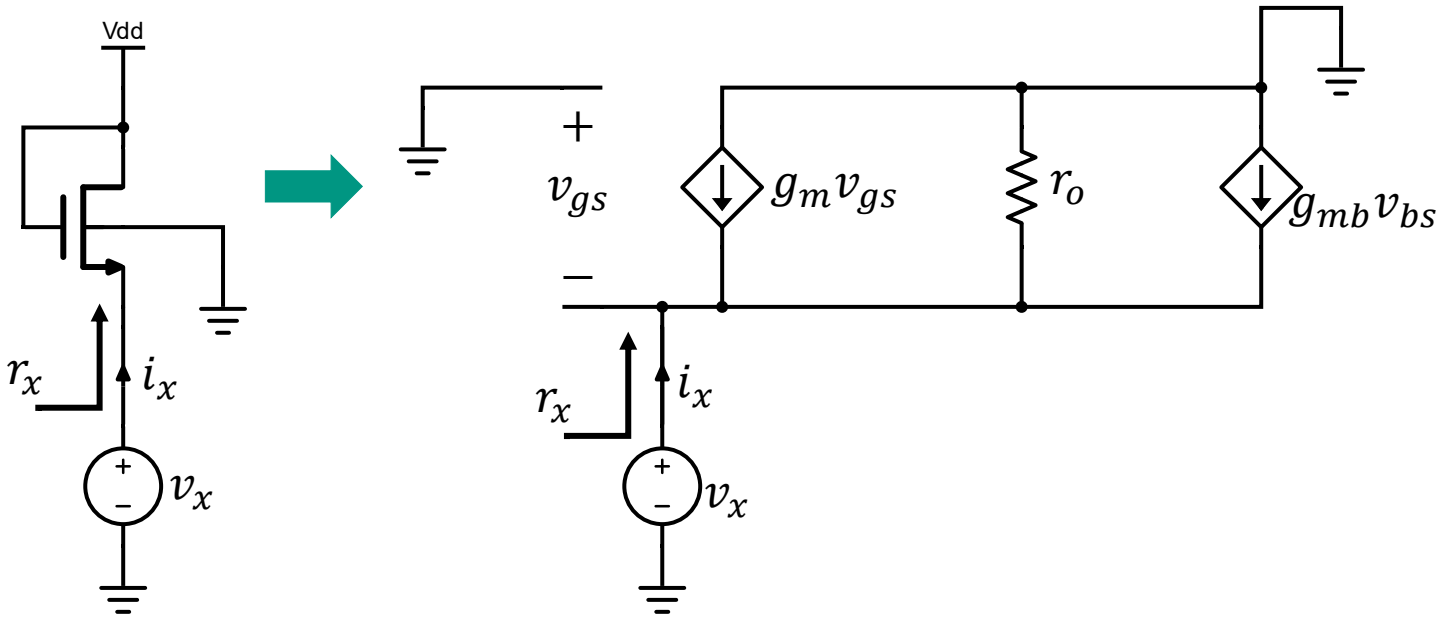
- In CMOS technologies, passive devices occupy large area, and it is challenging to fabricate resistors with high precision, as their resistance can vary significantly.
- To replace these imprecise devices, MOS transistors are often used as a load.
- A MOSFET with its gate and drain shorted can operate as a small-signal resistor. When a voltage is applied from drain to source for NMOS (from source to drain for PMOS), this gate–drain connection forward-biases the channel, which is why it is called a 'diode-connected' MOSFET.



CS Stage with Diode-Connected Load

Analysis of Diode Connected Device

- To use the diode-connected MOSFET as a load, let‘s calculate the equivalent small-signal resistance (R_x) seen from the source terminal.



$$v_{gs} = -v_x, v_{bs} = -v_x$$

$$i_x = -g_m v_{gs} + \frac{v_x}{r_o} - g_{mb} v_{bs}$$

$$i_x = g_m v_x + \frac{v_x}{r_o} + g_{mb} v_x$$

$$r_x = \frac{v_x}{i_x} = \frac{1}{g_m + \frac{1}{r_o} + g_{mb}} = \frac{1}{g_m} \parallel r_o \parallel \frac{1}{g_{mb}}$$

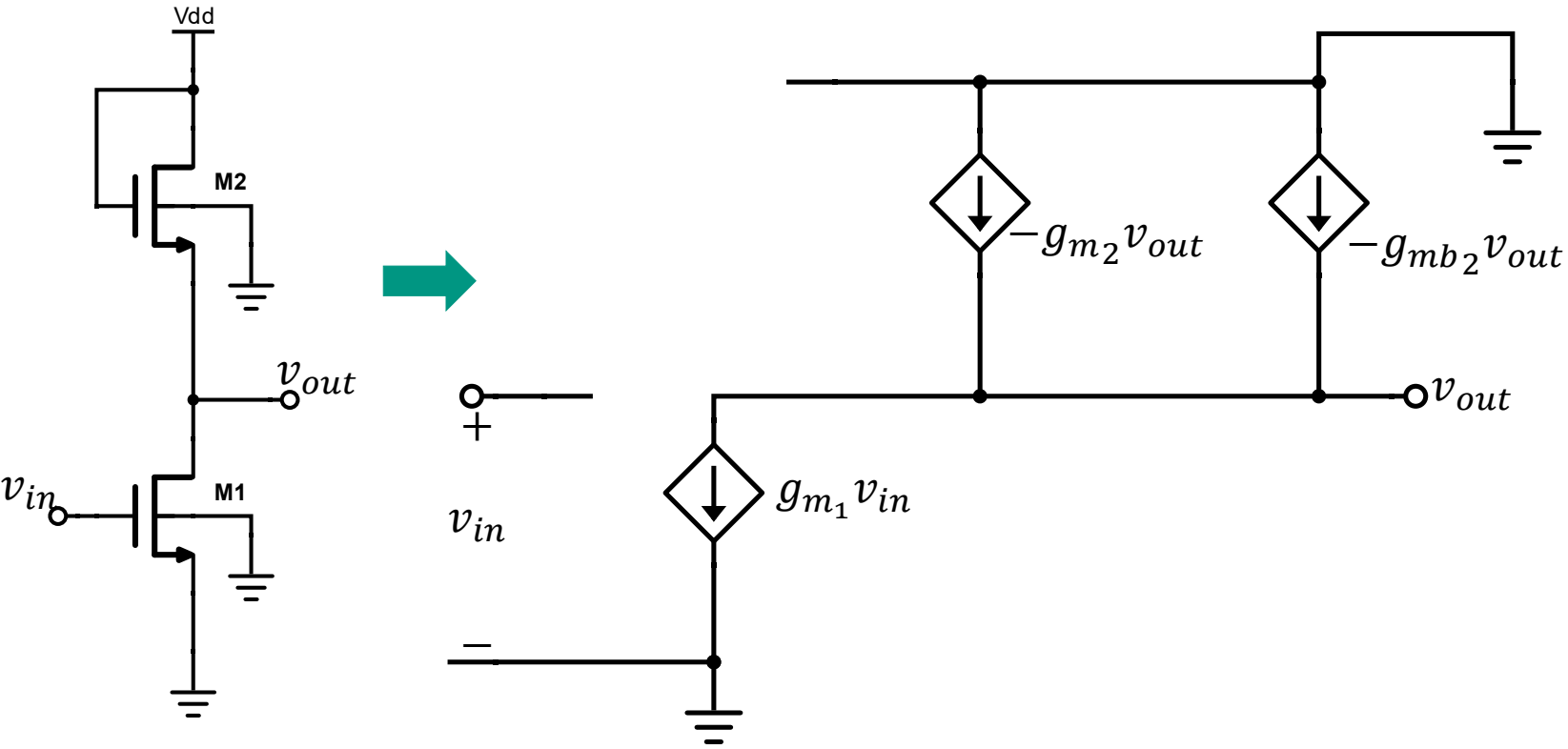
$$\text{Considering } r_o \gg \frac{1}{g_m}$$

$$\boxed{r_x \approx \frac{1}{g_m + g_{mb}}}$$

CS Stage with Diode-Connected Load

Voltage Gain Expression

- The output resistance (r_o) of both transistors are omitted in small-signal model.



$$g_{m_1}v_{in} = -v_{out}\left(g_{m_2} + g_{mb_2}\right)$$

$$\boxed{A_v = \frac{v_{out}}{v_{in}} = -\frac{g_{m_1}}{g_{m_2} + g_{mb_2}} = -g_{m_1}r_{x_2}}$$

$$\left(Recall: \frac{g_m}{g_{mb}} = \frac{1}{\eta}\right)$$

CS Stage with Diode-Connected Load

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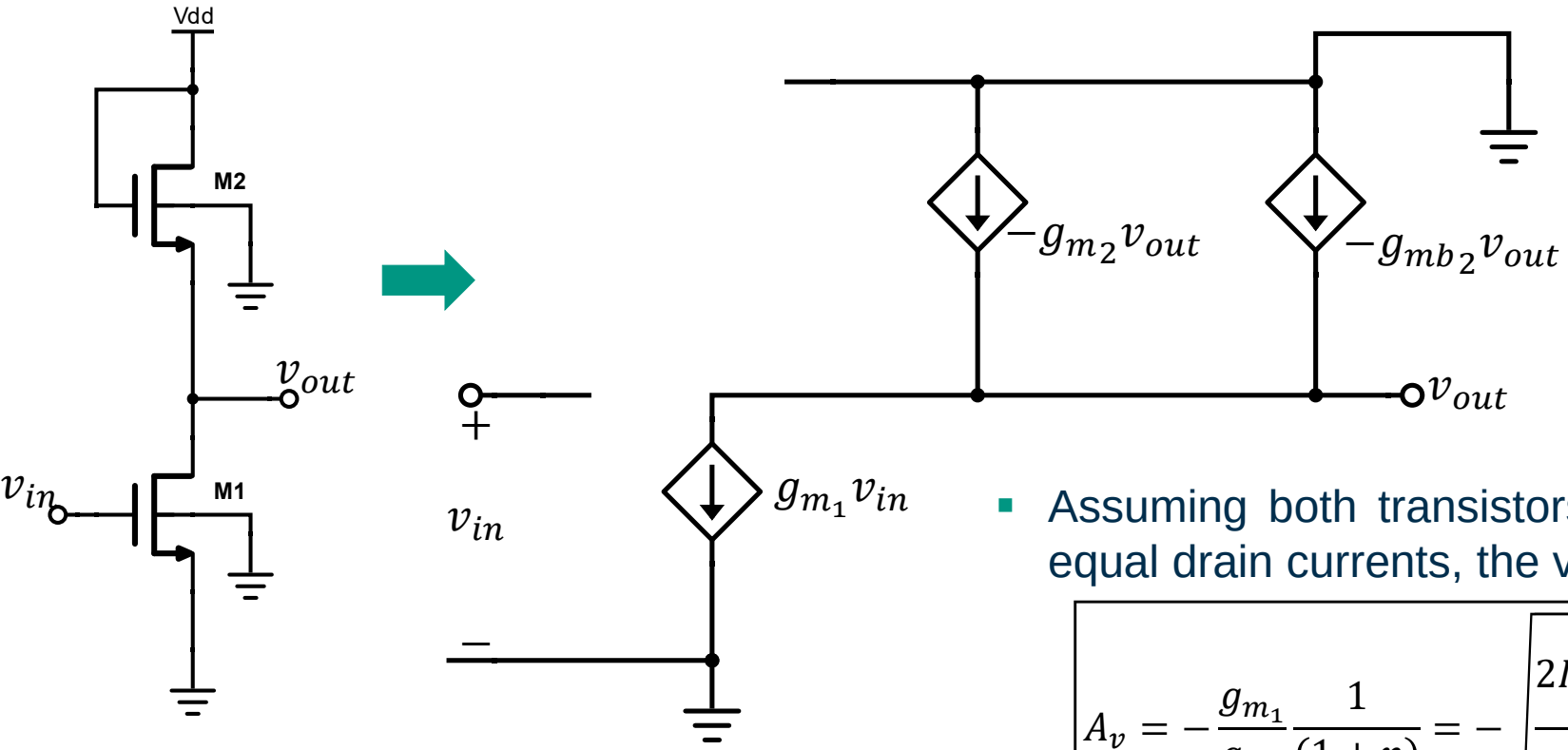

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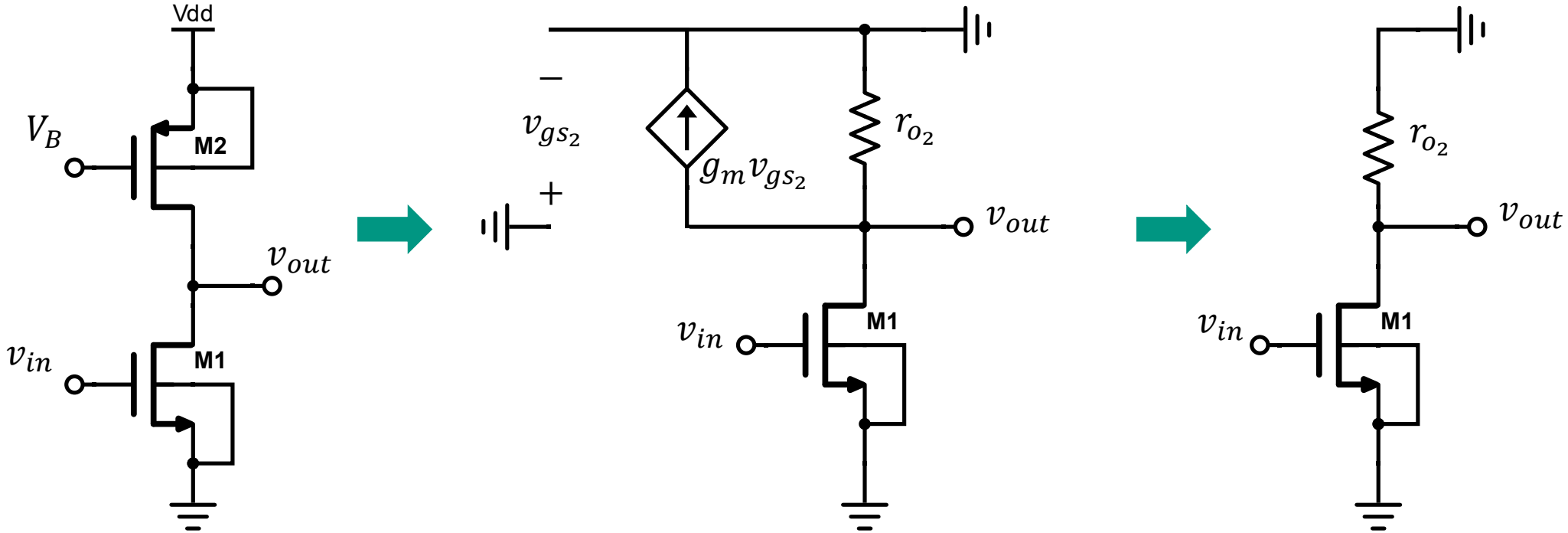
$$\left(Recall: \frac{g_m}{g_{mb}} = \frac{1}{\eta}\right)$$

- Assuming both transistors have the same $\mu_n C_{ox}$ and operate at equal drain currents, the voltage gain can be expressed as:

$$A_v = -\frac{g_{m_1}}{g_{m_2}}\frac{1}{(1+\eta)} = -\sqrt{\frac{2I_D\mu_n C_{ox}\left(\frac{W}{L}\right)_1}{2I_D\mu_n C_{ox}\left(\frac{W}{L}\right)_2}}\frac{1}{(1+\eta)} = -\sqrt{\frac{\left(\frac{W}{L}\right)_1}{\left(\frac{W}{L}\right)_2}}\frac{1}{(1+\eta)}$$

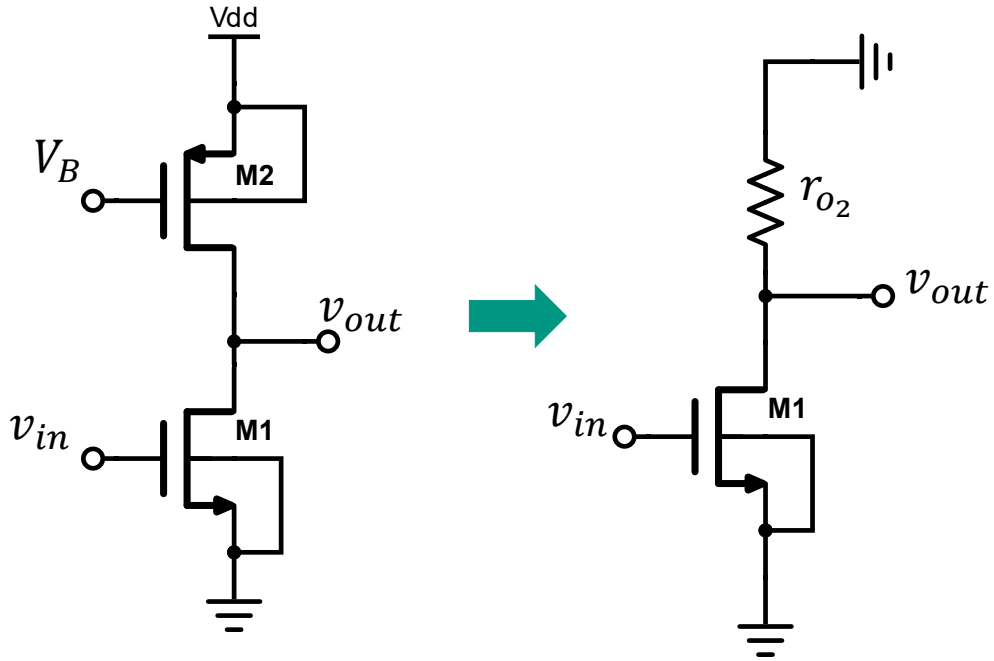
CS Stage with Current-Source Load

- The current-source load of a CS stage can be implemented using a PMOS transistor. Both transistors are biased in saturation region.



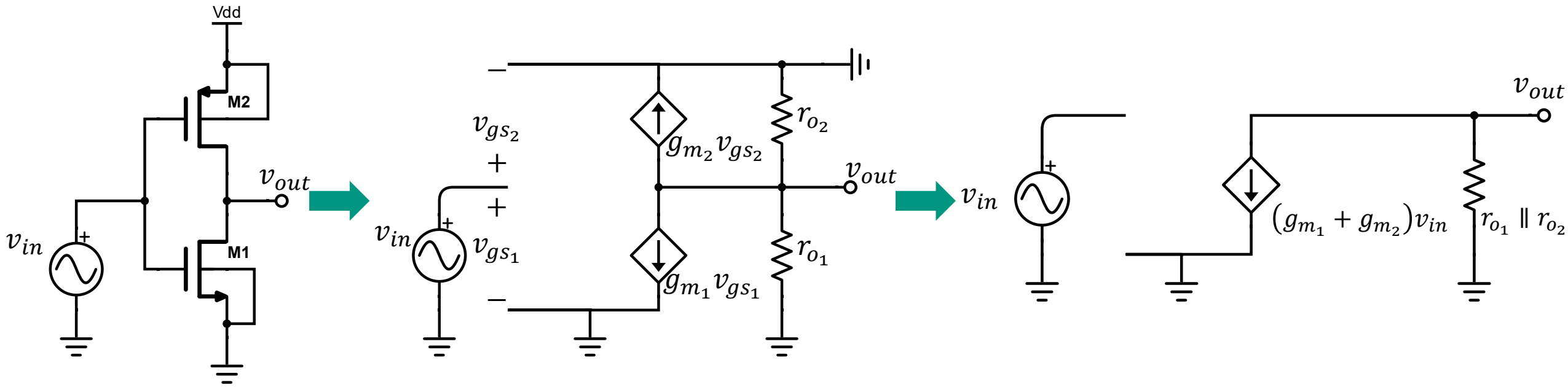
CS Stage with Current-Source Load

- A current-source load provides higher output resistance and is less dependent on voltage drop than a resistive load, The minimum voltage level to keep $|V_{DS}|$ in the saturation ($V_{D,sat}\ or\ V_{ov}$) of the load can be reduced to less than a hundred millivolts, thereby allowing greater voltage headroom.



$$A_v = \frac{v_{out}}{v_{in}} = -g_{m_1}(r_{o1} \parallel r_{o_2})$$

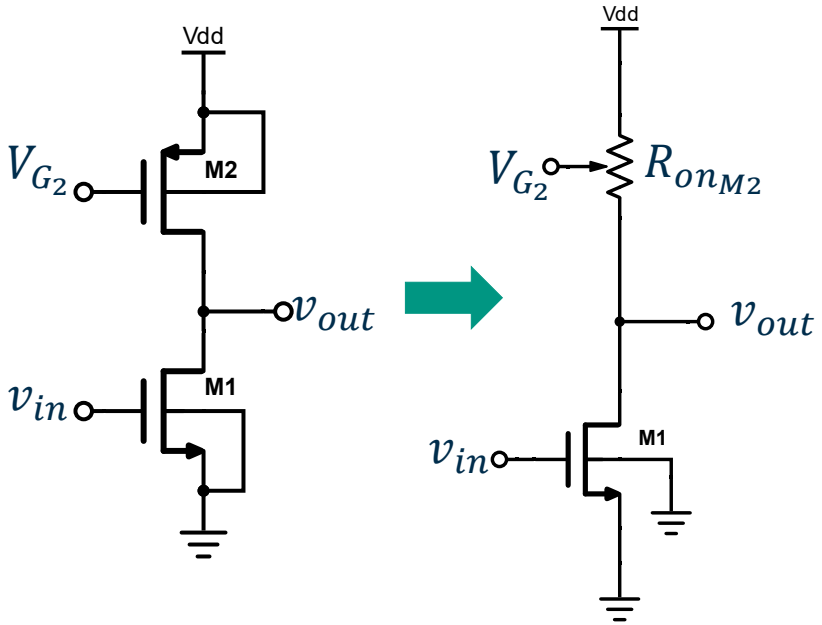
CS Stage with Active Load – CMOS Inverter Amplifier



$$\boxed{A_v = -(g_{m_1} + g_{m_2})(r_{o1} \parallel r_{o_2})}$$

CS Stage with Triode Load

- The load transistor can be operated in triode region. In this way, the load will operate like a variable resistor controlled by the load transistor's gate voltage (V_{G_2}).

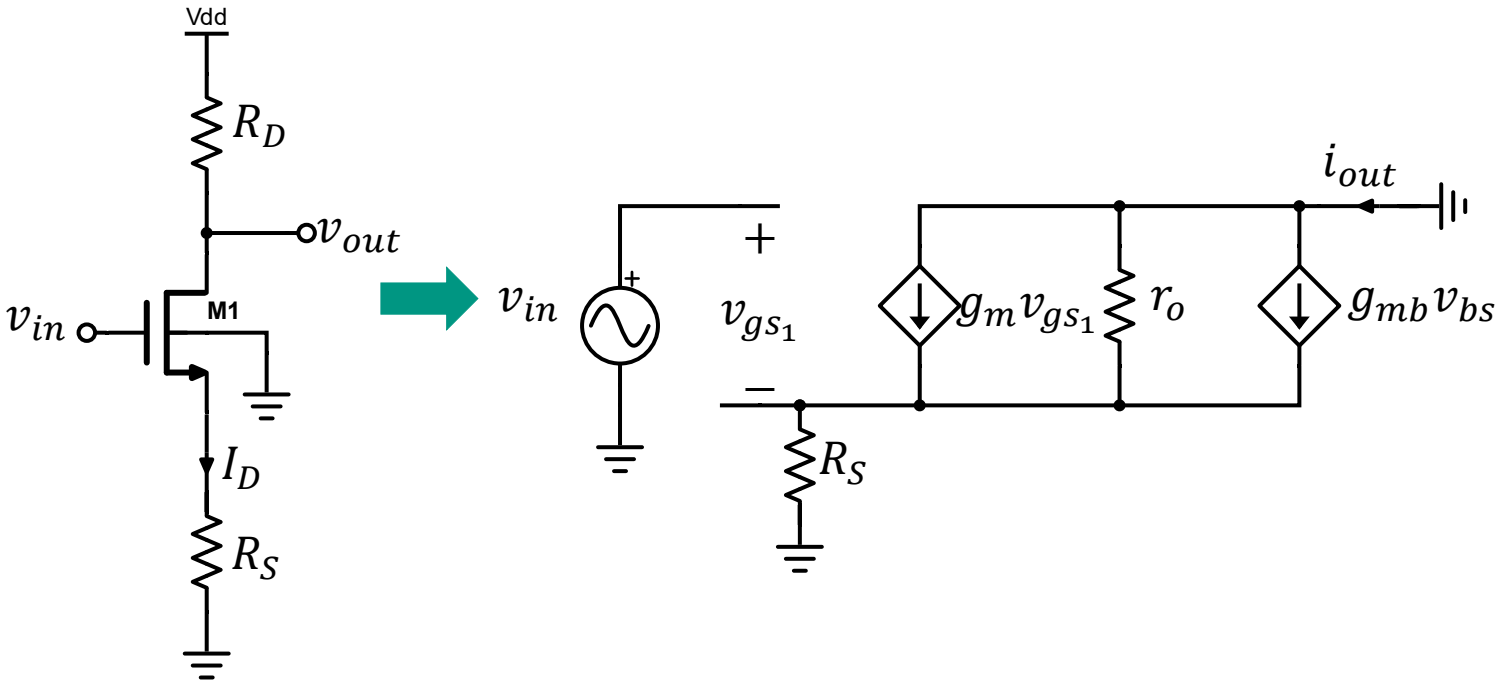


$$R_{on_{M2}} = \frac{1}{\mu_p C_{ox} \left(\frac{W}{L}\right)_2 \left(V_{DD} - V_{G_2} - |V_{TH_P}|\right)}$$

$$A_v = -g_{m_1} R_{on_{M2}}$$

CS Stage with Source Degeneration

- Source degeneration introduces negative feedback by adding a resistor to the source terminal. This technique improves the transistor's linearity, but with the trade-off of lowering its effective transconductance and overall gain.



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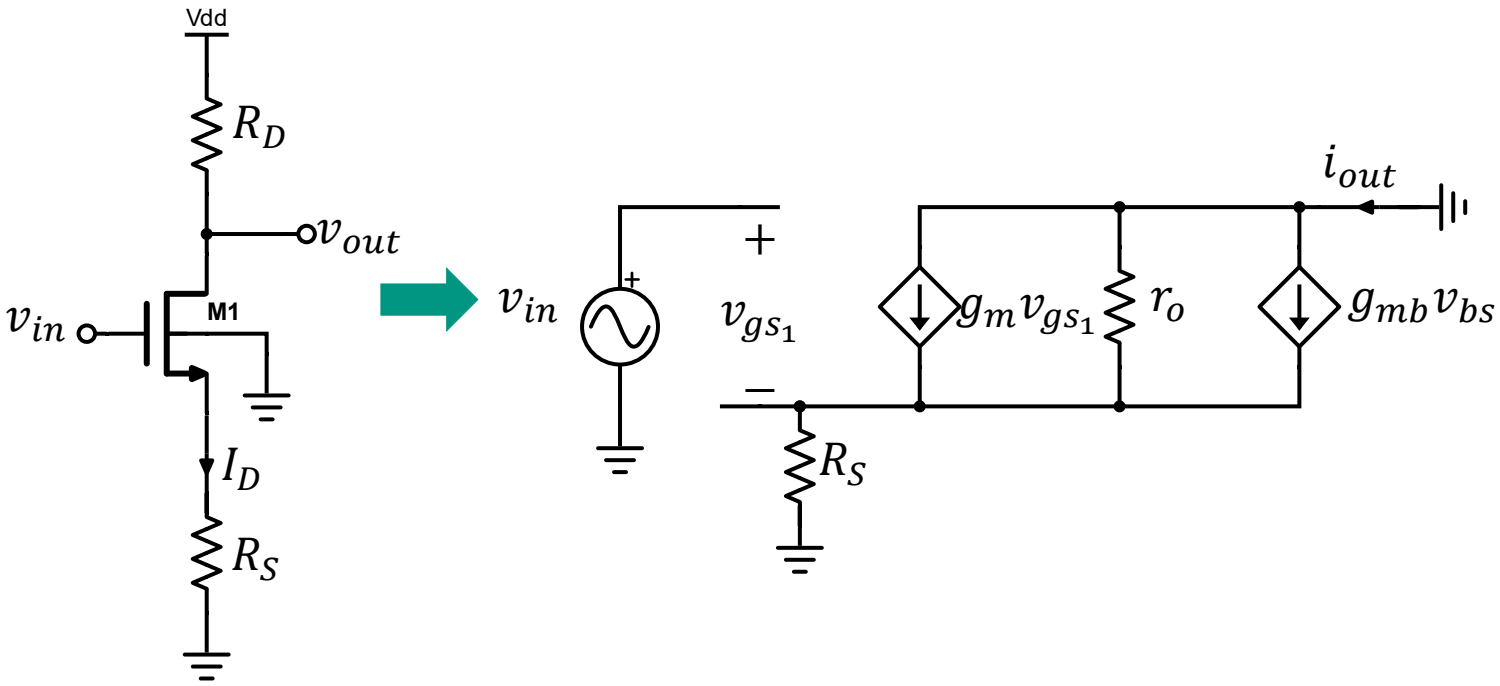


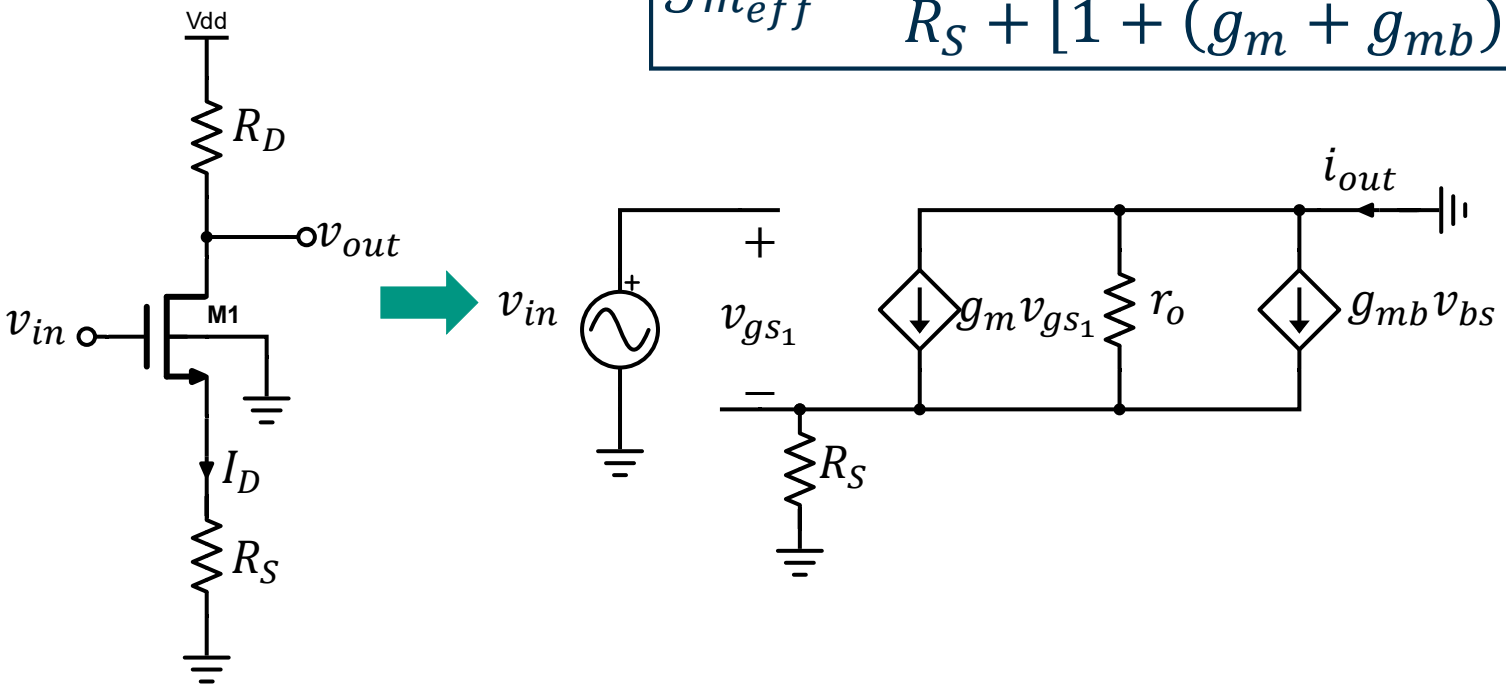
- The simplified effective transconductance:

$$g_{m_{eff}} = \frac{g_m}{1 + g_m R_S}$$

CS Stage with Source Degeneration

- The source degeneration transconductance in the presence of body effect and channel-length modulation (R_D excluded):

$$g_{m_{eff}} = \frac{g_m r_o}{R_S + [1 + (g_m + g_{mb})R_S]r_o}$$



CS Stage with Source Degeneration

Output Resistance of a Source Degenerated CS Stage

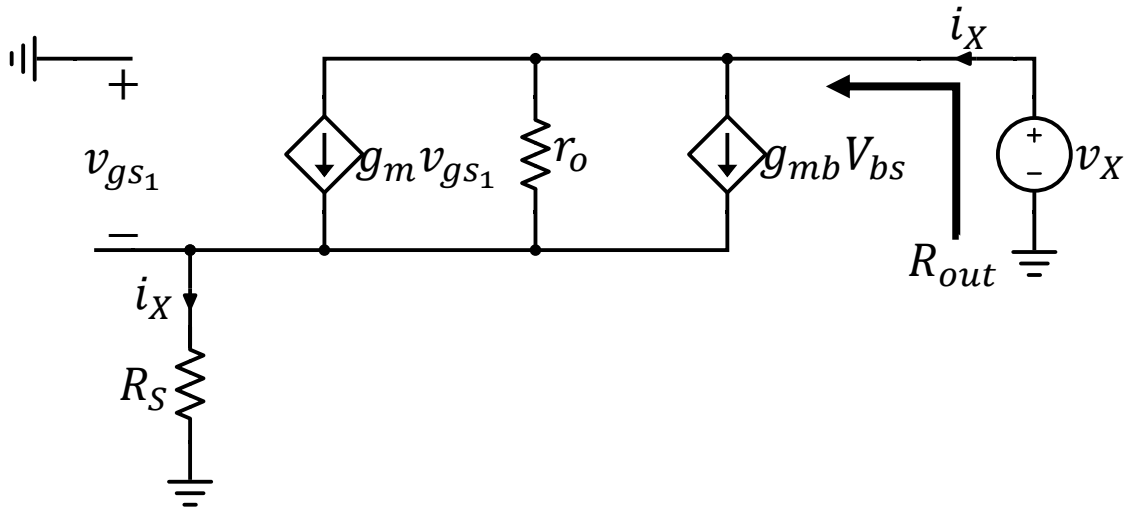
- The output resistance of the source degenerated CS Stage can be derived as:

$$\boxed{R_{out} \approx [1 + (\mathrm{g_m} + \mathrm{g_{mb}})\mathrm{R_S}]\mathrm{r_o}}$$

- By ignoring the body effect, simplifying to:

$$\boxed{R_{out} \approx (1 + g_m \mathrm{R_S})\mathrm{r_o}}$$

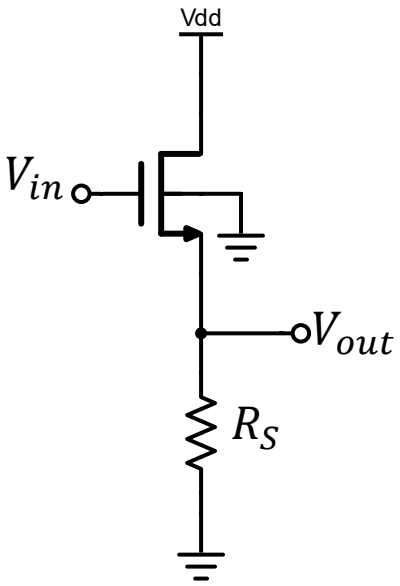
- Thus, the output resistance is boosted by $(1 + g_m \mathrm{R_S})$.



Source Follower

Source Follower (Common-Drain) Stage

- The standard gain formula of the CS Stage ($|A_v| = g_m R_{out}$) indicates that large load impedance results in higher gain. However, if the load impedance is low, the gain will drop. To drive low-impedance loads without losing signal amplitude, a source follower stage is used. For this reason, it is also known as a **buffer stage**.



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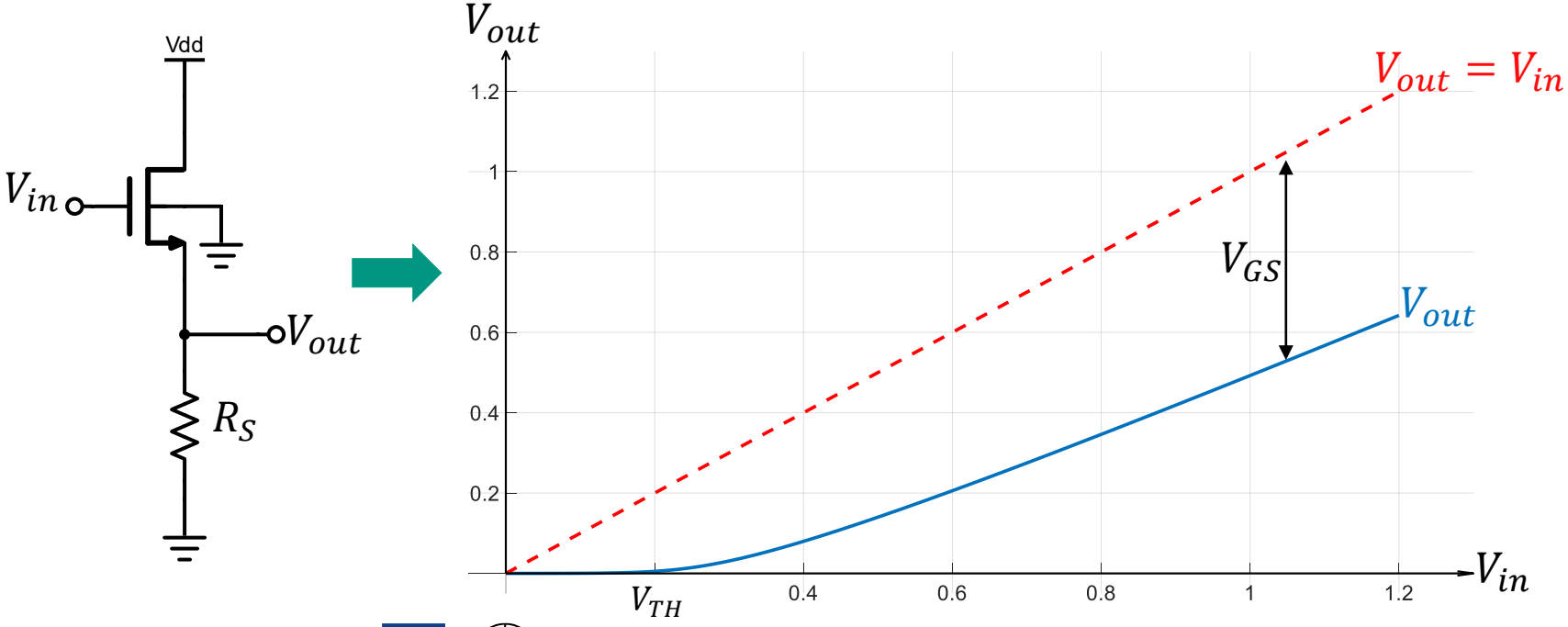

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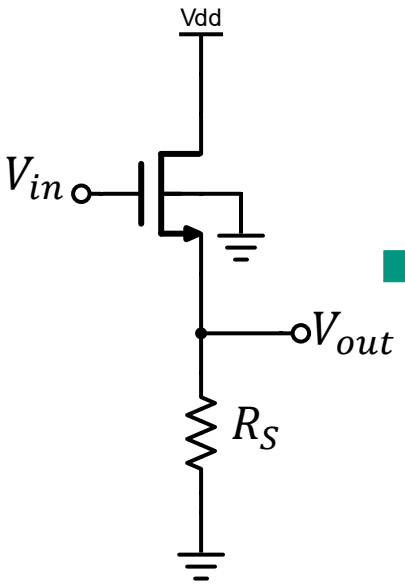
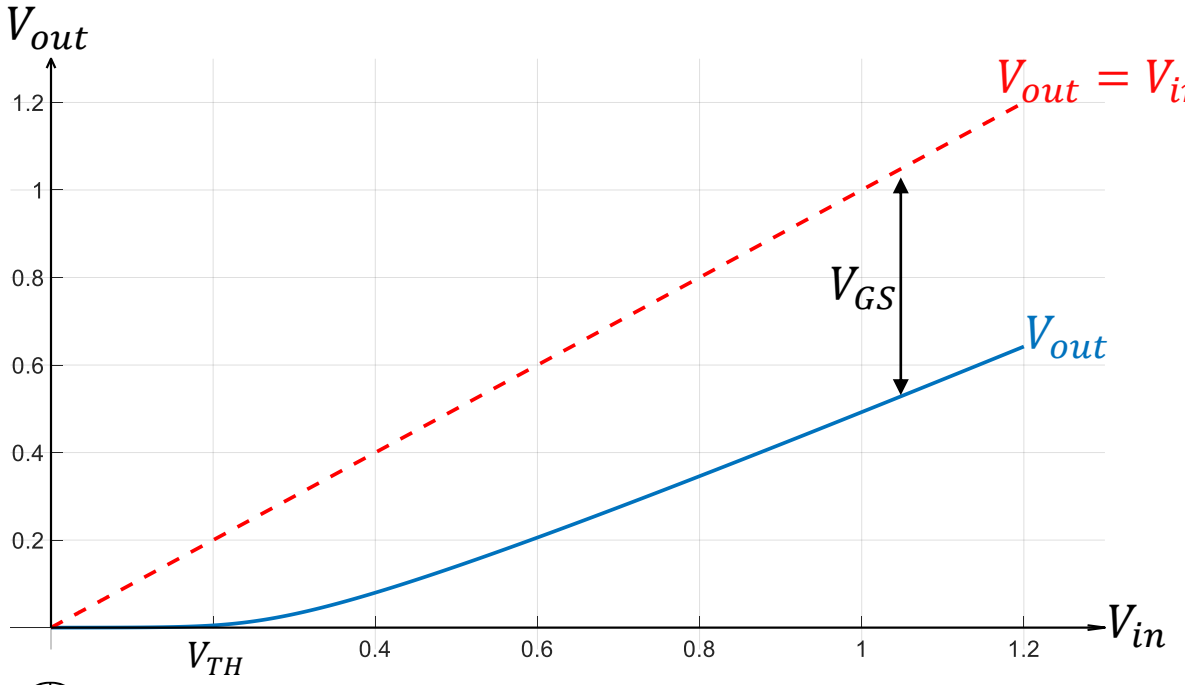
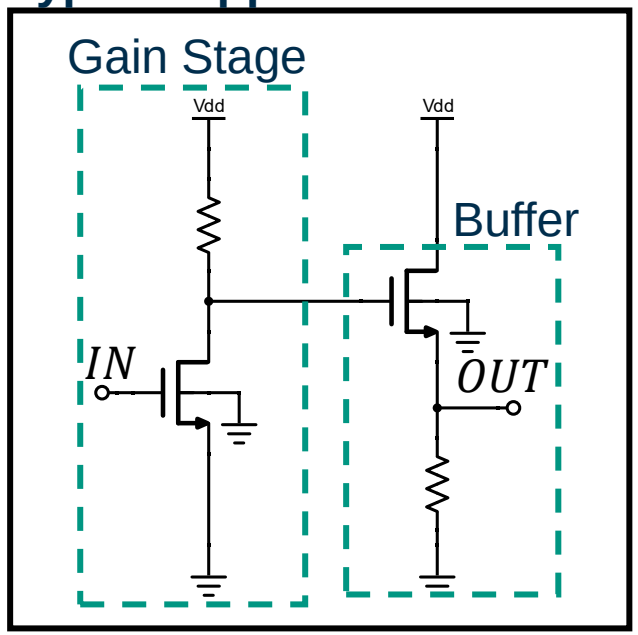


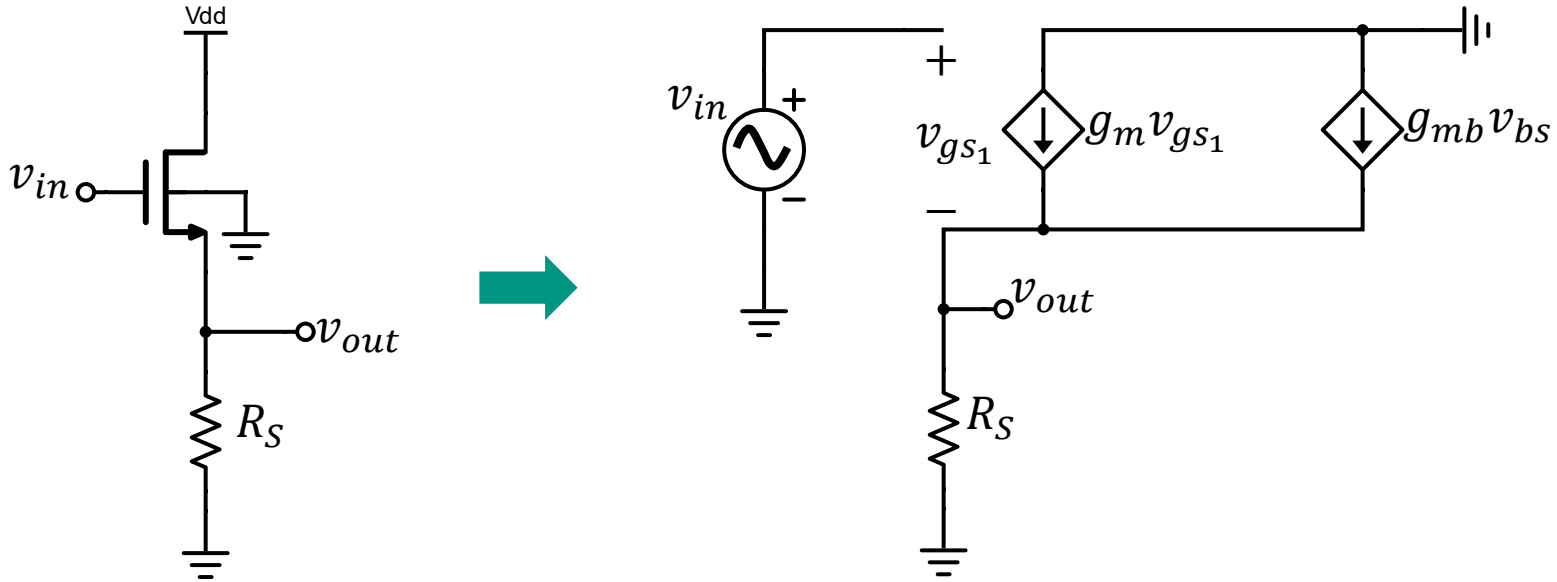


Typical Application



Source Follower (Common-Drain) Stage

Small-Signal Equivalent Circut

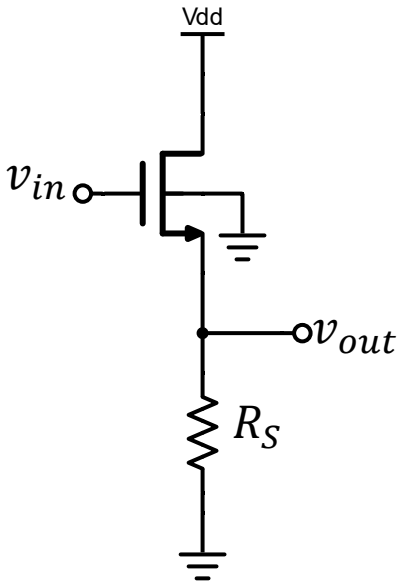


$$g_m v_{gs_1} + g_{mb} v_{bs} = \frac{v_{out}}{R_S}, \qquad v_{gs_1} = v_{in} - v_{out}, \qquad v_{bs} = -v_{out}$$

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

Source Follower (Common-Drain) Stage

Small-Signal Equivalent



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

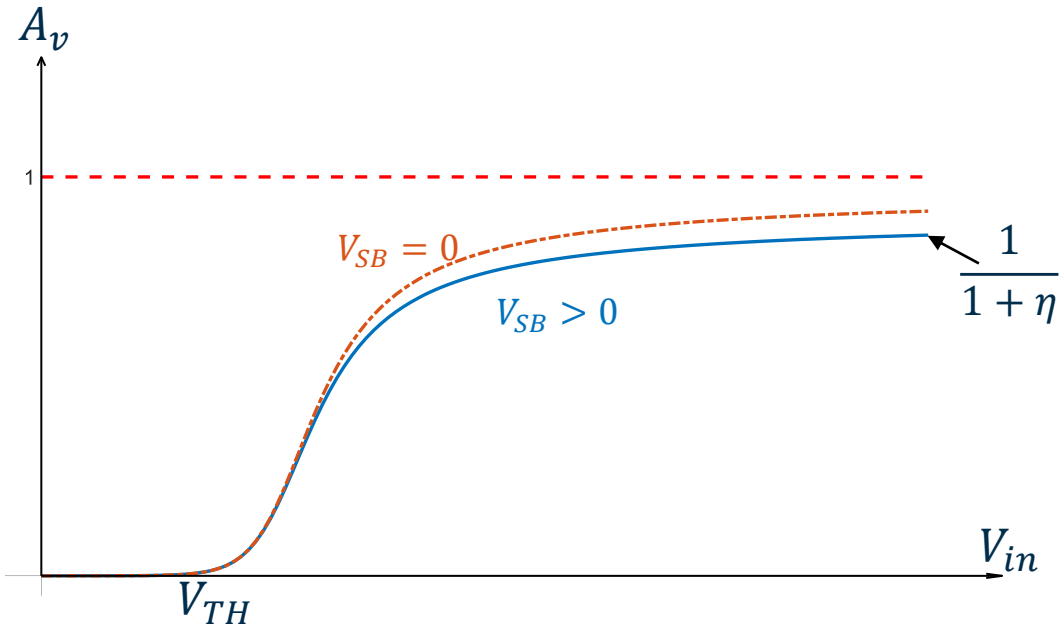
$$= \frac{g_m R_S}{1 + (1 + \eta) g_m R_S}$$

- For $g_m R_S \gg 1$,

$$\boxed{A_v = \frac{v_{out}}{v_{in}} \approx \frac{1}{1 + \eta}}$$

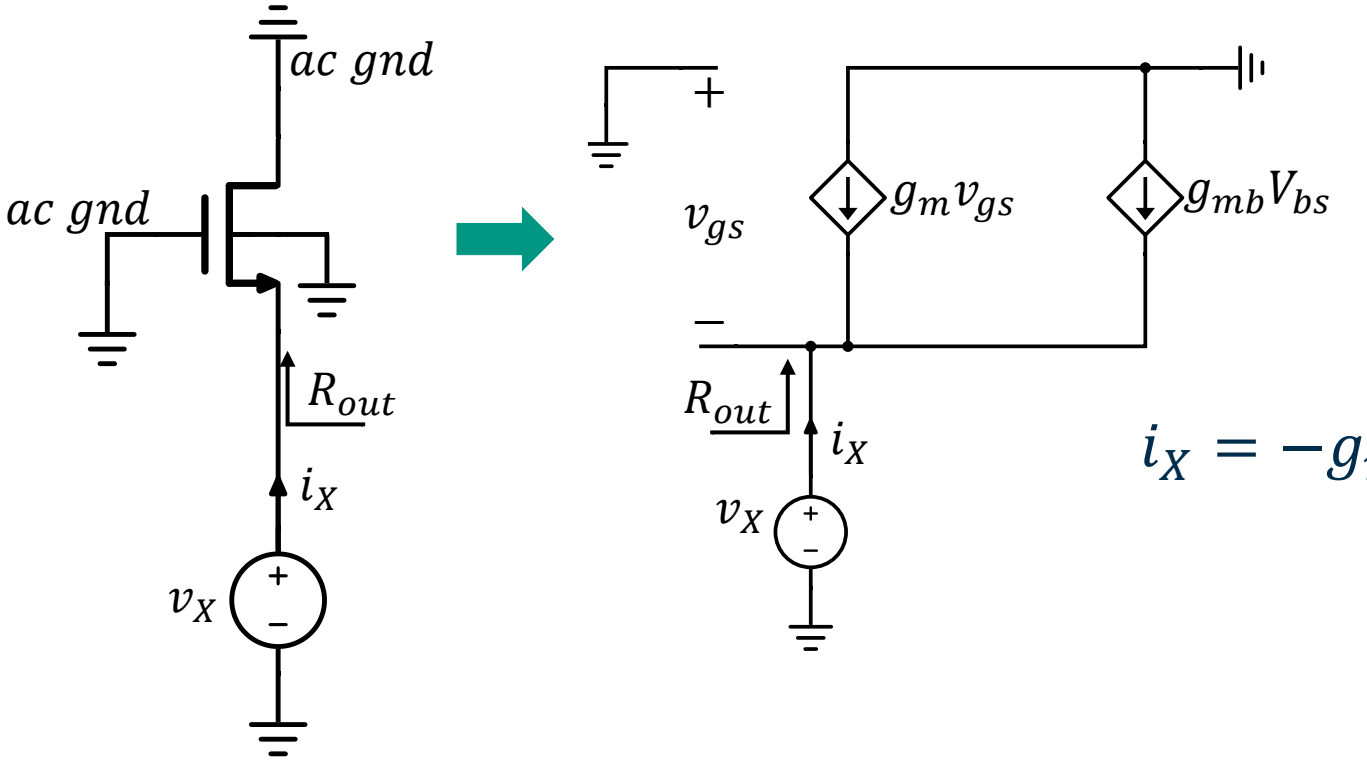
- Ignoring g_{mb} we get

$$A_v = \frac{v_{out}}{v_{in}} \approx 1$$



Source Follower (Common-Drain) Stage

Output Resistance



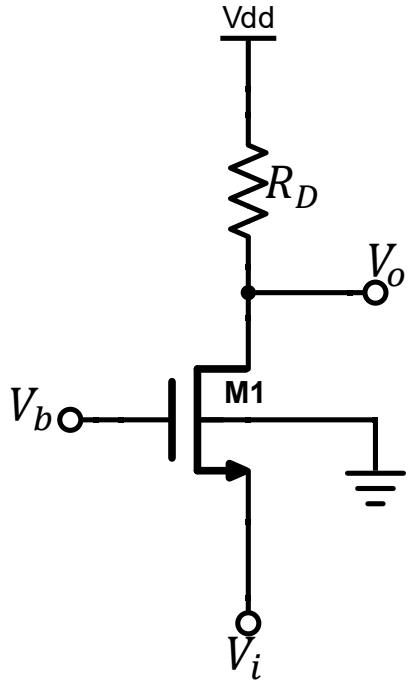
$$i_X = -g_m v_{gs} - g_{mb} V_{bs}, \qquad v_X = -v_{gs} = -V_{bs}$$

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

Common-Gate Amplifier

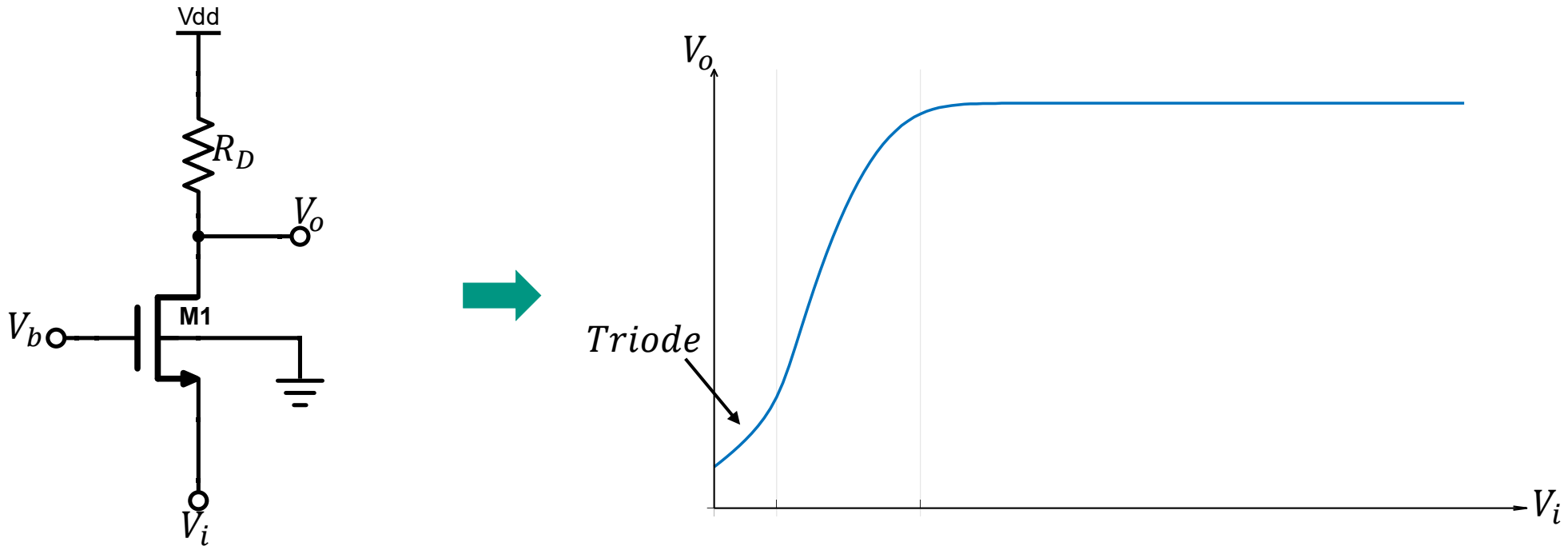
Common-Gate Stage

- The common-gate amplifier provides low input and high output impedance, operates as a non-inverting voltage amplifier. Since it offers approximately unity current gain, it is used as a current buffer. It is widely used in RF applications and forms the upper stage of the cascode amplifier.



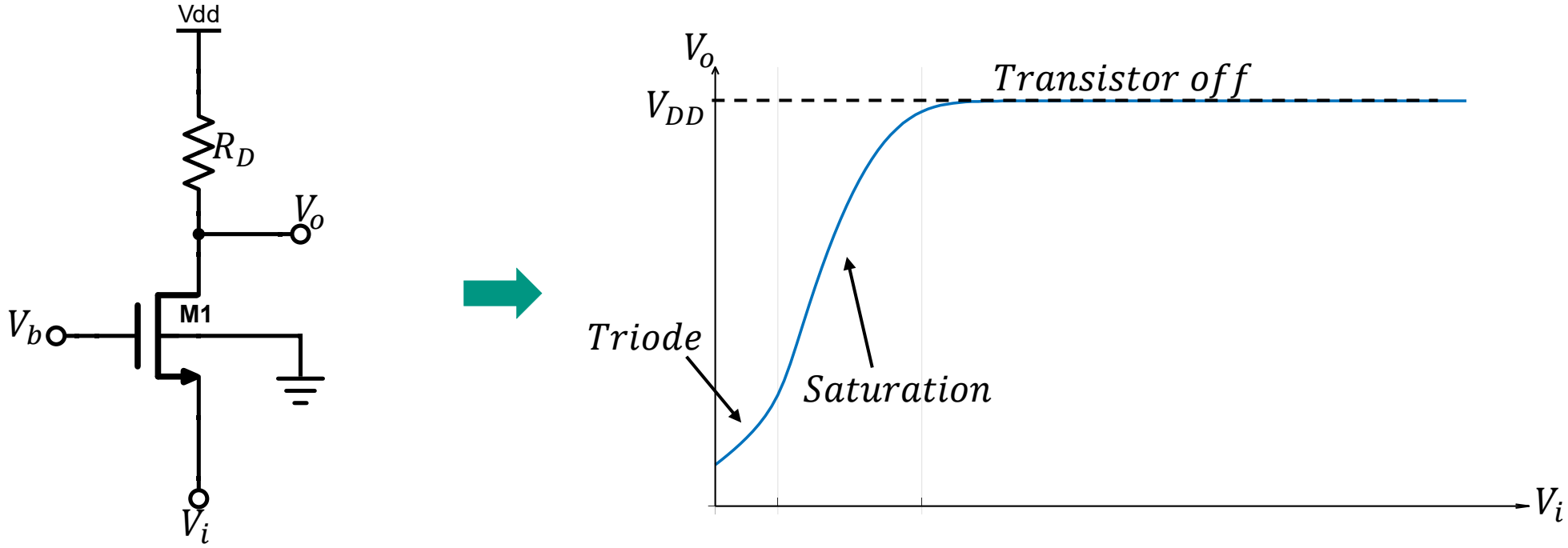
Common-Gate Stage

- At the DC level, V_b is fixed. As V_i increases, the transistor initially exhibits a very high overdrive ($V_{ov} = V_b - V_i - V_{TH}$) voltage, therefore, very low on-resistance (r_{on}), resulting in V_{DS} ($V_o - V_i$) lower than V_{ov}. Therefore, the MOSFET operates first in the **triode region**.



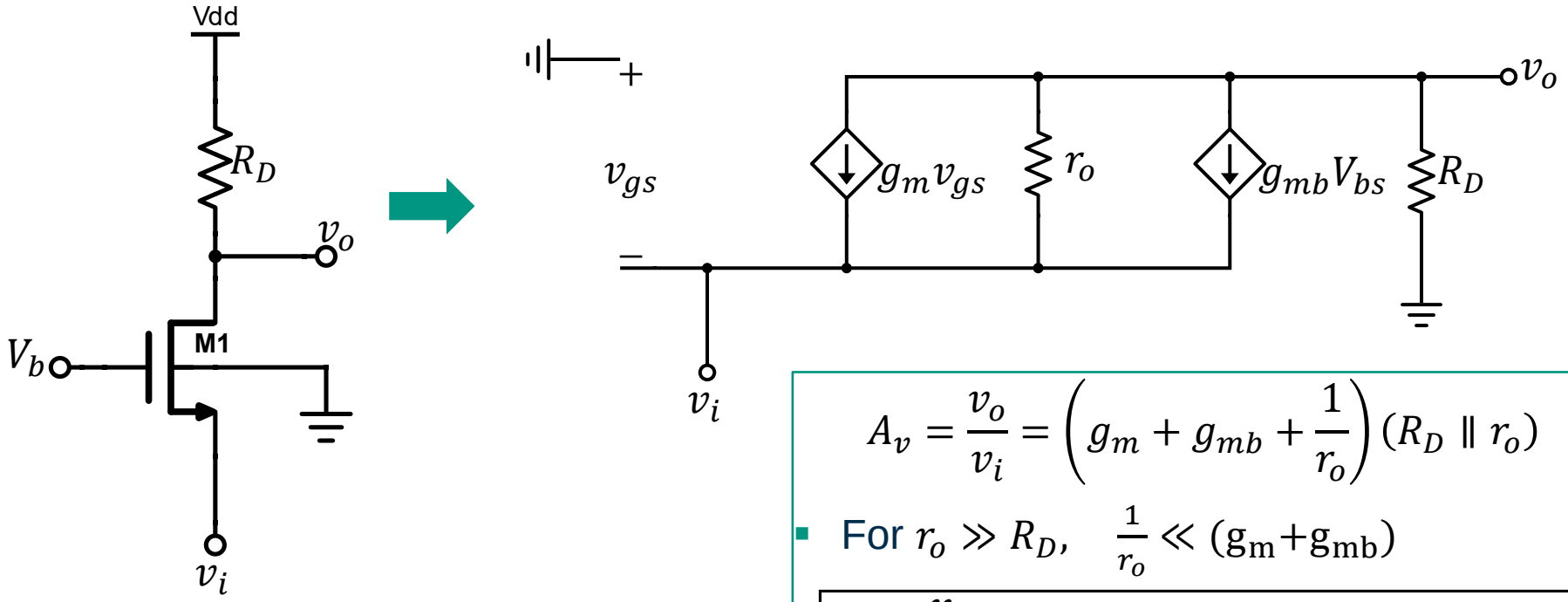
Common-Gate Stage

- As V_i continues to increase, V_{ov} decreases, which increases r_{on}. This will satisfy $V_{DS}>V_{ov}$. → **Saturation**.
- Eventually, as $V_b - V_i$ drops below V_{TH}, **the transistor turns off** and drain voltage approaches to V_{DD}.



Common-Gate Stage

Small Signal Analysis



$$A_v = \frac{v_o}{v_i} = \left(g_m + g_{mb} + \frac{1}{r_o}\right)(R_D \parallel r_o)$$

- For $r_o \gg R_D$, $\frac{1}{r_o} \ll (g_m + g_{mb})$

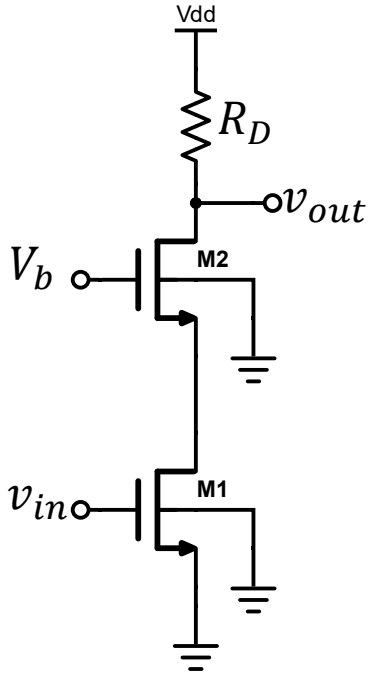
$$\boxed{A_v = \frac{v_o}{v_i} \approx (g_m + g_{mb})R_D = g_m(1+\eta)R_D}$$

- Note that the gain is positive, and body effect increases the equivalent transconductance.

Cascode Amplifier

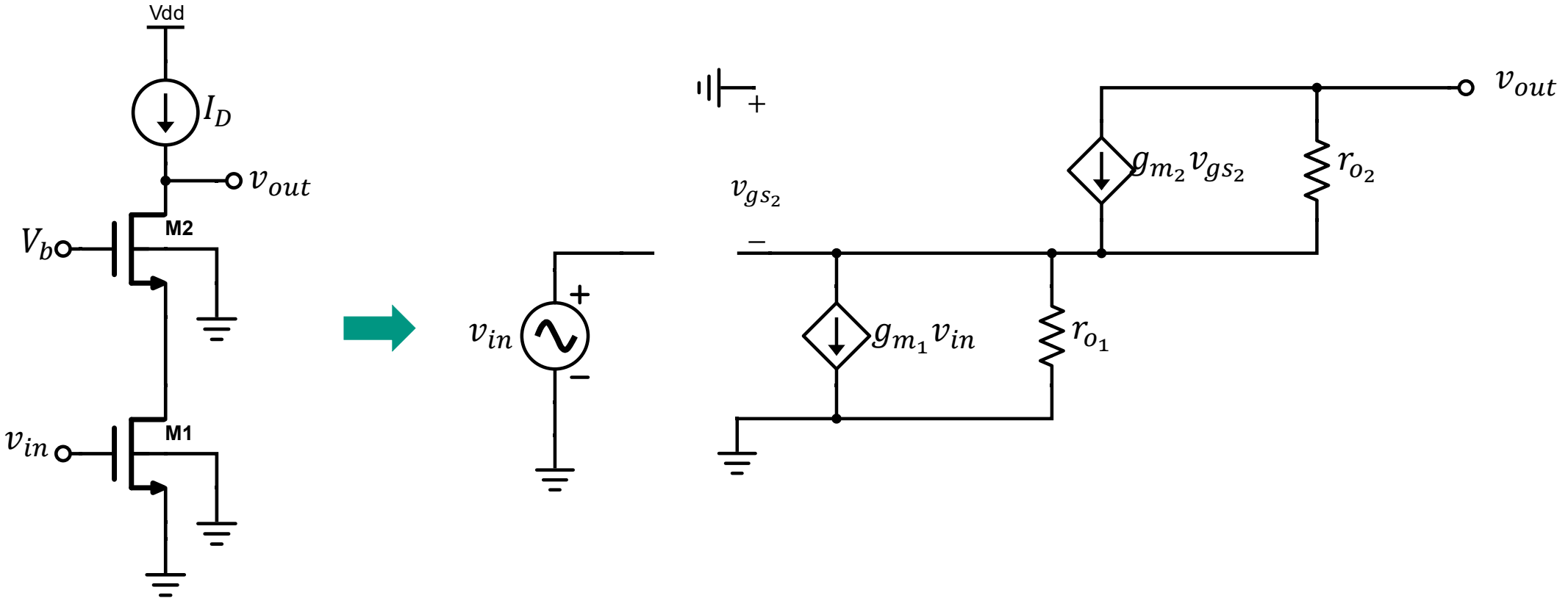
Cascode Stage

- The cascade of a CS stage and a CG stage is called a “cascode”. This topology is providing many useful properties.
- Compared to a single transistor amplifier, it offers a higher output impedance, improved gain bandwidth, and better isolation between the input and output. It has the ability to suppress the Miller effect, thereby enhancing high-frequency performance.



Cascode Stage

Small-Signal Analysis (Body Effect Omitted)



Cascode Stage

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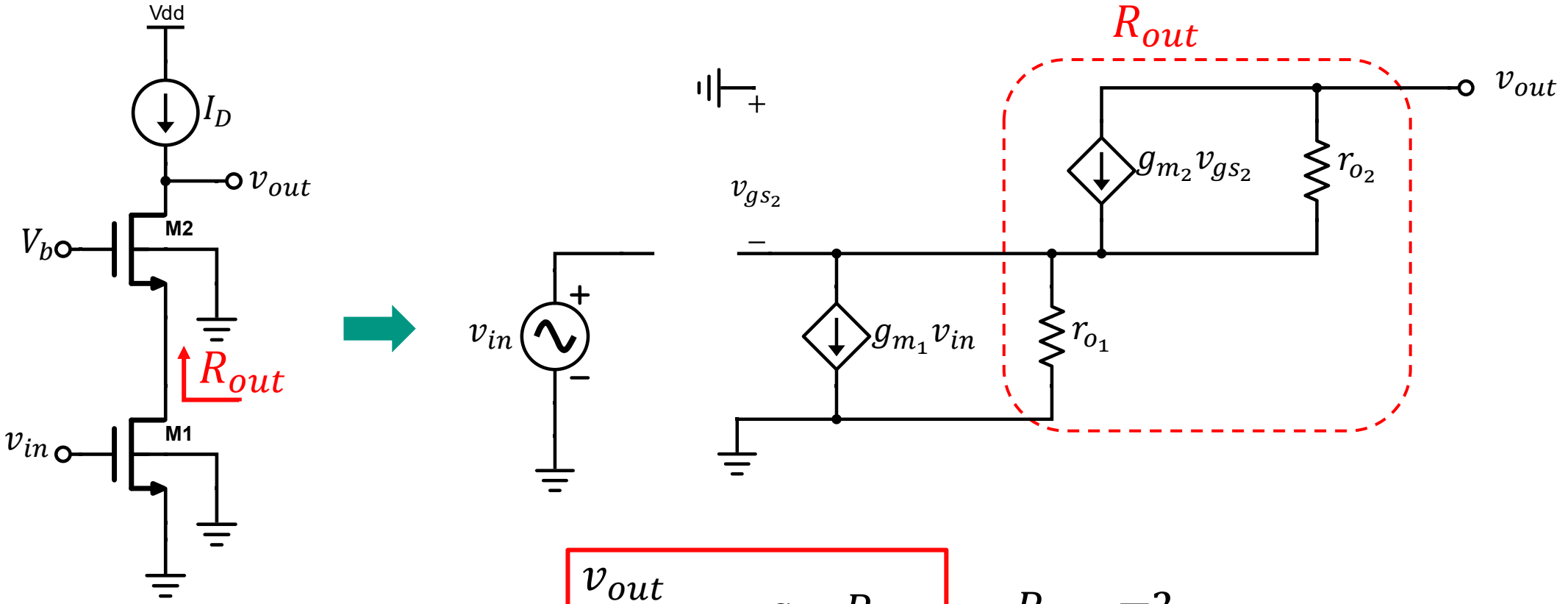
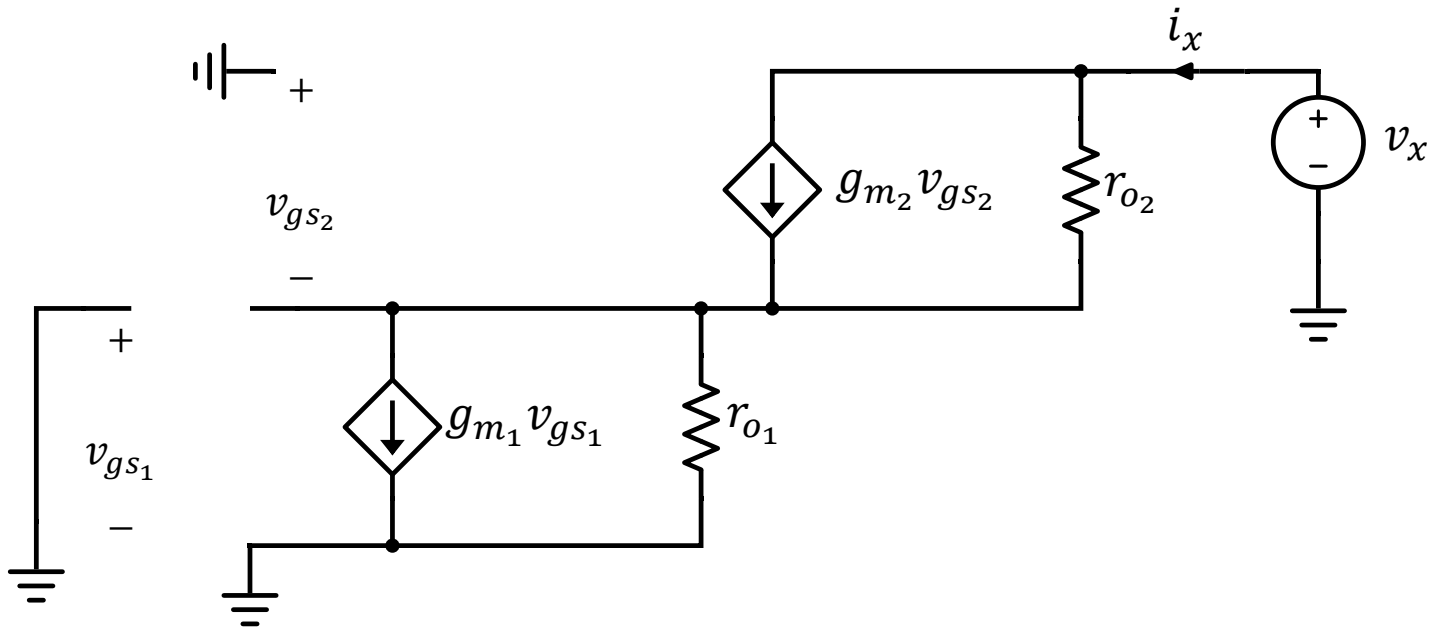


$$\frac{v_{out}}{v_{in}} = -g_{m_1}R_{out}$$

$R_{out} = ?$

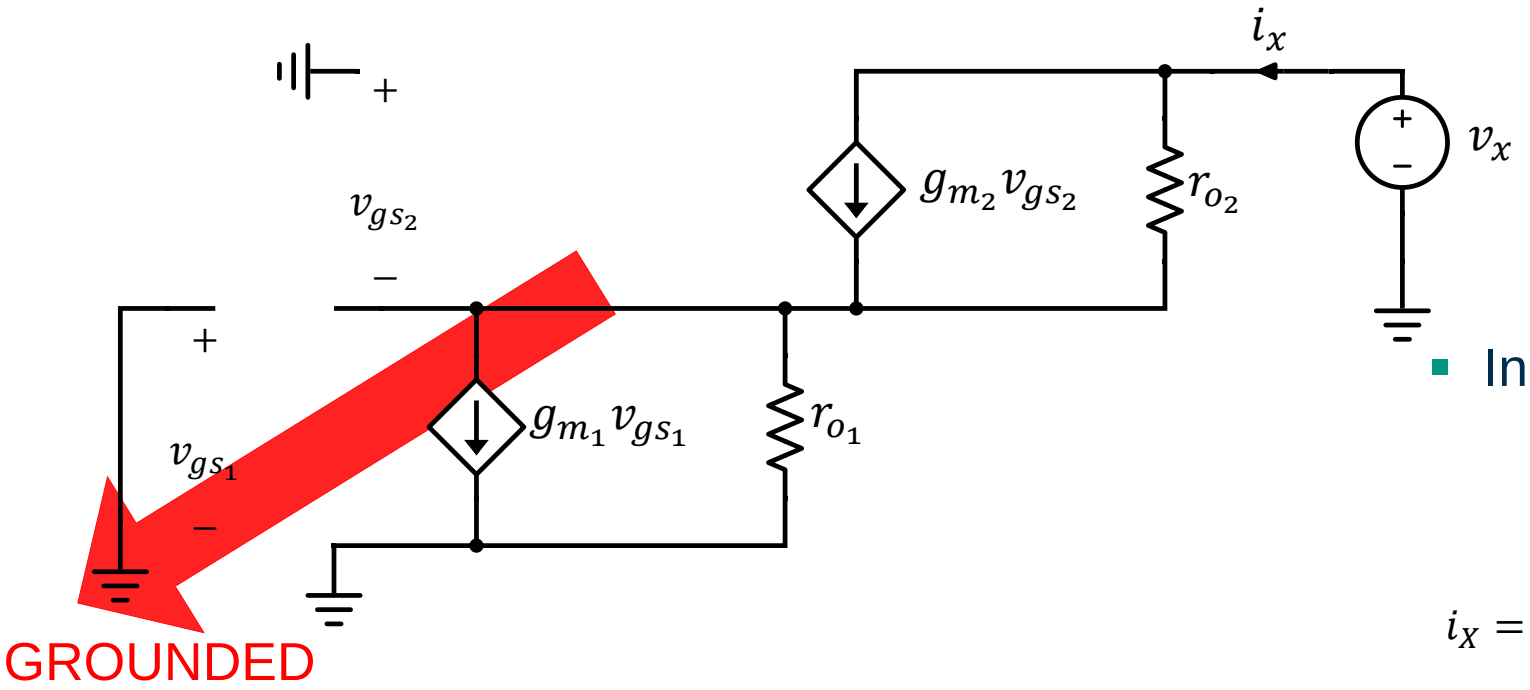
Cascode Stage

Small-Signal Analysis (Body Effect Omitted) – R_{out} Analysis



Cascode Stage

Small-Signal Analysis (Body Effect Omitted) – R_{out} Analysis



- Input port is grounded.

$$v_{gs_1} = 0 \Rightarrow g_{m_1}v_{gs_1} = 0$$

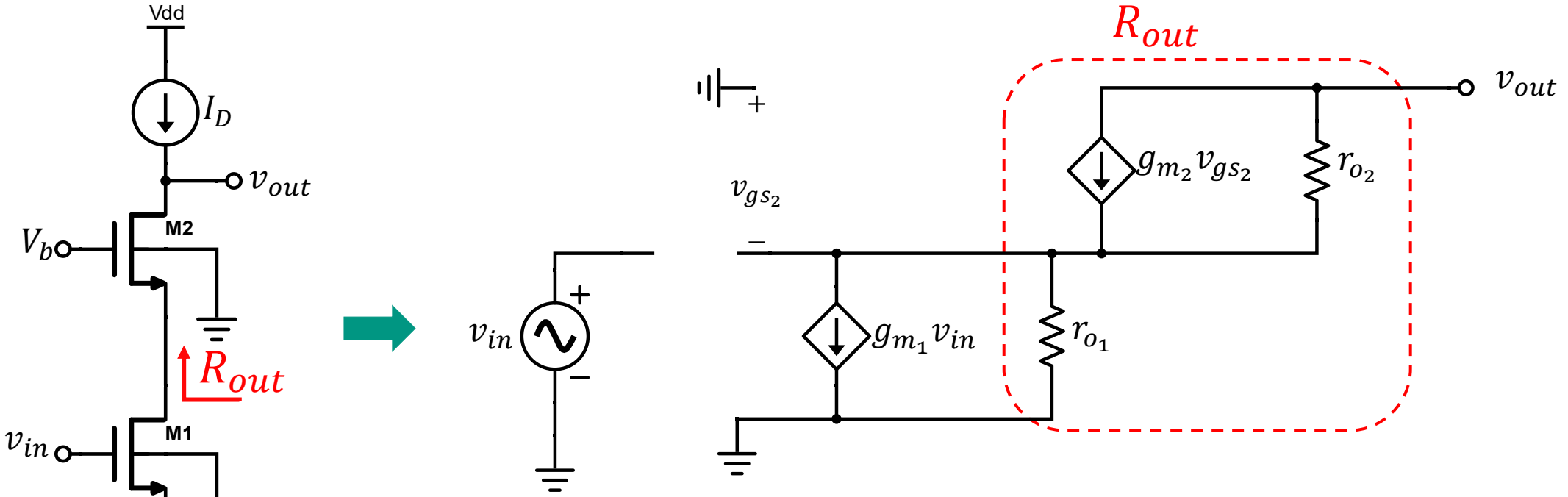
$$v_{gs_2} = -i_x r_{o_1}$$

$$i_X = g_{m_2}v_{gs_2} + \frac{(v_x + v_{gs_2})}{r_{o_2}} = -i_x g_{m_2} r_{o_1} - i_x \frac{r_{o_1}}{r_{o_2}} + \frac{v_x}{r_{o_2}}$$

$$\boldsymbol{R_{out} = \frac{v_x}{i_x} = g_{m_2} r_{o_1} r_{o_2} + r_{o_1} + r_{o_2}}$$

Cascode Stage

Small-Signal Analysis (Body Effect Omitted)

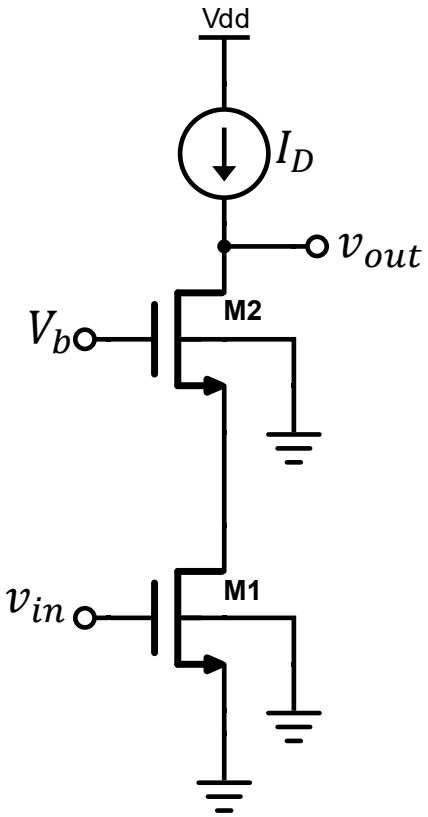


$$A_v = \frac{v_{out}}{v_{in}} = -g_{m_1}R_{out} = -g_{m_1}\left(g_{m_2}r_{o_1}r_{o_2} + r_{o_1} + r_{o_2}\right)$$

$$\boxed{A_v \approx -g_{m_1}g_{m_2}r_{o_1}r_{o_2}}$$

Cascode Stage

Small-Signal Analysis (Body Effect Omitted)



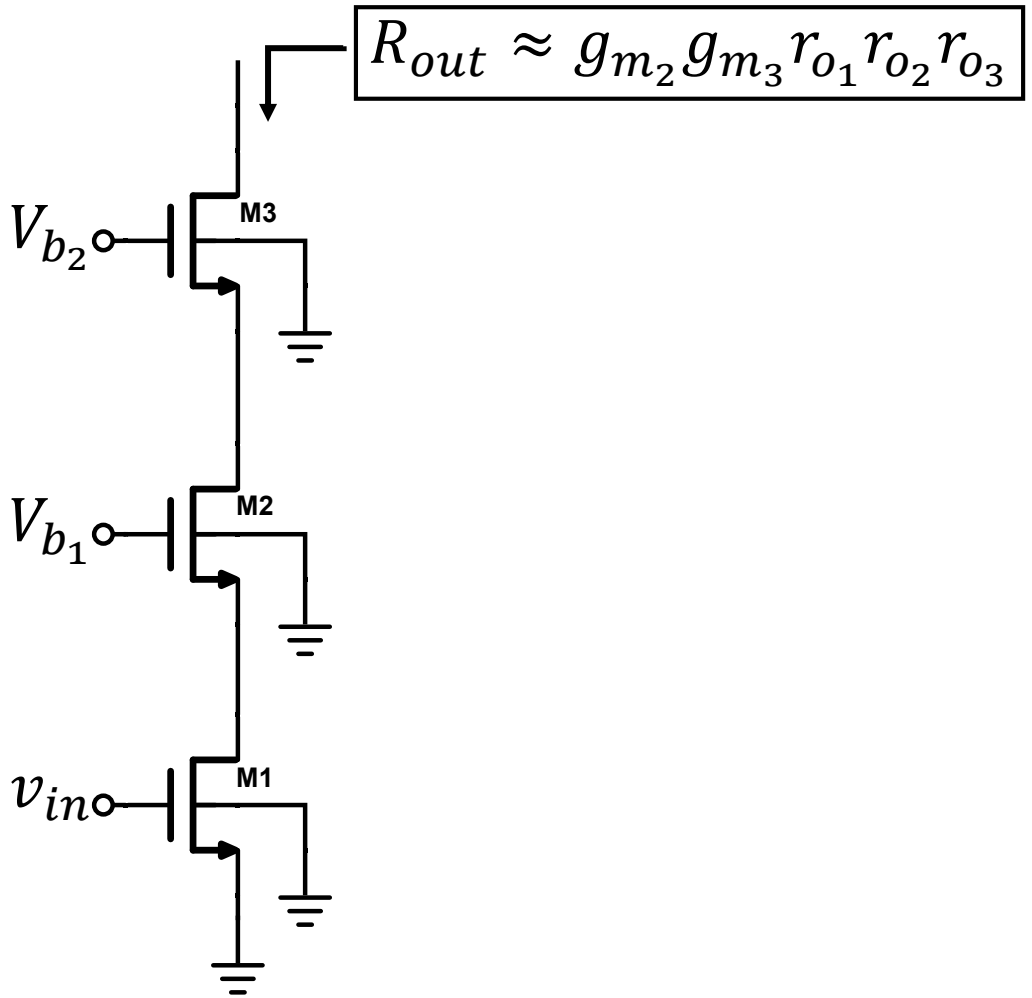
$$\boxed{A_v \approx -g_{m_1} g_{m_2} r_{o_1} r_{o_2}}$$

- The output resistance is boosted by a factor of the intrinsic gain of the cascading transistor, $g_{m_2} r_{o_2}$.
- The boosted resistance multiplies the overall gain.
- Note that for $g_{m_1} = g_{m_2}$ and $r_{o_1} = r_{o_2}$, the overall gain simplifies to

$$|\boldsymbol{A_v}| = (\boldsymbol{g_m r_o})^{\boldsymbol{2}}.$$

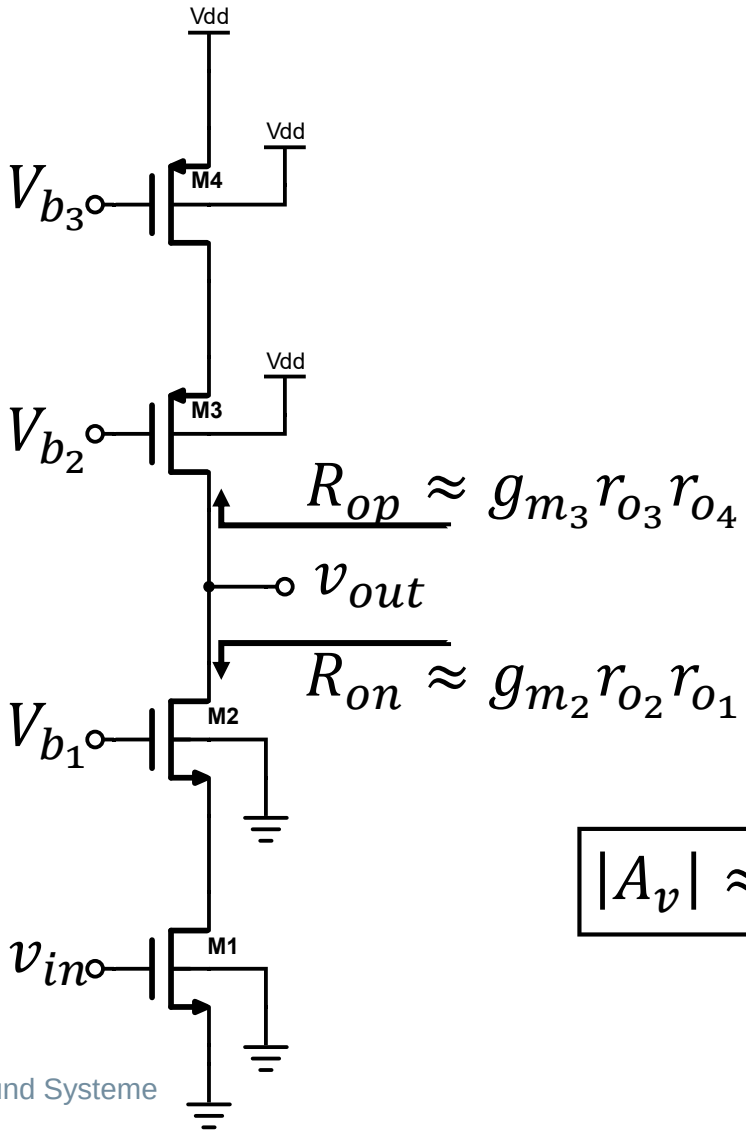
Cascode Stage

Triple Cascode



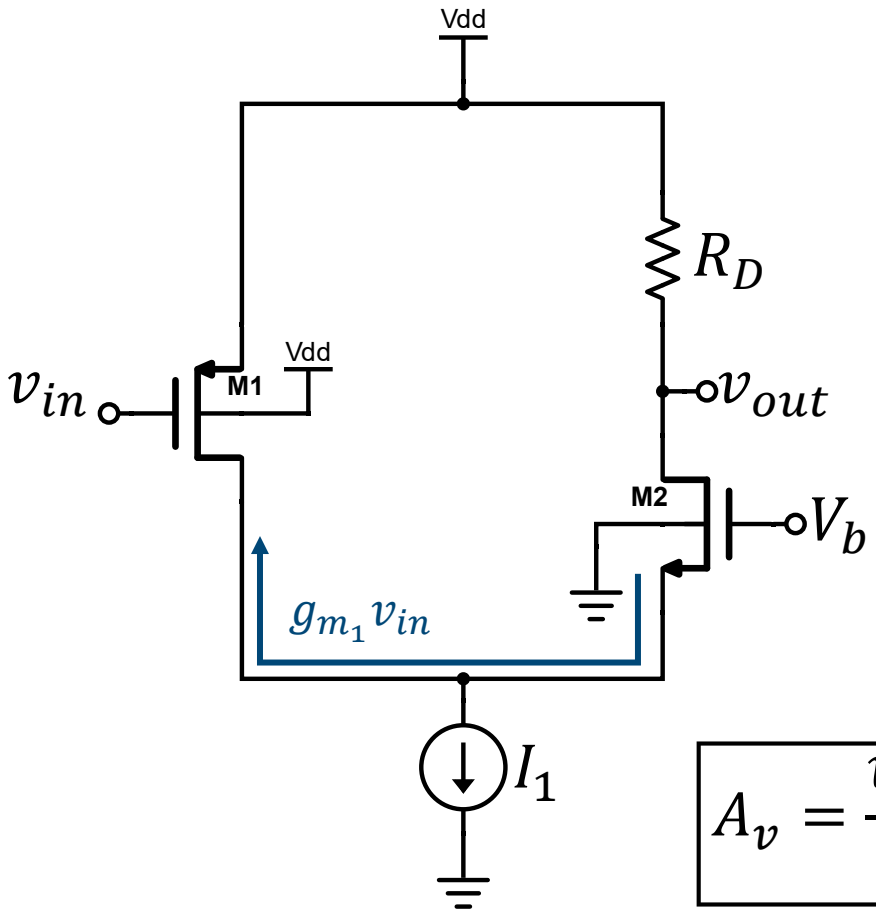
Cascode Stage

NMOS Cascode Amplifier with PMOS Cascode Load

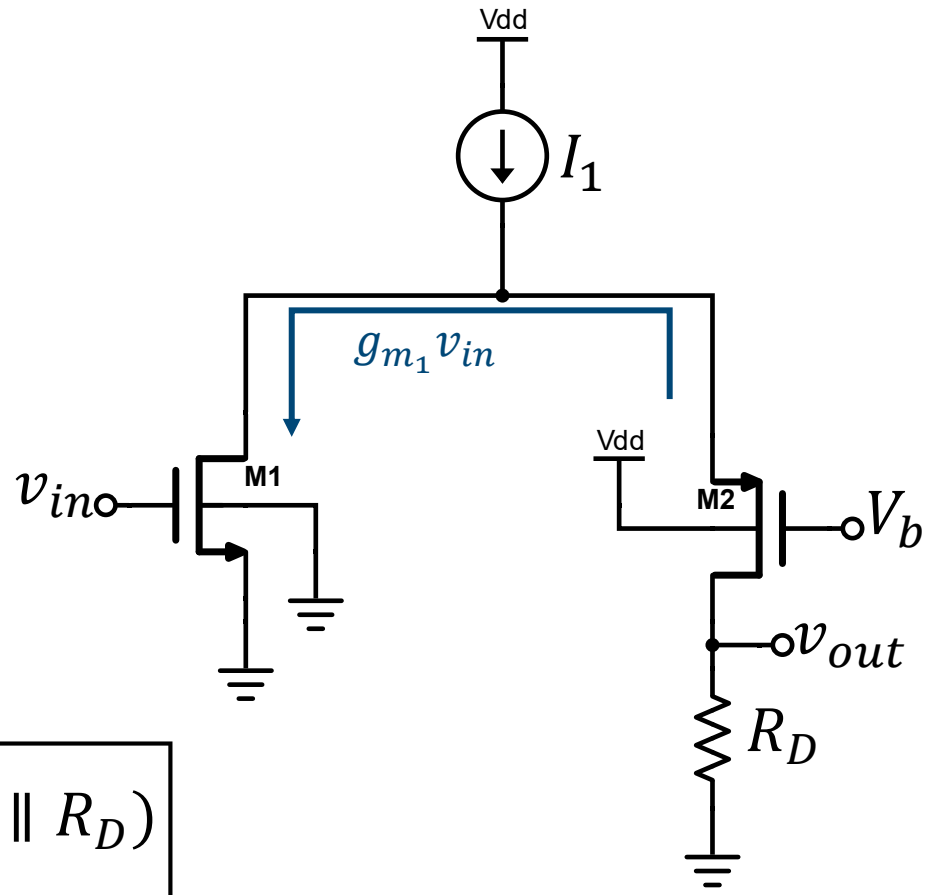


$$|A_v| \approx g_{m_1}\left(R_{op} \parallel R_{on}\right)$$

Folded Cascode



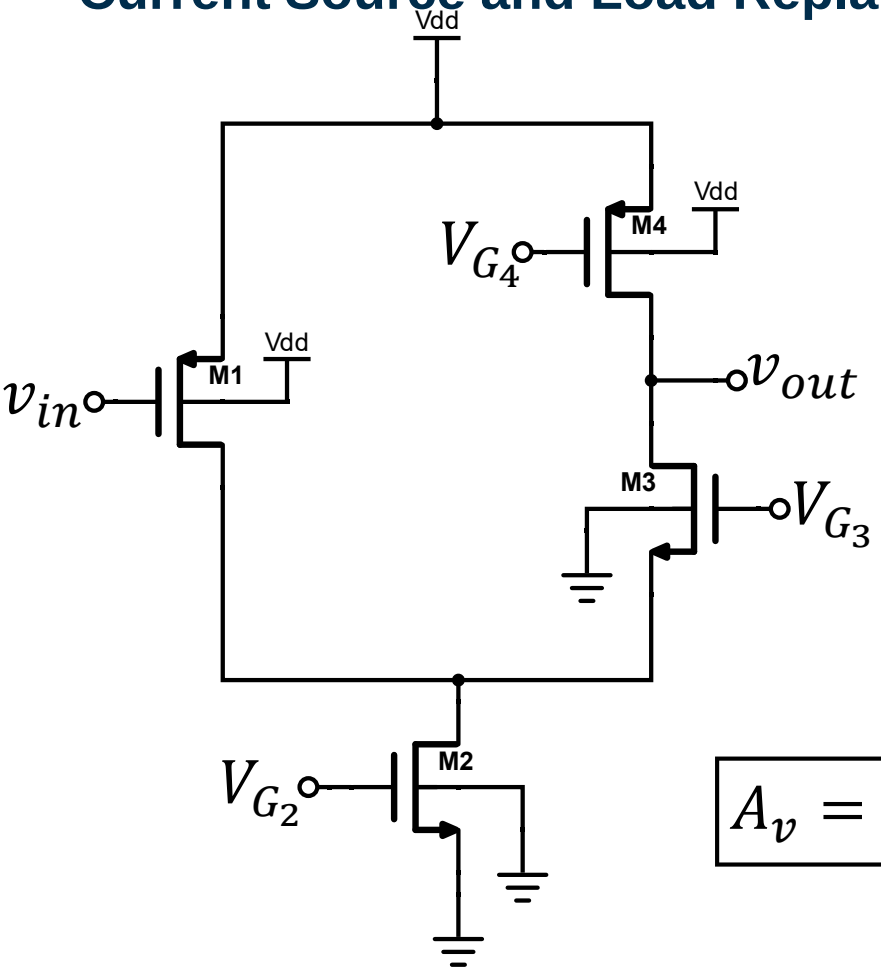
$$A_v = \frac{v_{out}}{v_{in}} \approx -g_{m_1}(g_{m_2} r_{o_2} r_{o_1} \parallel R_D)$$



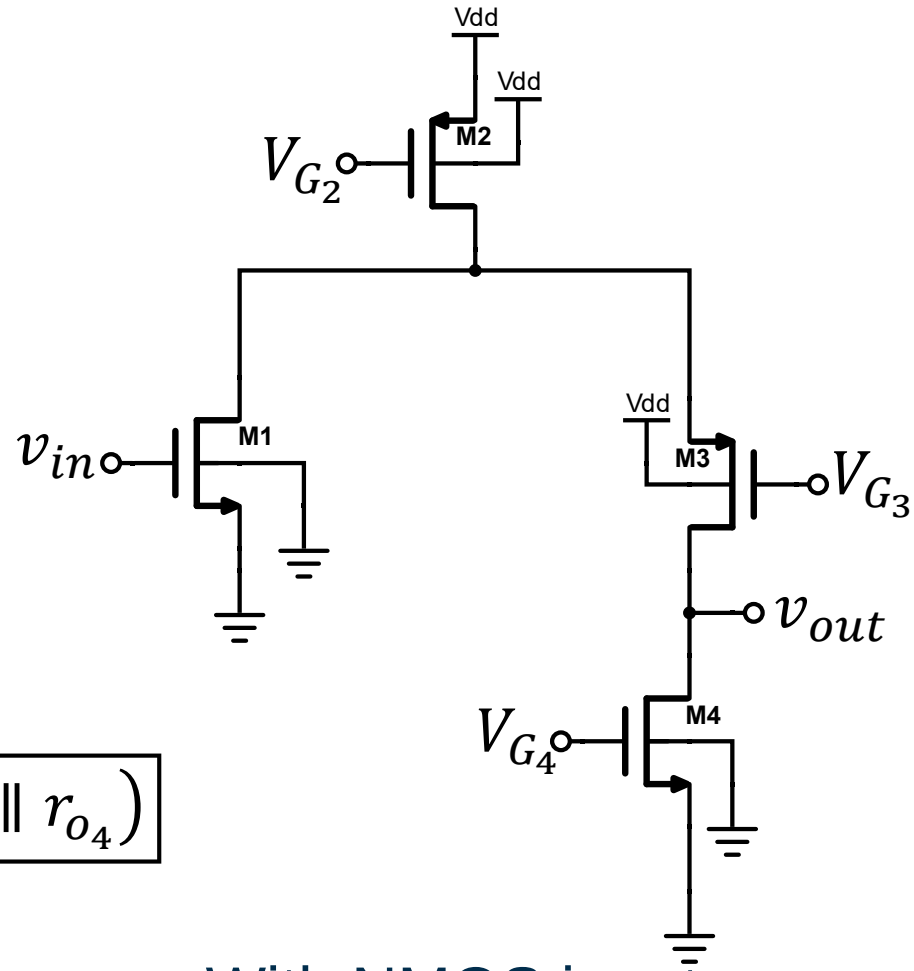
- With PMOS input
- With NMOS input

Folded Cascode

Current Source and Load Replaced with Active Devices



$$A_v = -g_{m_1}\left(\left[g_{m_3} r_{o_3}\left(r_{o_1} \parallel r_{o_2}\right)\right] \parallel r_{o_4}\right)$$



- With PMOS input
- With NMOS input