Lecture 20

OUTLINE

- Review of MOSFET Amplifiers
- MOSFET Cascode Stage
- MOSFET Current Mirror

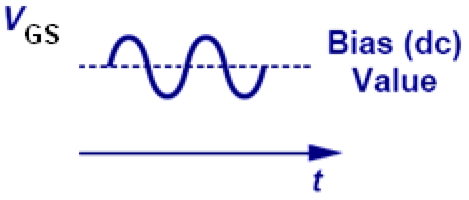
- Reading: Chapter 9

Review: MOSFET Amplifier Design

- A MOSFET amplifier circuit should be designed to
  1. ensure that the MOSFET operates in the saturation region,
  2. allow the desired level of DC current to flow, and
  3. couple to a small-signal input source and to an output "load".

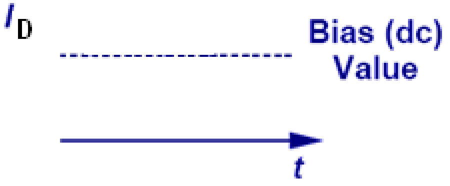
→ Proper "DC biasing" is required!

(DC analysis using large-signal MOSFET model)



- Key amplifier parameters:

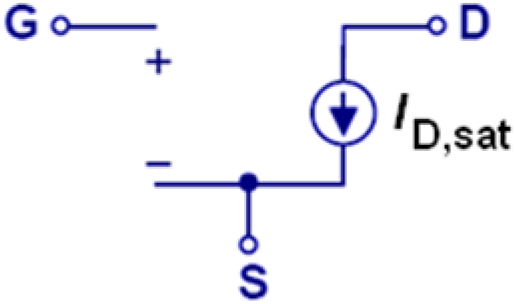
(AC analysis using small-signal MOSFET model)



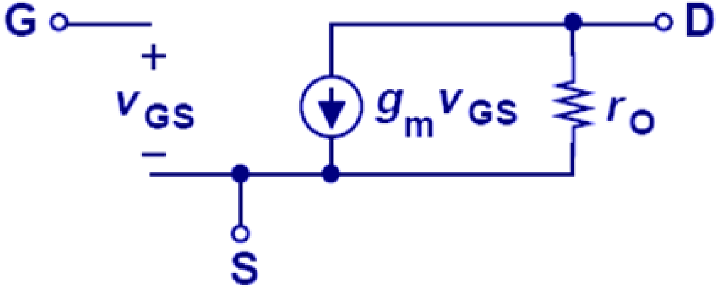
  - **Voltage gain A_v** $\equiv v_{out}/v_{in}$
  - **Input resistance R_{in}** $\equiv$ resistance seen between the input node and ground (with output terminal floating)
  - **Output resistance R_{out}** $\equiv$ resistance seen between the output node and ground (with input terminal grounded)

MOSFET Models

- The large-signal model is used to determine the DC operating point (V_{GS}, V_{DS}, I_D) of the MOSFET.



- The small-signal model is used to determine how the output responds to an input signal.



Comparison of Amplifier Topologies

Common Source

- **Large $A_v < 0$**
  - degraded by R_S
- **Large R_{in}**
  - determined by biasing circuitry
- **$R_{out} \cong R_D$**
- **r_o decreases A_v & R_{out}**
  but impedance seen looking into the drain can be "boosted" by source degeneration

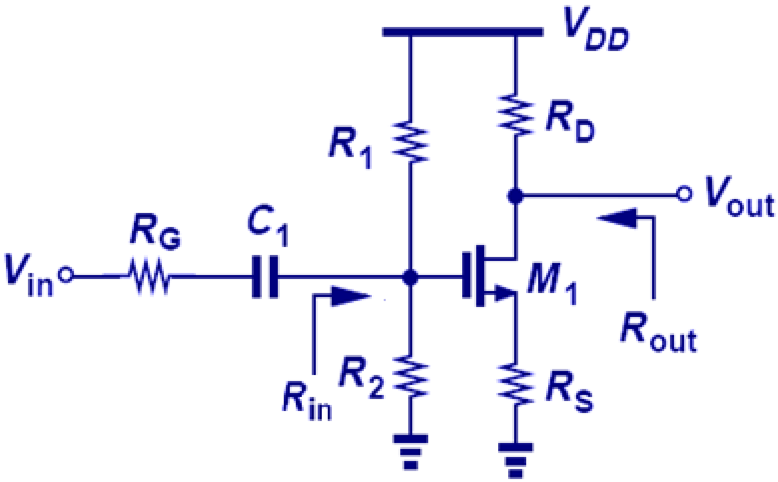
Common Gate

- **Large $A_v > 0$**
  -degraded by R_S
- **Small R_{in}**
  - decreased by R_S
- **$R_{out} \cong R_D$**
- **r_o decreases A_v & R_{out}**
  but impedance seen looking into the drain can be "boosted" by source degeneration

Source Follower

- **$0 < A_v \leq 1$**
- **Large R_{in}**
  - determined by biasing circuitry
- **Small R_{out}**
  - decreased by R_S
- **r_o decreases A_v & R_{out}**

Common Source Stage



$\lambda = 0$

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

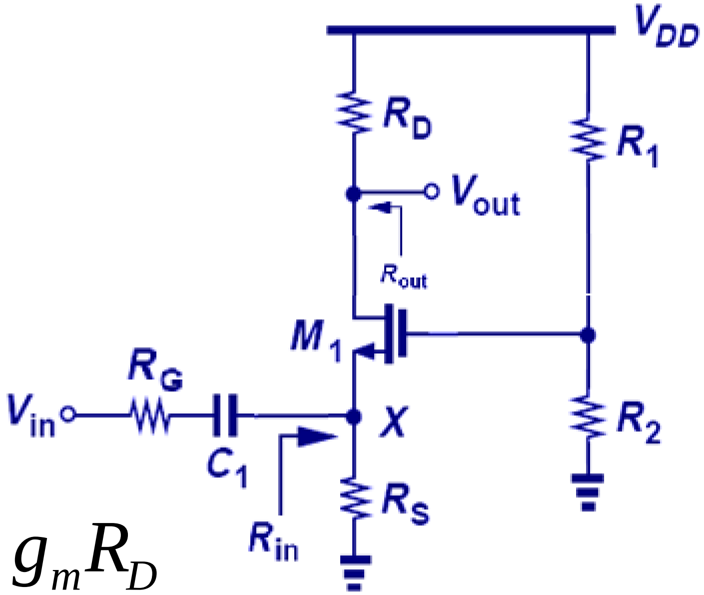
$$R_{in} = R_1 \parallel R_2$$

$$R_{out} = R_D$$

$\lambda \neq 0$

$$R_{out} \cong R_D \| (r_O + g_m r_O R_S)$$

Common Gate Stage



$\underline{\lambda = 0}$

$$A_v = \frac{R_S \| (1/g_m)}{R_S \| (1/g_m) + R_G} \cdot g_m R_D$$

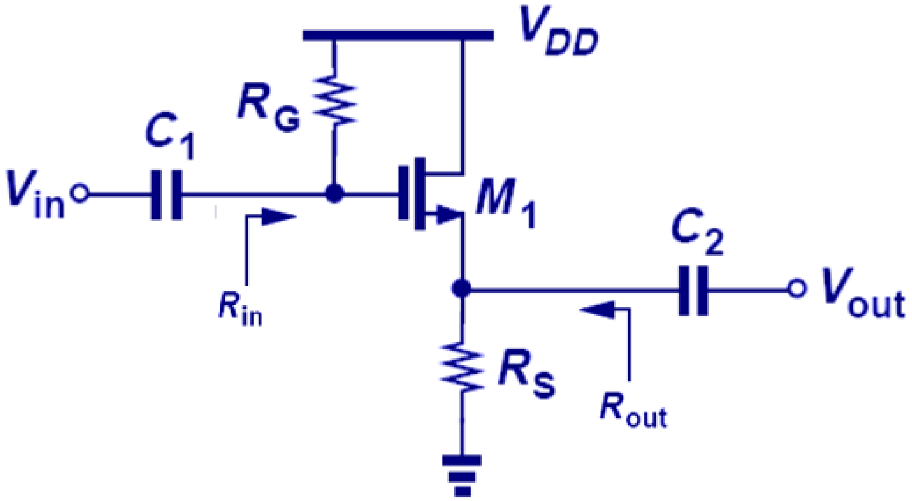
$$R_{in} \approx \frac{1}{g_m} \| R_S$$

$$R_{out} = R_D$$

$\underline{\lambda \neq 0}$

$$R_{out} \cong R_D \| (r_O + g_m r_O R_S)$$

Source Follower



$\lambda = 0$

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

$$R_{in} = R_G$$

$$R_{out} = \frac{1}{g_m} \| R_S$$

$\lambda \neq 0$

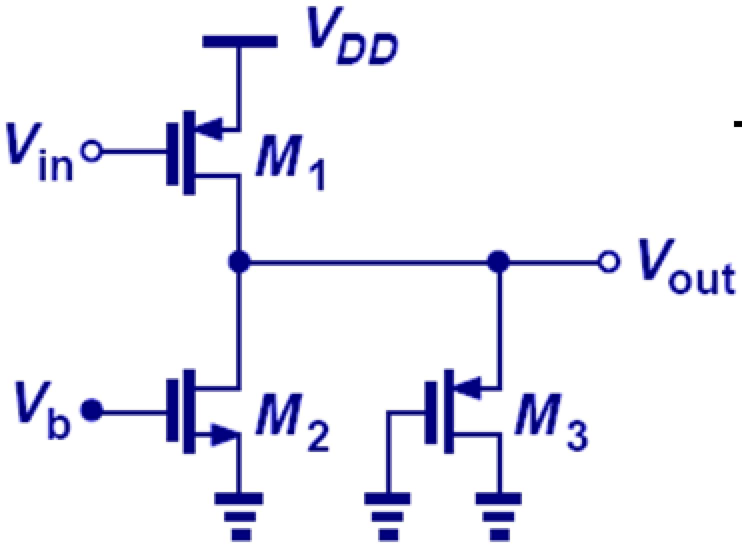
$$A_v = \frac{r_O \| R_S}{\frac{1}{g_m} + r_O \| R_S}$$

$$R_{in} = R_G$$

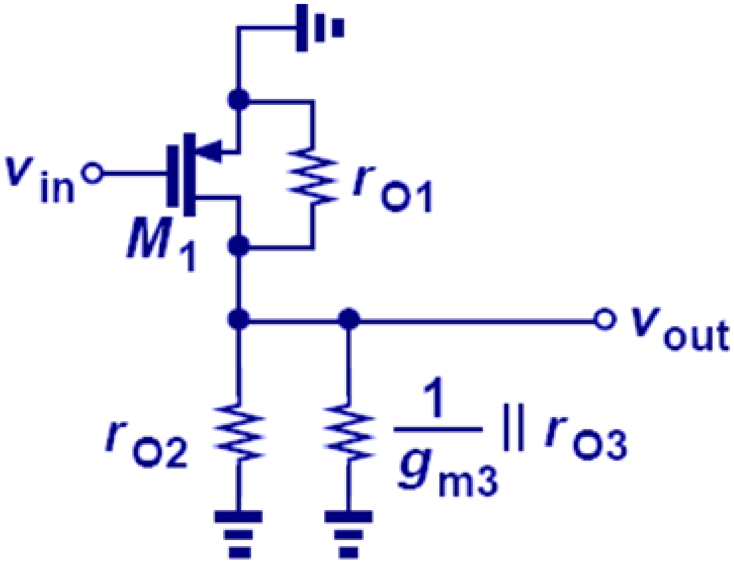
$$R_{out} = \frac{1}{g_m} \| r_o \| R_S$$

CS Stage Example 1

- M_1 is the amplifying device; M_2 and M_3 serve as the load.



Equivalent circuit for small-signal analysis, showing resistances connected to the drain

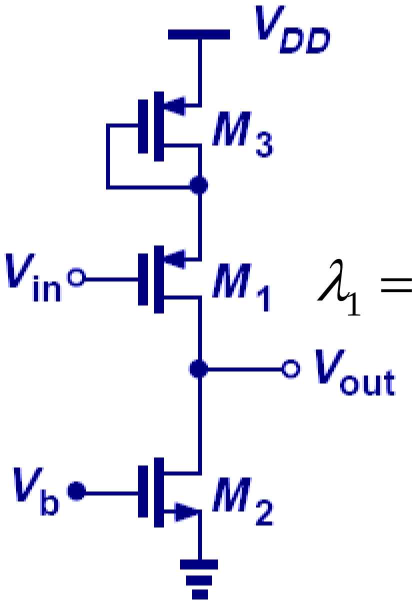


$$A_v = -g_{m1}\left(\frac{1}{g_{m3}} \| r_{O3} \| r_{O2} \| r_{O1}\right)$$

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

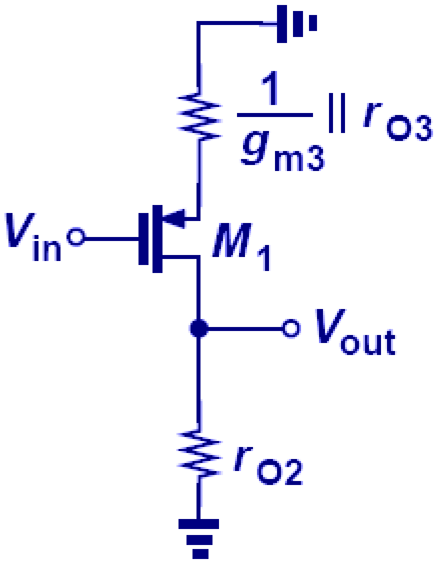
CS Stage Example 2

- M_1 is the amplifying device; M_3 serves as a source (degeneration) resistance; M_2 serves as the load.



$\lambda_1 = 0$

Equivalent circuit for small-signal analysis

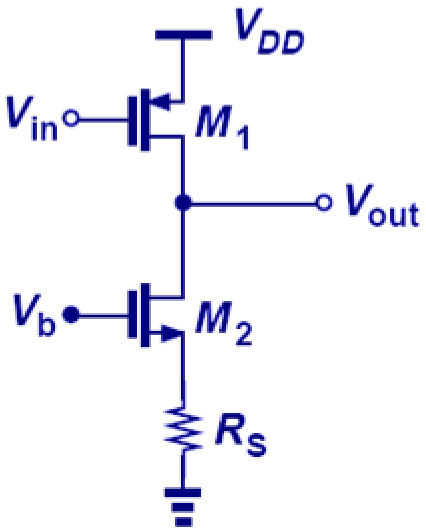


$$A_v = -\frac{r_{O2}}{\frac{1}{g_{m1}} + \frac{1}{g_{m3}} \| r_{O3}}$$

CS Stage *vs.* CG Stage

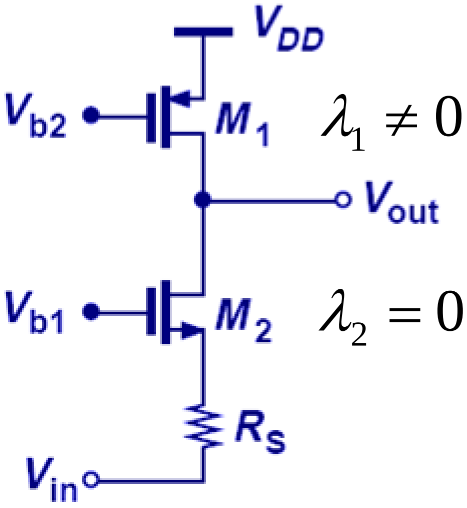
- With the input signal applied at different locations, these circuits behave differently, although they are identical in other aspects.

Common source amplifier



$$A_v = -g_{m1}\{[(1+g_{m2}r_{O2})R_S + r_{O2}] \| r_{O1}\}$$

Common gate amplifier



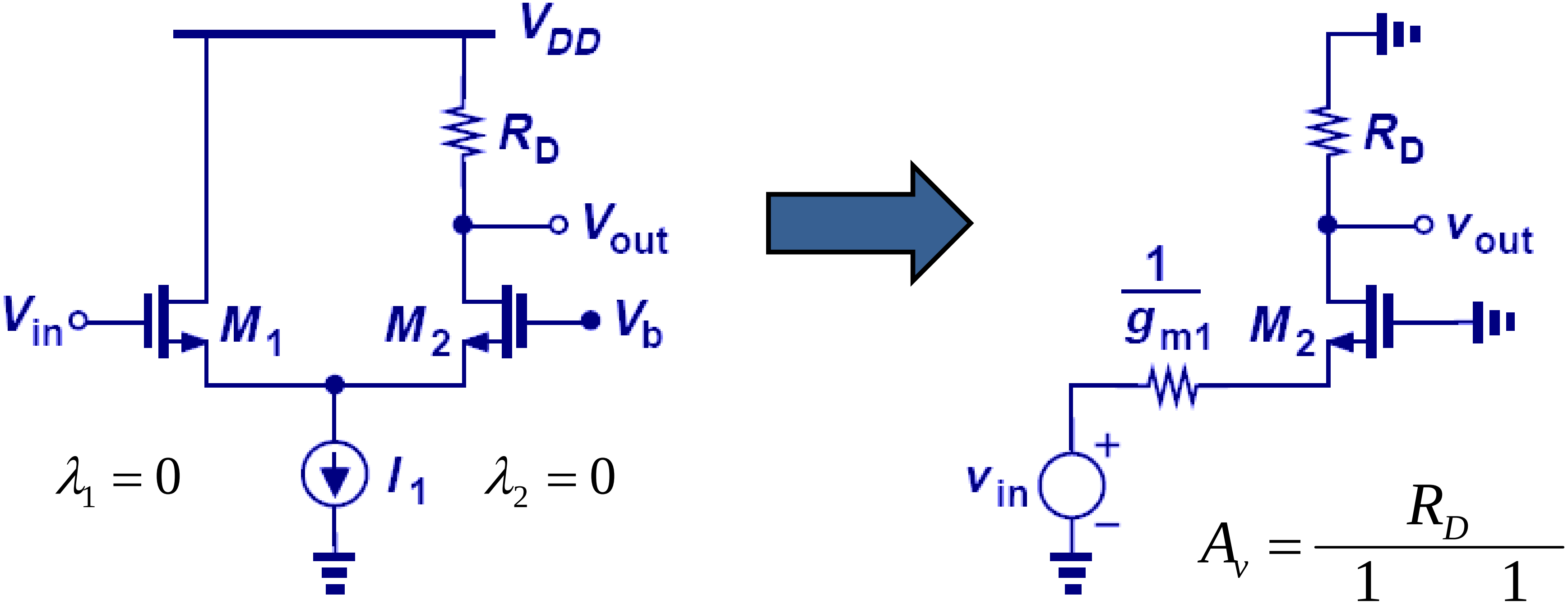
$\lambda_1 \neq 0$

$\lambda_2 = 0$

$$A_v = \frac{r_{O1}}{\frac{1}{g_{m2}} + R_S}$$

Composite Stage Example 1

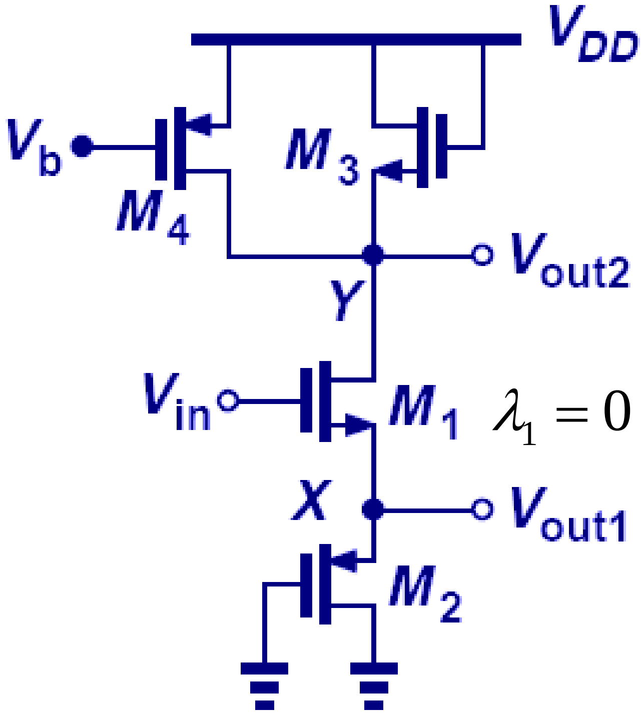
- By replacing M_1 and the current source with a Thevenin equivalent circuit, and recognizing the right side as a CG stage, the voltage gain can be easily obtained.



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

Composite Stage Example 2

- This example shows that by probing different nodes in a circuit, different output signals 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.

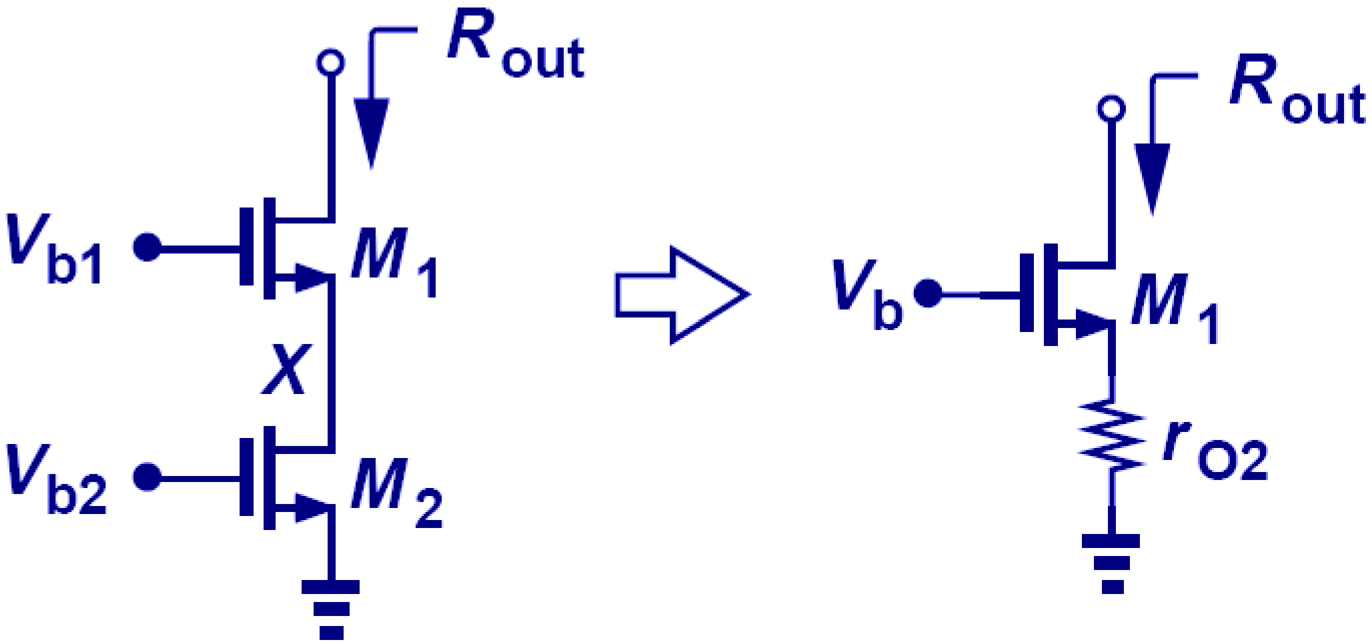


$\lambda_1 = 0$

$$\frac{v_{out1}}{v_{in}} = \frac{\frac{1}{g_{m2}} \| r_{O2}}{\frac{1}{g_{m1}} + \frac{1}{g_{m2}} \| r_{O2}}$$

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

NMOS Cascode Stage

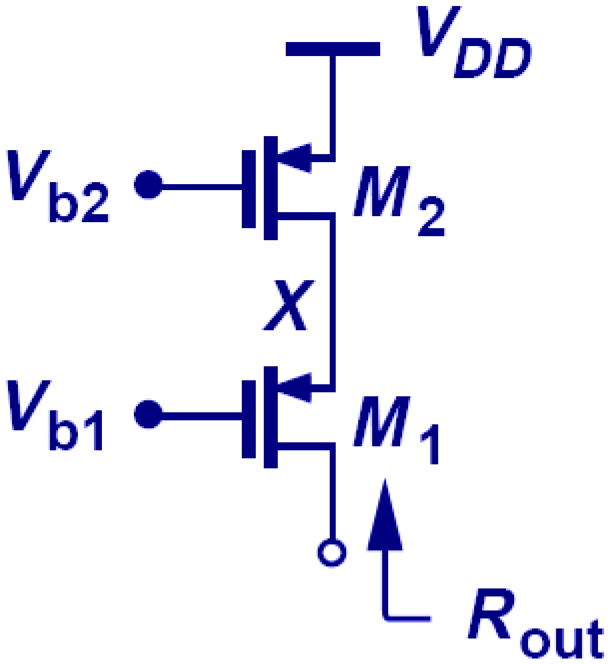


$$R_{out} = (1 + g_{m1}r_{O1})r_{O2} + r_{O1}$$

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

- Unlike a BJT cascode, the output impedance is not limited by β.

PMOS Cascode Stage

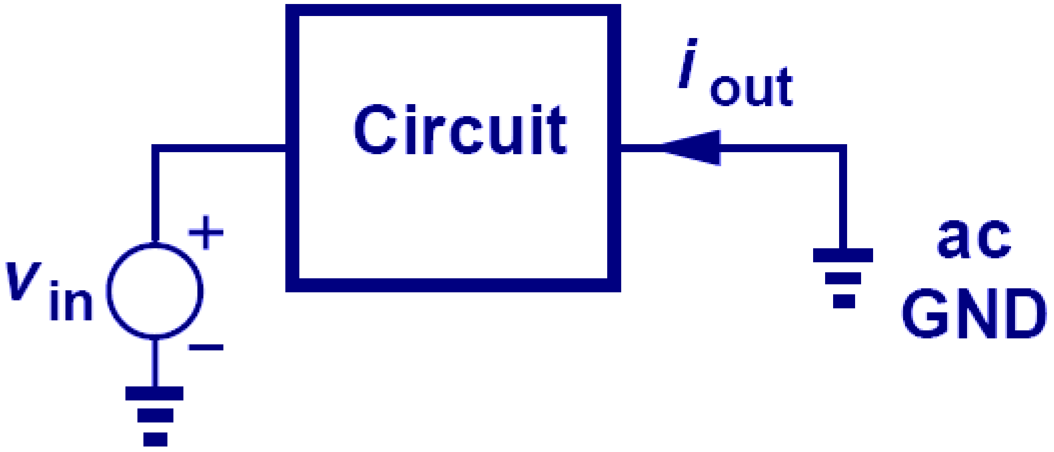


$$R_{out} = (1 + g_{m1} r_{O1}) r_{O2} + r_{O1}$$

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

Short-Circuit Transconductance

- The short-circuit transconductance is a measure of the strength of a circuit in converting an input voltage signal into an output current signal:

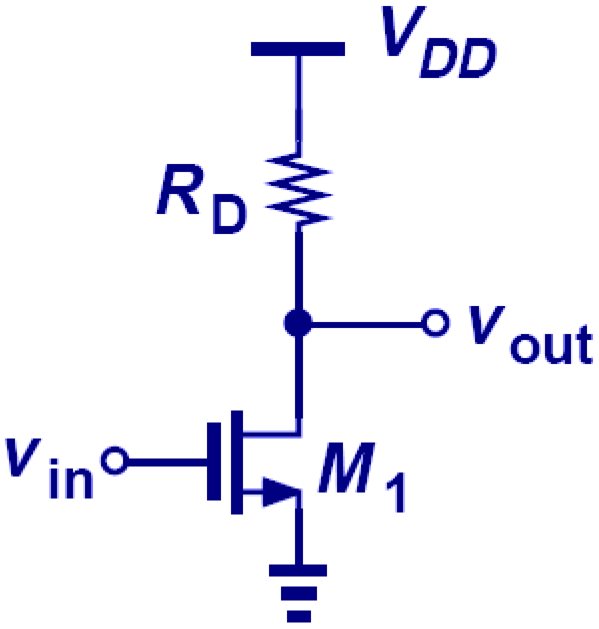


$$G_m \equiv \left.\frac{i_{out}}{v_{in}}\right|_{v_{out}=0}$$

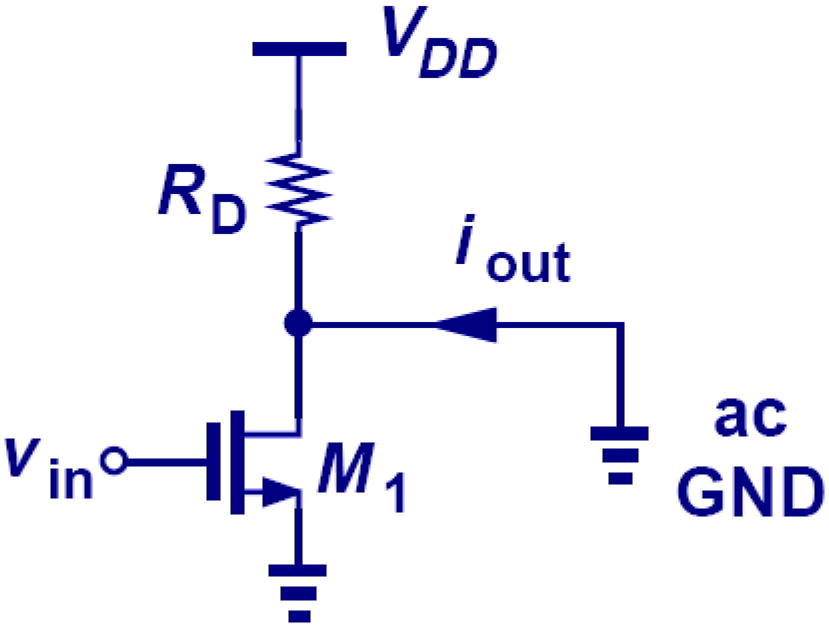
- The voltage gain of a linear circuit is $A_v = -G_m R_{out}$

  (R_{out} is the output resistance of the circuit)

Transconductance Example



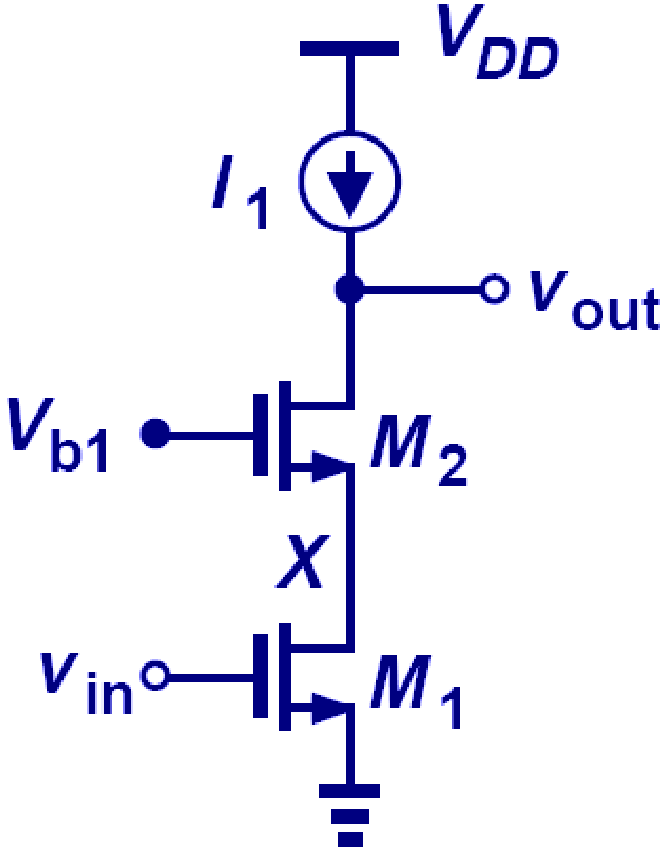
(a)



(b)

$$G_m = g_{m1}$$

MOS Cascode Amplifier



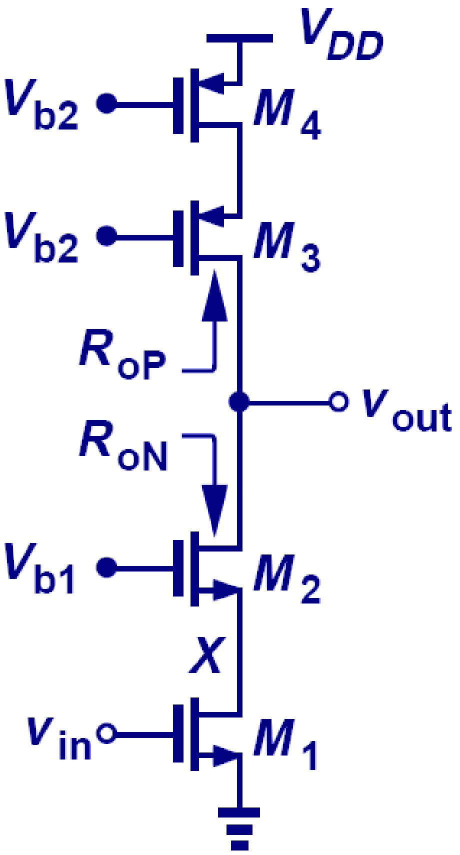
$$A_v = -G_m R_{out}$$

$$A_v \approx -g_{m1}\left[(1+g_{m2}r_{O2})r_{O1}+r_{O2}\right]$$

$$A_v \approx -g_{m1}r_{O1}g_{m2}r_{O2}$$

PMOS Cascode Current Source as Load

- A large load impedance can be achieved by using a PMOS cascode current source.



$$R_{oN} \approx g_{m2} r_{O2} r_{O1}$$

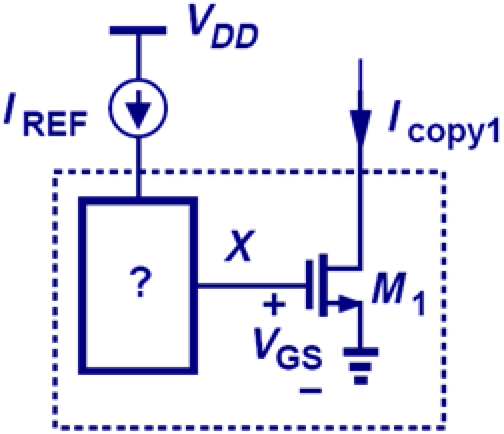
$$R_{oP} \approx g_{m3} r_{O3} r_{O4}$$

$$R_{out} = R_{oN} \parallel R_{oP}$$

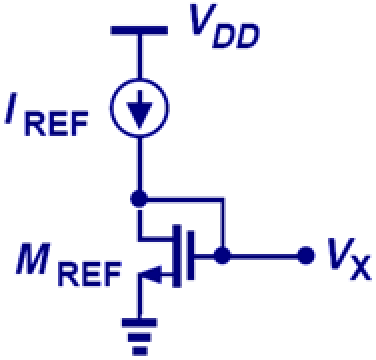
MOS Current Mirror

- The motivation behind a current mirror is to duplicate a (scaled version of the) "golden current" to other locations.

Current mirror concept



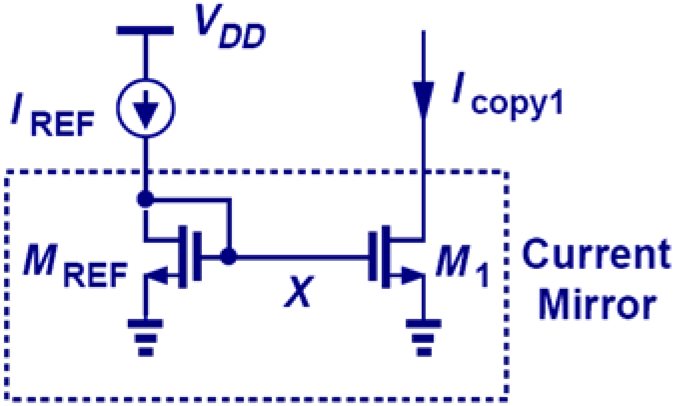
Generation of required V_{GS}



$$I_{REF} = \frac{1}{2}\mu_n C_{ox}\left(\frac{W}{L}\right)_{REF}(V_X - V_{TH})^2$$

$$V_X = \sqrt{\frac{2I_{REF}}{\mu_n C_{ox}(W/L)_1}} + V_{TH1}$$

Current Mirror Circuitry

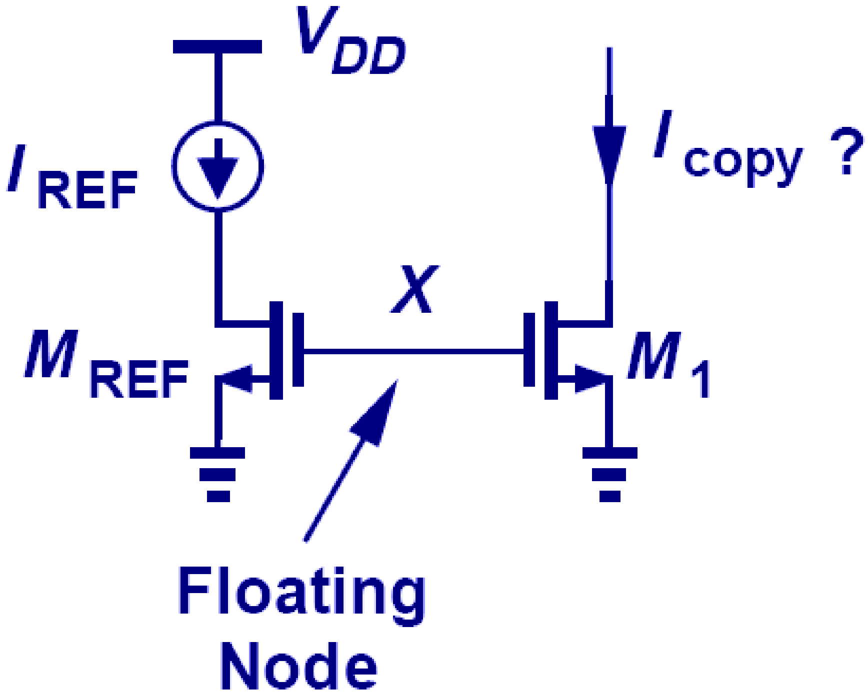


$$I_{copy1} = \frac{1}{2}\mu_n C_{ox}\left(\frac{W}{L}\right)_1(V_X - V_{TH})^2$$

$$\boxed{I_{copy1} = \frac{(W/L)_1}{(W/L)_{REF}} I_{REF}}$$

MOS Current Mirror – NOT!

- This is not a current mirror, because the relationship between V_X and I_{REF} is not clearly defined.

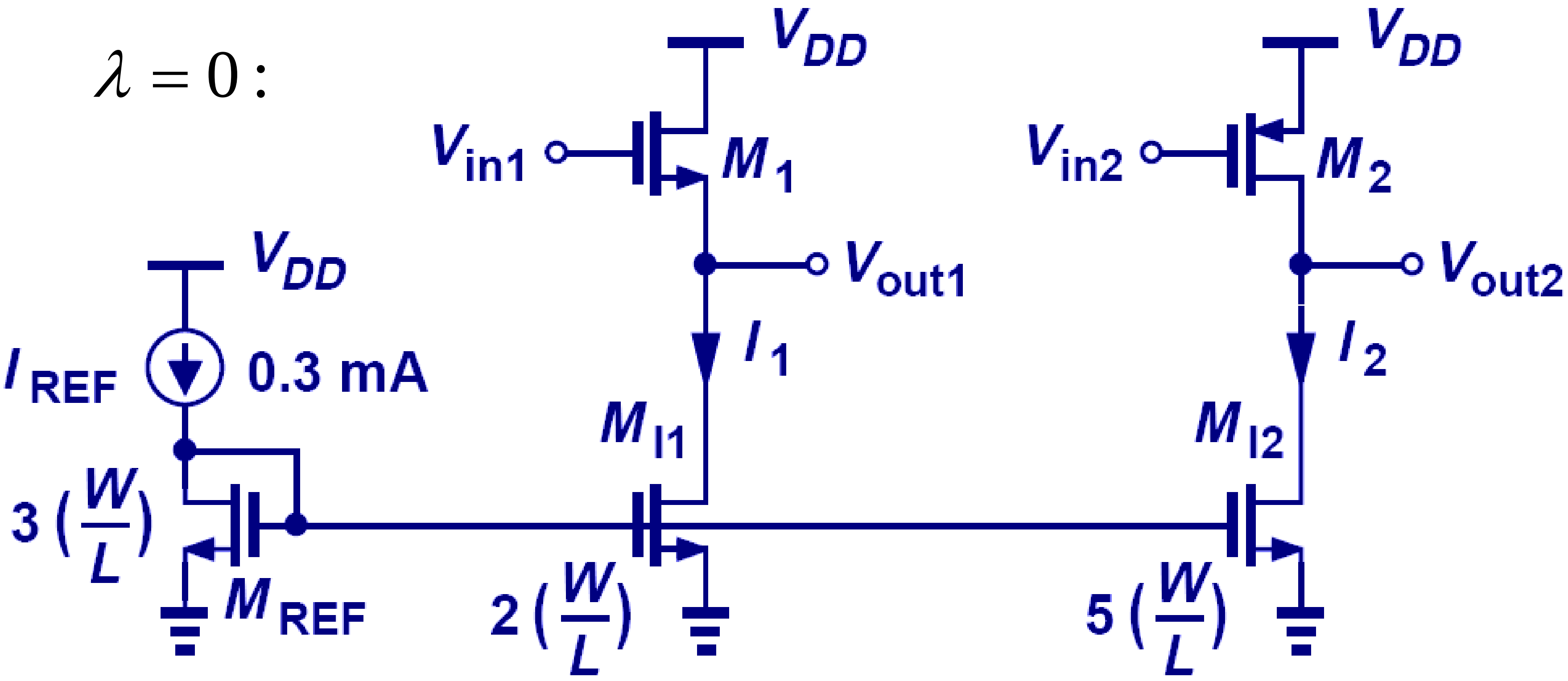


- The only way to clearly define V_X with I_{REF} is to use a diode-connected MOS since it provides square-law I-V relationship.

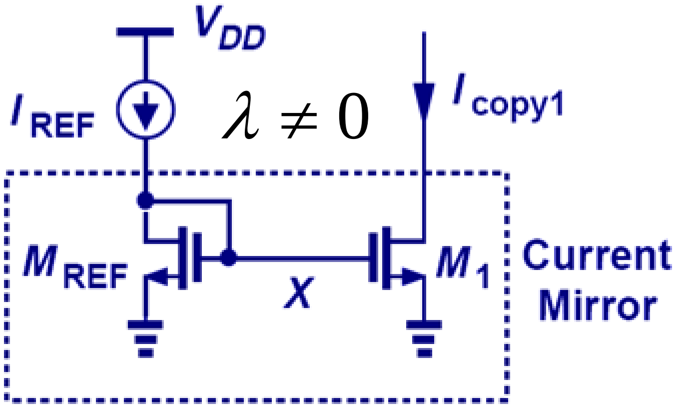
Example: Current Scaling

- MOS current mirrors can be used to scale I_{REF} up or down
  - $I_1 = 0.2\text{mA}$; $I_2 = 0.5\text{mA}$

$\lambda = 0:$



Impact of Channel-Length Modulation



$\lambda \neq 0$

$$I_{copy1} = \frac{1}{2}\mu_n C_{ox}\left(\frac{W}{L}\right)_1 (V_X - V_{TH})^2 \left[1+\lambda\left(V_{DS1} - V_{D,sat}\right)\right]$$

$$= \frac{1}{2}\mu_n C_{ox}\left(\frac{W}{L}\right)_1 (V_X - V_{TH})^2 \left[1+\lambda\left(V_{DS1} - V_{GS} + V_{TH}\right)\right]$$

$$I_{REF} = \frac{1}{2}\mu_n C_{ox}\left(\frac{W}{L}\right)_{REF} (V_X - V_{TH})^2 \left[1+\lambda\left(V_{GS} - V_{D,sat}\right)\right]$$

$$= \frac{1}{2}\mu_n C_{ox}\left(\frac{W}{L}\right)_{REF} (V_X - V_{TH})^2 \left[1+\lambda V_{TH}\right]$$

$$\boxed{I_{copy1} = \frac{(W/L)_1}{(W/L)_{REF}} I_{REF} \frac{1+\lambda\left(V_{DS1} - V_{GS} + V_{TH}\right)}{1+\lambda V_{TH}} = \frac{(W/L)_1}{(W/L)_{REF}} I_{REF} \left(1 + \frac{\lambda\left(V_{DS1} - V_{GS}\right)}{1+\lambda V_{TH}}\right)}$$

CMOS Current Mirror