Fundamentals of Microelectronics

- CH1 Why Microelectronics?
- CH2 Basic Physics of Semiconductors
- CH3 Diode Circuits
- CH4 Physics of Bipolar Transistors
- CH5 Bipolar Amplifiers
- CH6 Physics of MOS Transistors
- CH7 CMOS Amplifiers
- CH8 Operational Amplifier As A Black Box

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Chapter 7 CMOS Amplifiers

- 7.1 General Considerations
- 7.2 Common-Source Stage
- 7.3 Common-Gate Stage
- 7.4 Source Follower
- 7.5 Summary and Additional Examples

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Chapter Outline

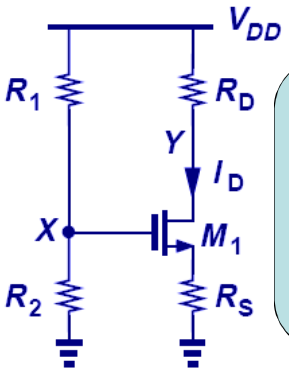
General Concepts

- Biasing of MOS Stages
- Realization of Current Sources

MOS Amplifiers

- Common-Source Stage
- Common-Gate Stage
- Source Follower

MOS Biasing

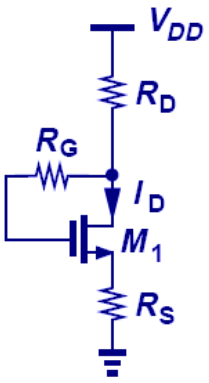


$$V_{GS} = -(V_1 - V_{TH}) + \sqrt{V_1^2 + 2V_1\left(\frac{R_2 V_{DD}}{R_1 + R_2} - V_{TH}\right)}$$

$$V_1 = \frac{1}{\mu_n C_{ox}\frac{W}{L}R_S}$$

- Voltage at X is determined by V_{DD}, R_1, and R_2.
- V_{GS} can be found using the equation above, and I_D can be found by using the NMOS current equation.

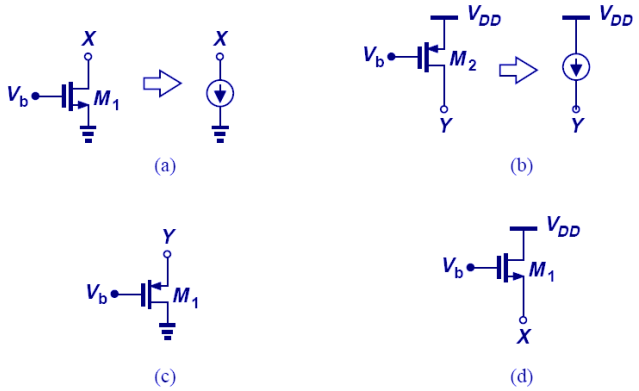
Self-Biased MOS Stage



$$I_D R_D + V_{GS} + R_S I_D = V_{DD}$$

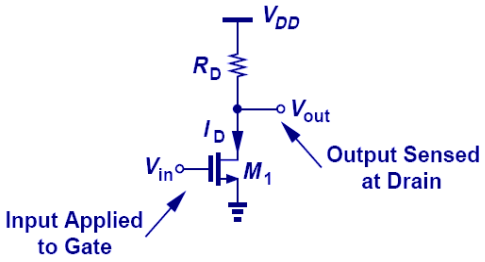
- The circuit above is analyzed by noting M1 is in saturation and no potential drop appears across R_G.

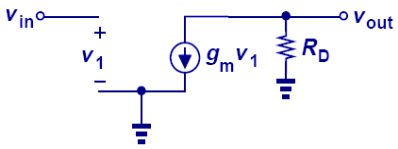
Current Sources



- When in saturation region, a MOSFET behaves as a current source.
- NMOS draws current from a point to ground (sinks current), whereas PMOS draws current from V_{DD} to a point (sources current).

Common-Source Stage



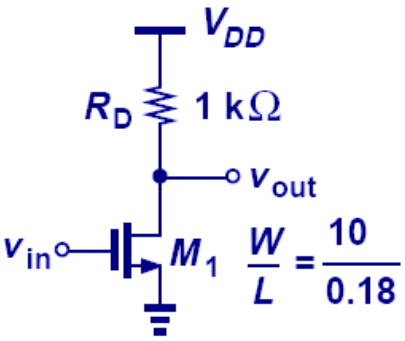


$$\lambda = 0$$

$$A_v = -g_m R_D$$

$$A_v = -\sqrt{2\mu_n C_{ox} \frac{W}{L} I_D R_D}$$

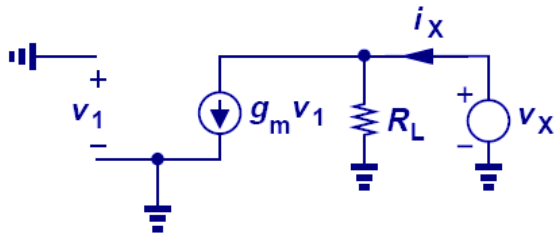
Operation in Saturation



$$R_D I_D < V_{DD} - (V_{GS} - V_{TH})$$

- In order to maintain operation in saturation, V_{out} cannot fall below V_{in} by more than one threshold voltage.
- The condition above ensures operation in saturation.

CS Stage with λ=0



$$A_v = -g_m R_L$$
$$R_{in} = \infty$$
$$R_{out} = R_L$$

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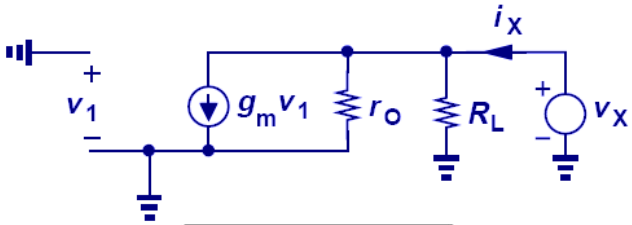
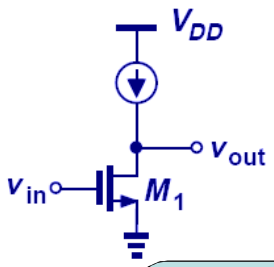
CS Stage with λ ≠ 0

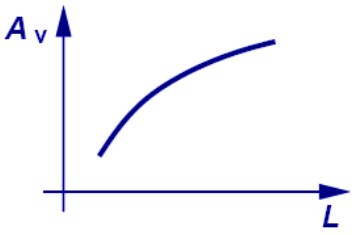


$$A_v = -g_m (R_L \parallel r_O)$$
$$R_{in} = \infty$$
$$R_{out} = R_L \parallel r_O$$

- However, Early effect and channel length modulation affect CE and CS stages in a similar manner.

CS Gain Variation with Channel Length

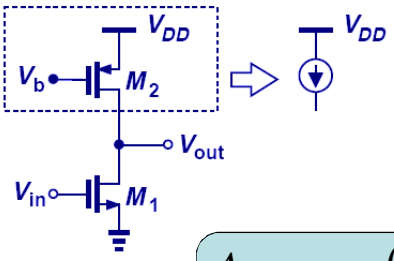


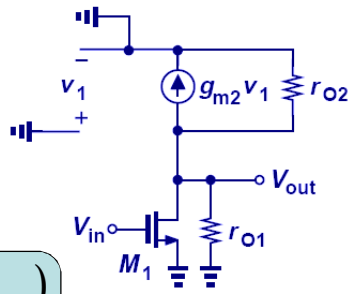


$$|A_v| = \frac{\sqrt{2\mu_n C_{ox}\frac{W}{L}}}{\lambda\sqrt{I_D}} \propto \sqrt{\frac{2\mu_n C_{ox} WL}{I_D}}$$

- Since λ is inversely proportional to L, the voltage gain actually becomes proportional to the square root of L.

CS Stage with Current-Source Load

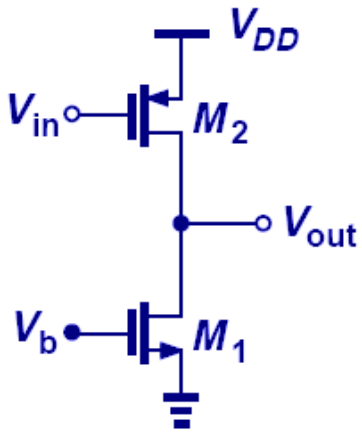




$$A_v = -g_{m1}(r_{O1} \parallel r_{O2})$$
$$R_{out} = r_{O1} \parallel r_{O2}$$

- To alleviate the headroom problem, an active current-source load is used.
- This is advantageous because a current-source has a high output resistance and can tolerate a small voltage drop across it.

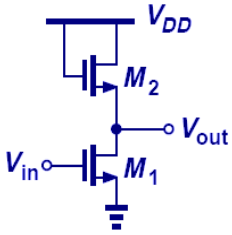
PMOS CS Stage with NMOS as Load

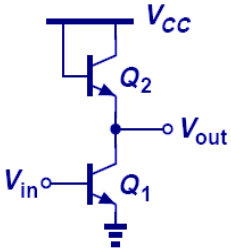


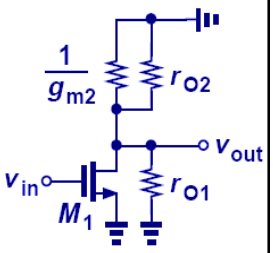
$$A_v = -g_{m2}(r_{O1} \| r_{O2})$$

- Similarly, with PMOS as input stage and NMOS as the load, the voltage gain is the same as before.

CS Stage with Diode-Connected Load





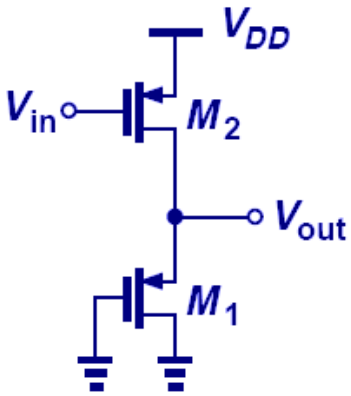


$$A_v = -g_{m1} \cdot \frac{1}{g_{m2}} = -\sqrt{\frac{(W/L)_1}{(W/L)_2}}$$

$$A_v = -g_{m1}\left(\frac{1}{g_{m2}} \| r_{O2} \| r_{O1}\right)$$

- Lower gain, but less dependent on process parameters.

CS Stage with Diode-Connected PMOS Device



$$A_v = -g_{m2}\left(\frac{1}{g_{m1}} \parallel r_{o1} \parallel r_{o2}\right)$$

- Note that PMOS circuit symbol is usually drawn with the source on top of the drain.

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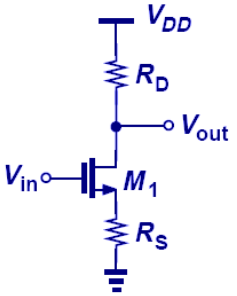
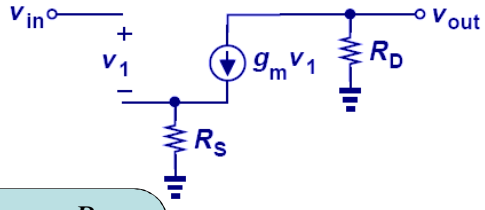
CS Stage with Degeneration

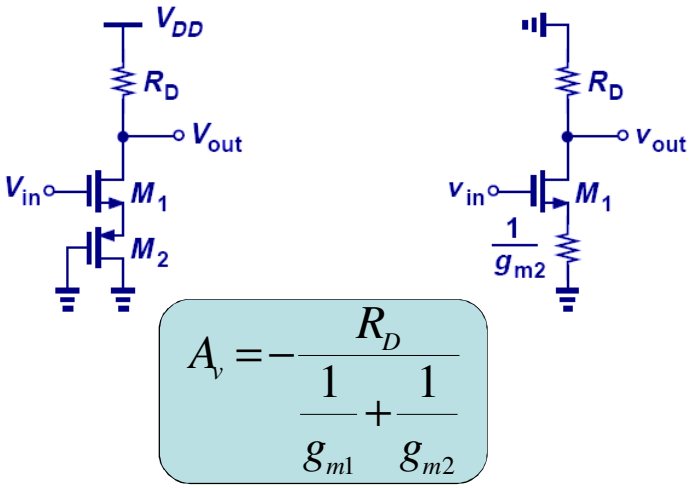




$$A_v = -\frac{R_D}{\frac{1}{g_m} + R_S}$$
$$\lambda = 0$$

- Similar to bipolar counterpart, when a CS stage is degenerated, its gain, I/O impedances, and linearity change.

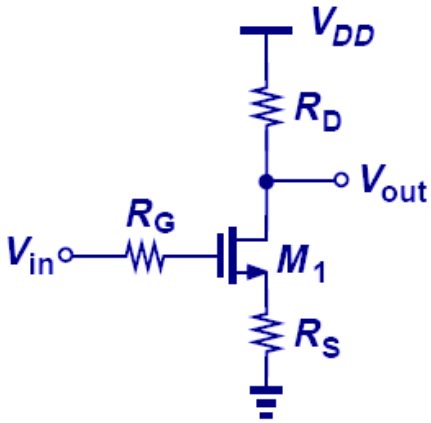
Example of CS Stage with Degeneration



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

- A diode-connected device degenerates a CS stage.

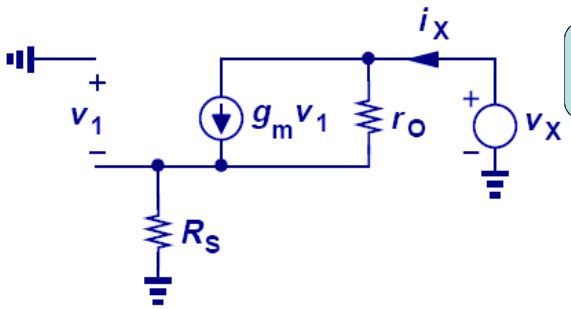
CS Stage with Gate Resistance



$$V_{R_G} = 0$$

- Since at low frequencies, the gate conducts no current, gate resistance does not affect the gain or I/O impedances.

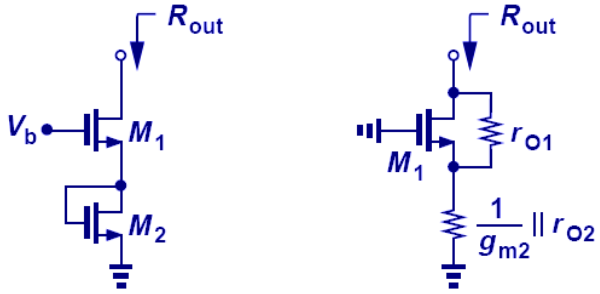
Output Impedance of CS Stage with Degeneration



$$r_{out} \approx g_m r_O R_S + r_O$$

- Similar to the bipolar counterpart, degeneration boosts output impedance.

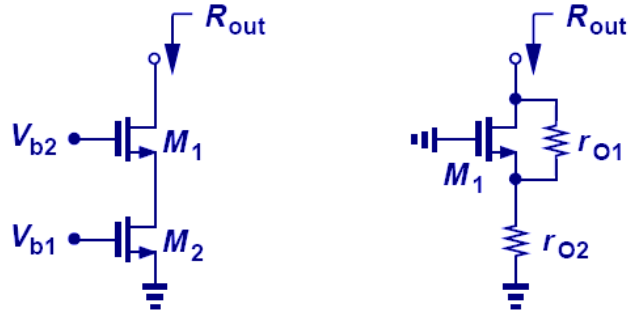
Output Impedance Example (I)



$$R_{out} = r_{O1}\left(1 + g_{m1}\frac{1}{g_{m2}}\right) + \frac{1}{g_{m2}}$$

- When $1/g_m$ is parallel with r_{O2}, we often just consider $1/g_m$.

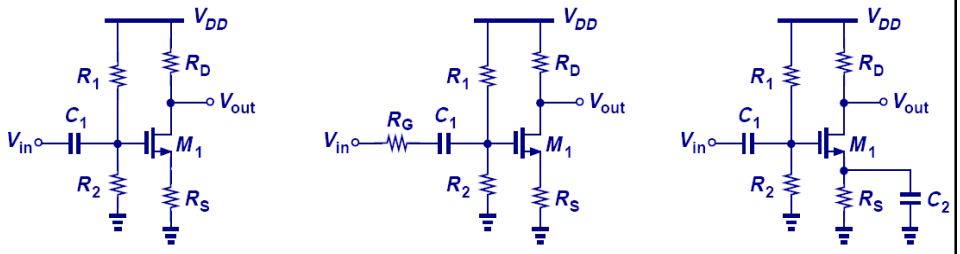
Output Impedance Example (II)



$$R_{out} \approx g_{m1} r_{O1} r_{O2} + r_{O1}$$

- In this example, the impedance that degenerates the CS stage is r_O, instead of $1/g_m$ in the previous example.

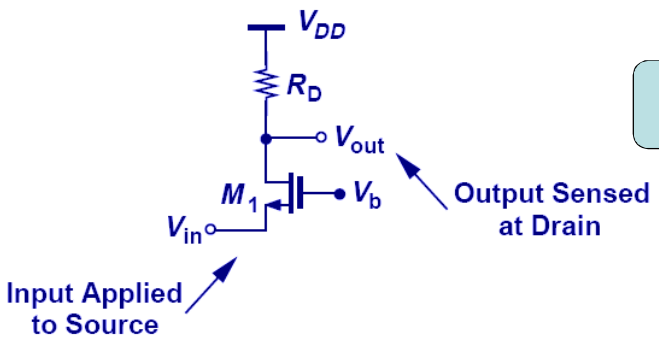
CS Core with Biasing



$$A_v = \frac{R_1 \| R_2}{R_G + R_1 \| R_2} \cdot \frac{-R_D}{\frac{1}{g_m} + R_S}, A_v = -\frac{R_1 \| R_2}{R_G + R_1 \| R_2} g_m R_D$$

- Degeneration is used to stabilize bias point, and a bypass capacitor can be used to obtain a larger small-signal voltage gain at the frequency of interest.

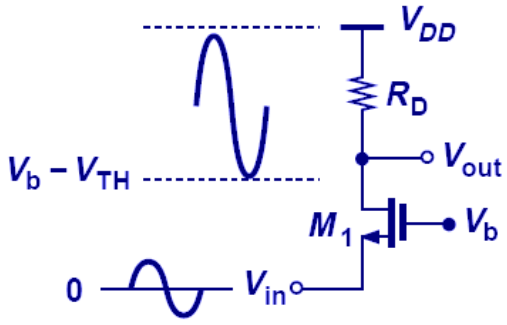
Common-Gate Stage



$$A_v = g_m R_D$$

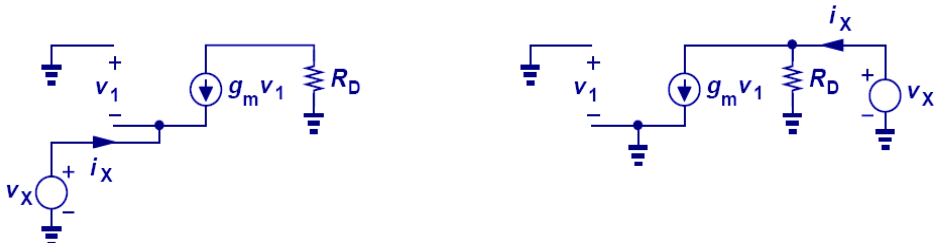
- Common-gate stage is similar to common-base stage: a rise in input causes a rise in output. So the gain is positive.

Signal Levels in CG Stage



- In order to maintain M_1 in saturation, the signal swing at V_{out} cannot fall below V_b-V_{TH}.

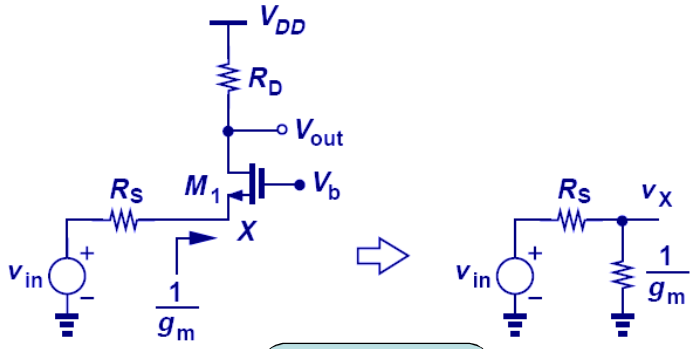
I/O Impedances of CG Stage



$$R_{in} = \frac{1}{g_m} \qquad \lambda = 0 \qquad R_{out} = R_D$$

- The input and output impedances of CG stage are similar to those of CB stage.

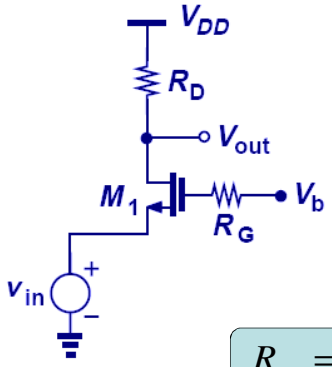
CG Stage with Source Resistance

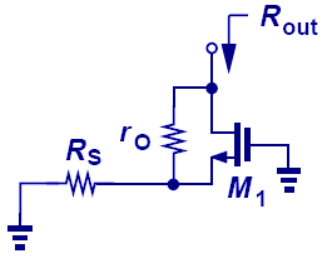


$$A_v = \frac{R_D}{\frac{1}{g_m} + R_S}$$

- When a source resistance is present, the voltage gain is equal to that of a CS stage with degeneration, only positive.

Generalized CG Behavior

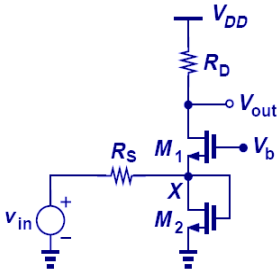


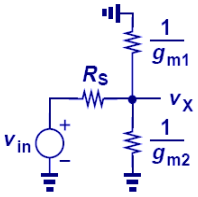


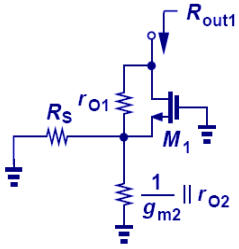
$$R_{out} = (1 + g_m r_O) R_S + r_O$$

- When a gate resistance is present it does not affect the gain and I/O impedances since there is no potential drop across it (at low frequencies).
- The output impedance of a CG stage with source resistance is identical to that of CS stage with degeneration.

Example of CG Stage



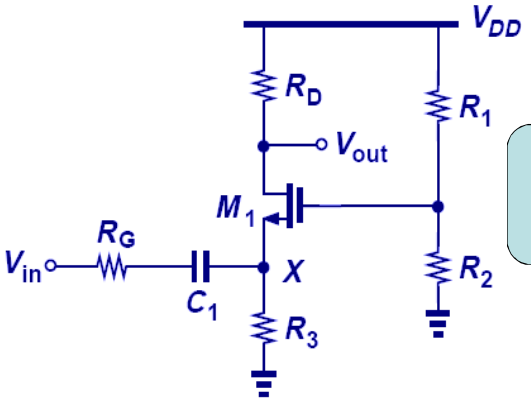




$$\frac{v_{out}}{v_{in}} = \frac{g_{m1} R_D}{1 + (g_{m1} + g_{m2}) R_S} \qquad R_{out} \approx \left[g_{m1} r_{O1} \left(\frac{1}{g_{m2}} \| R_S \right) + r_{O1} \right] \| R_D$$

- Diode-connected M_2 acts as a resistor to provide the bias current.

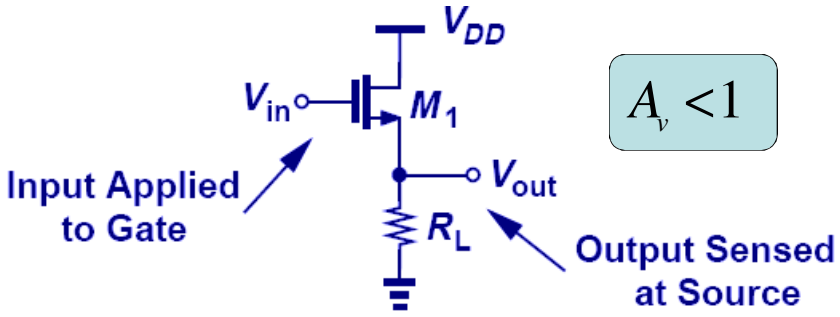
CG Stage with Biasing



$$\frac{v_{out}}{v_{in}} = \frac{R_3 \| (1/g_m)}{R_3 \| (1/g_m) + R_S} \cdot g_m R_D$$

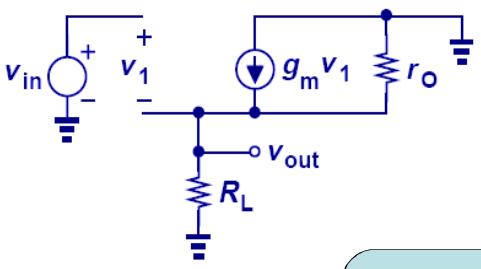
- R_1 and R_2 provide gate bias voltage, and R_3 provides a path for DC bias current of M_1 to flow to ground.

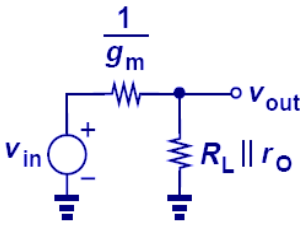
Source Follower Stage



$$A_v < 1$$

Source Follower Core

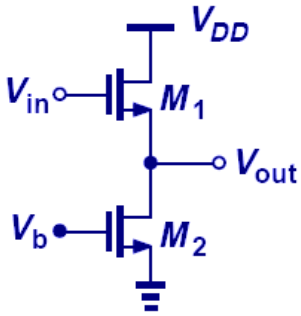


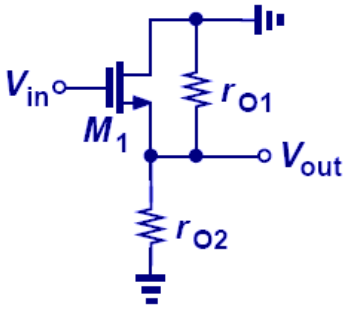


$$\frac{v_{out}}{v_{in}} = \frac{r_O \| R_L}{\frac{1}{g_m} + r_O \| R_L}$$

- Similar to the emitter follower, the source follower can be analyzed as a resistor divider.

Source Follower Example

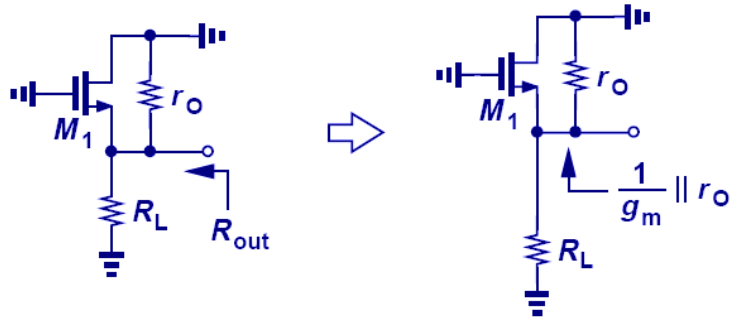




$$A_v = \frac{r_{O1} \| r_{O2}}{\frac{1}{g_{m1}} + r_{O1} \| r_{O2}}$$

- In this example, M_2 acts as a current source.

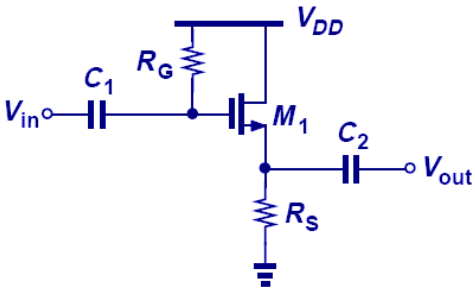
Output Resistance of Source Follower



$$R_{out} = \frac{1}{g_m} \| r_O \| R_L \approx \frac{1}{g_m} \| R_L$$

- The output impedance of a source follower is relatively low, whereas the input impedance is infinite (at low frequencies); thus, a good candidate as a buffer.

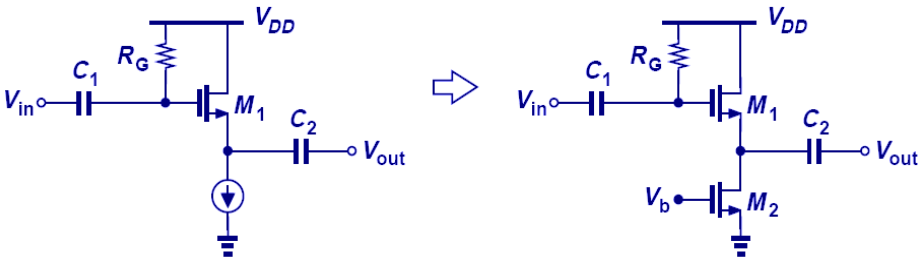
Source Follower with Biasing



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

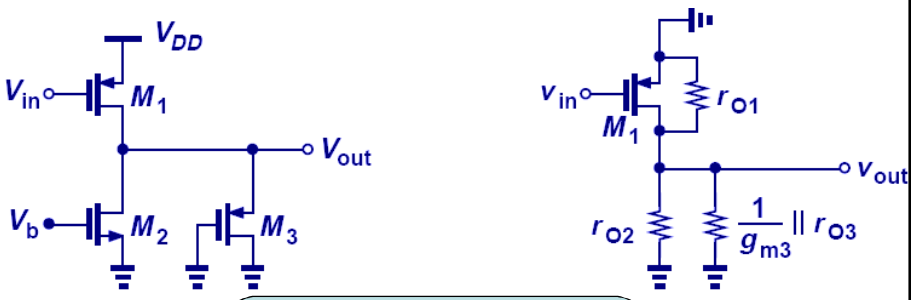
- R_G sets the gate voltage to V_{DD}, whereas R_S sets the drain current.
- The quadratic equation above can be solved for I_D.

Supply-Independent Biasing



- If R_s is replaced by a current source, drain current I_D becomes independent of supply voltage.

Example of a CS Stage (I)

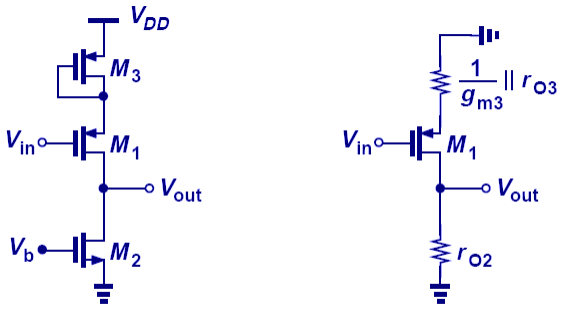


$$A_v = -g_{m1}\left(\frac{1}{g_{m3}} \| r_{O1} \| r_{O2} \| r_{O3}\right)$$

$$R_{out} = \frac{1}{g_{m3}} \| r_{O1} \| r_{O2} \| r_{O3}$$

- M_1 acts as the input device and M_2, M_3 as the load.

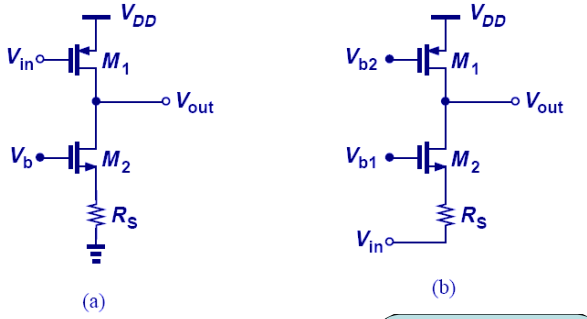
Example of a CS Stage (II)



$$A_v = -\frac{r_{O2}}{\frac{1}{g_{m1}} + \frac{1}{g_{m3}} \| r_{O3}}$$

- M_1 acts as the input device, M_3 as the source resistance, and M_2 as the load.

Examples of CS and CG Stages

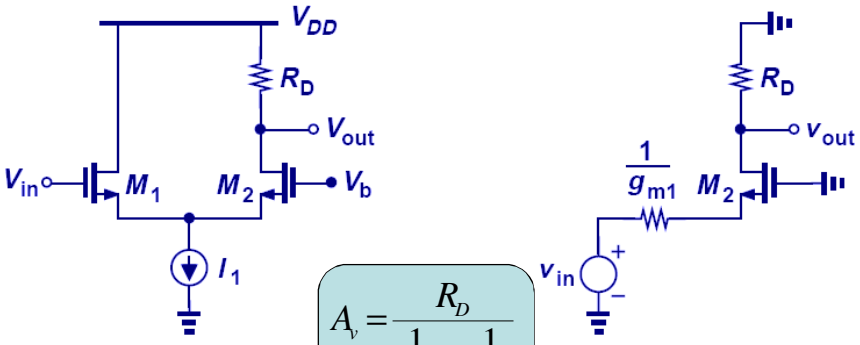


$$A_{v\_CS} = -g_{m2}\left[(1+g_{m1}r_{O1})R_S + r_{O1}\right] \| r_{O1}$$

$$A_{v\_CG} = \frac{r_{O2}}{\frac{1}{g_m} + R_S}$$

- With the input connected to different locations, the two circuits, although identical in other aspects, behave differently.

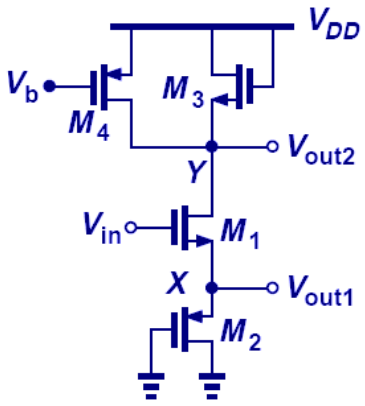
Example of a Composite Stage (I)



$$A_v = \frac{R_D}{\frac{1}{g_{m1}} + \frac{1}{g_{m2}}}$$

- By replacing the left side with a Thevenin equivalent, and recognizing the right side is actually a CG stage, the voltage gain can be easily obtained.

Example of a Composite Stage (II)



$$\frac{v_{out2}}{v_{in}} = -\frac{\frac{1}{g_{m3}} \| r_{O3} \| r_{O4}}{\frac{1}{g_{m2}} \| r_{O2} + \frac{1}{g_{m1}}}$$

- This example shows that by probing different places in a circuit, different types of output can be obtained.
- V_{out1} is a result of M_1 acting as a source follower whereas V_{out2} is a result of M_1 acting as a CS stage with degeneration.