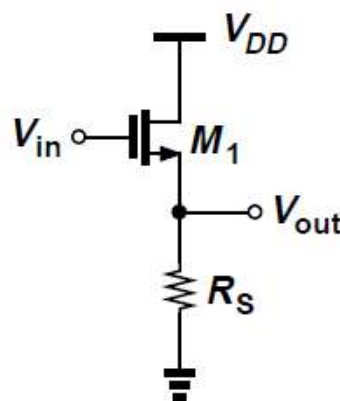
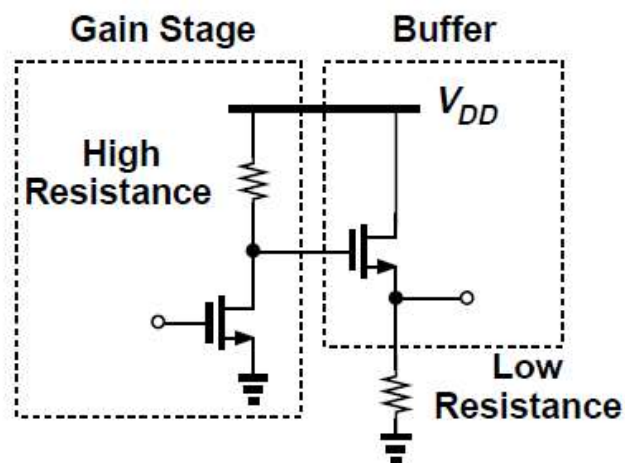


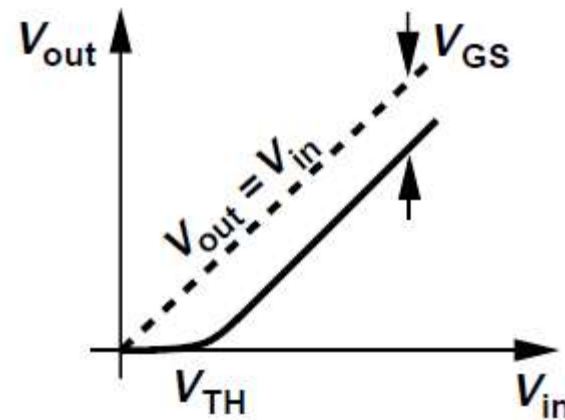
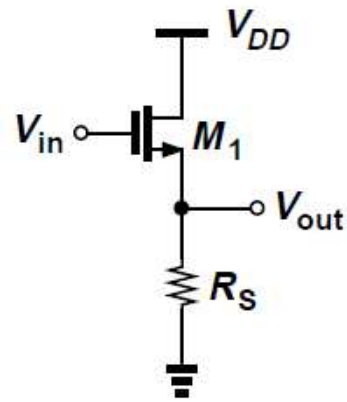
# Source Follower



- Source follower (also called “common-drain” stage) senses the input at the gate and drives load at the source
- It presents a high input impedance, allowing source potential to “follow” the gate voltage
- Acts as a voltage buffer



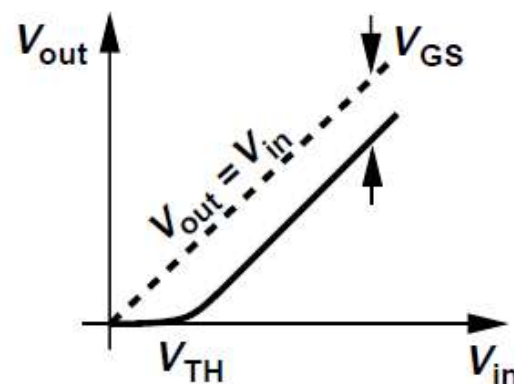
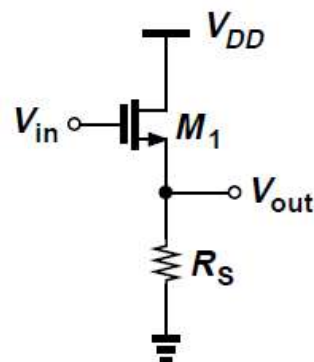
# Source Follower



- For  $V_{in} < V_{TH}$ ,  $M_1$  is off and  $V_{out} = 0$
- As  $V_{in}$  exceeds  $V_{TH}$ ,  $M_1$  turns on in saturation since  $V_{DS} = V_{DD}$  and  $V_{GS} - V_{TH} \approx 0$  and  $I_{D1}$  flows through  $R_S$
- As  $V_{in}$  increases further,  $V_{out}$  follows the input with a difference (level shift) equal to  $V_{GS}$
- Input-output characteristic neglecting channel-length modulation can be expressed as

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

# Source Follower



- For  $V_{in} < V_{TH}$ ,  $M_1$  is off and  $V_{out} = 0$
- Differentiating both sides of large-signal equation for  $V_{out}$ ,

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

- Since  $\frac{\partial V_{TH}}{\partial V_{in}} = (\frac{\partial V_{TH}}{\partial V_{SB}})(\frac{\partial V_{SB}}{\partial V_{in}}) = \eta \frac{\partial V_{out}}{\partial V_{in}}$ ,

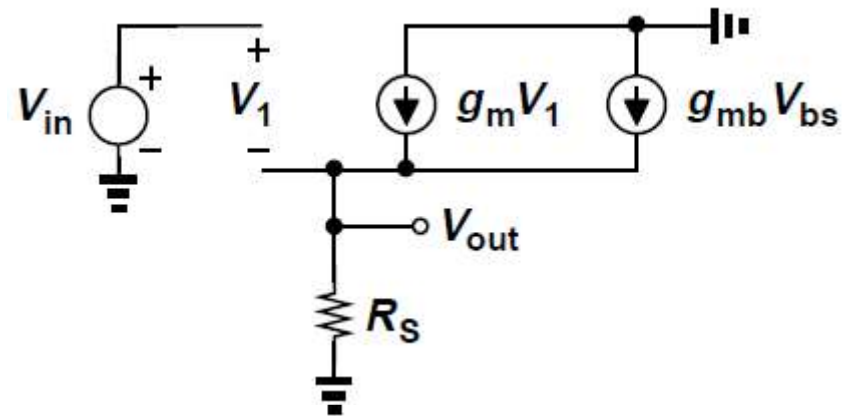
- Therefore, 
$$\frac{\partial V_{out}}{\partial V_{in}} = \frac{\mu_n C_{ox} \frac{W}{L} (V_{in} - V_{TH} - V_{out}) R_S}{1 + \mu_n C_{ox} \frac{W}{L} (V_{in} - V_{TH} - V_{out}) R_S (1 + \eta)}$$

- Note that 
$$g_m = \mu_n C_{ox} \frac{W}{L} (V_{in} - V_{TH} - V_{out})$$

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

# Source Follower

- Small-signal gain can be obtained more easily using small-signal equivalent model



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

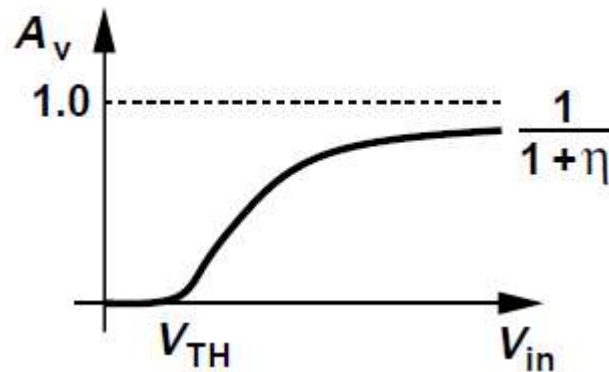
- We have,
- KVL:

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

- KCL:

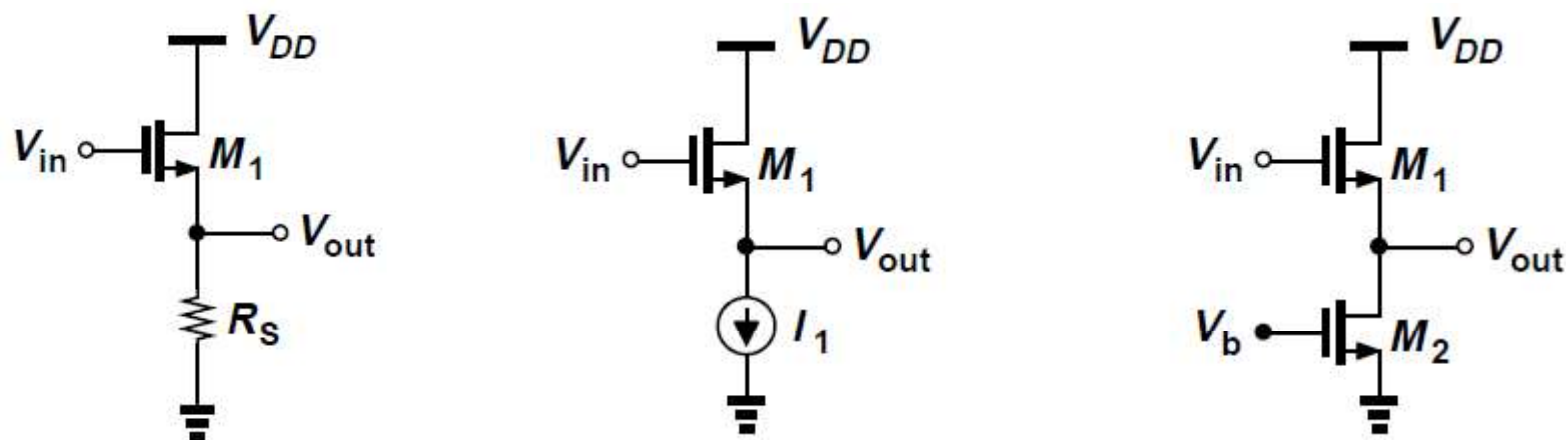
$$V_{out} / V_{in} = g_m R_S / [1 + (g_m + g_{mb}) R_S]$$

# Source Follower



- Voltage gain begins from zero for  $V_{in} \approx V_{TH}$  ( $g_m \approx 0$ ), and monotonically increases
- As drain current and  $g_m$  increase,  $A_v$  approaches 
$$g_m / (g_m + g_{mb}) = 1 / (1 + \eta)$$
- Since  $\eta$  itself slowly decreases with  $V_{out}$ ,  $A_v$  would eventually become equal to unity, but for typical allowable source-bulk voltages,  $\eta$  remains greater than roughly than 0.2
- Even if  $R_S = \infty$ , voltage gain of a source follower is not equal to one

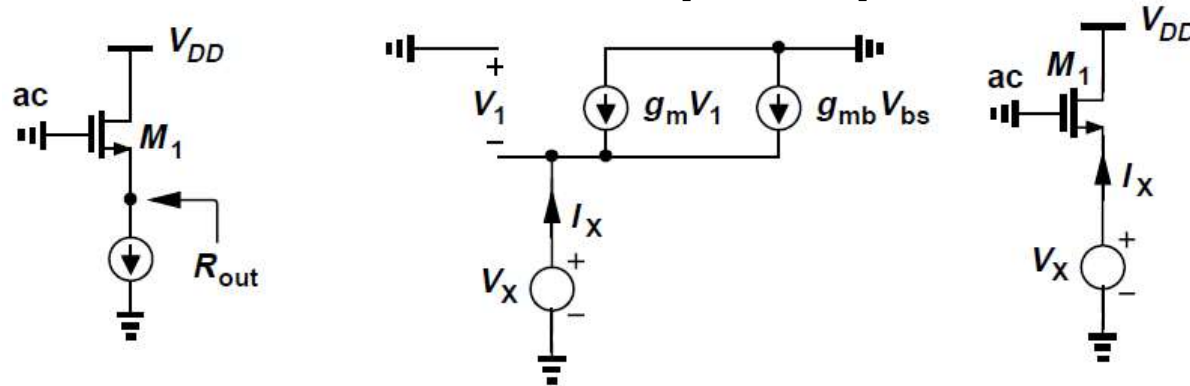
# Source Follower



- Drain current of  $M_1$  depends heavily of input dc level
- Even if  $V_{TH}$  is relatively constant, the increase in  $V_{GS}$  means that  $V_{out}$  ( $=V_{in} - V_{GS}$ ) does not follow  $V_{in}$  faithfully, incurring nonlinearity
- To alleviate this issue, the resistor can be replaced by a constant current source
- Current source is itself is implemented as an NMOS transistor operating in the saturation region

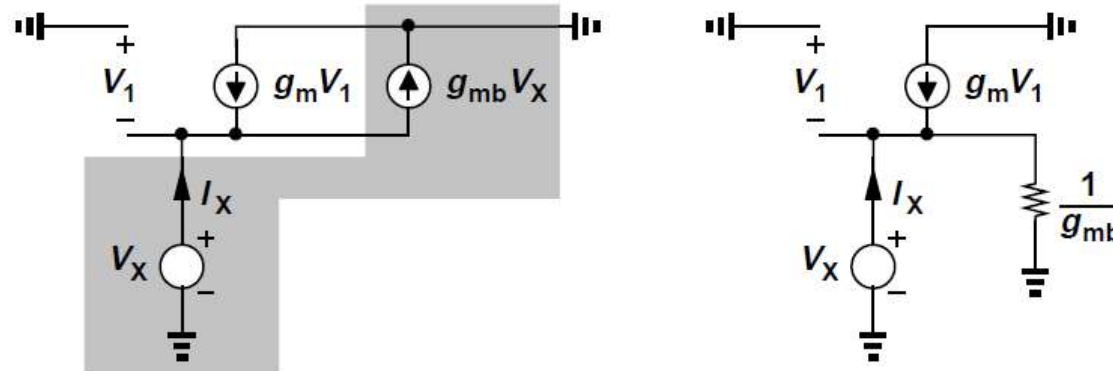
# Source Follower

## Calculation of output impedance



- From small-signal equivalent circuit,  $V_X = -V_{bs}$
- It follows that  $I_X - g_m V_X - g_{mb} V_X = 0$  and  $R_{out} = \frac{1}{g_m + g_{mb}}$
- Body effect decreases output resistance of source followers
- If  $V_X$  decreases by  $\Delta V$  so the drain current increases
  - w/o body effect,  $V_{GS}$  increases by  $\Delta V$
  - with body effect,  $V_{TH}$  decreases as well, thus  $(V_{GS} - V_{TH})^2$  and  $I_{D1}$  increase by a greater amount, hence lower output impedance

# Source Follower



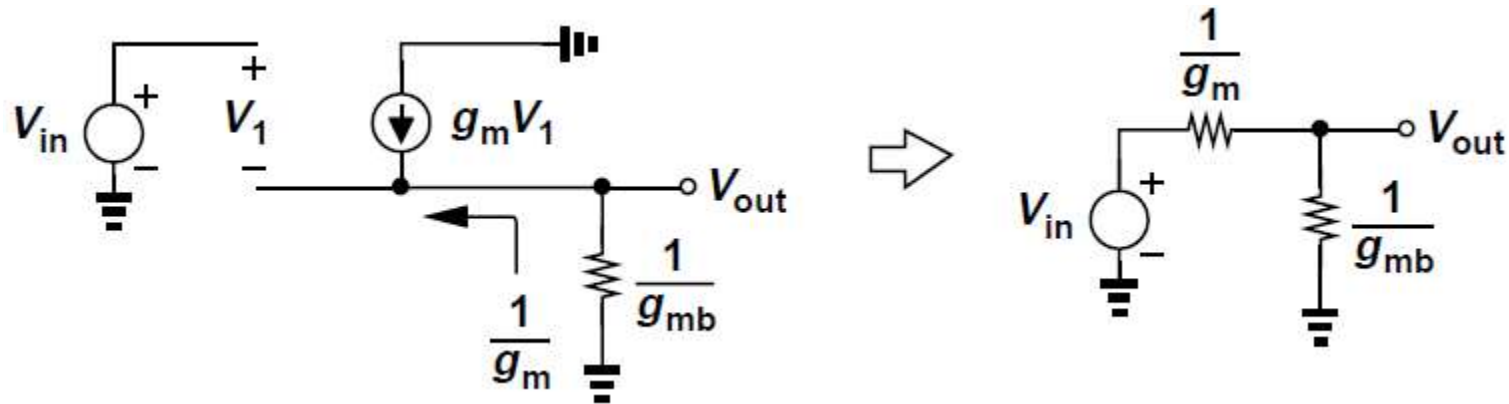
- Magnitude of the current source  $g_{mb} V_{bs} = g_{mb} V_X$  is linearly proportional to the voltage across it, can be modelled by a resistor equal to  $1/g_{mb}$  (valid only for source followers)
- This appears in parallel with the output, decreasing the overall output resistance
- Since without  $1/g_{mb}$ , the output resistance is  $1/g_m$ , we conclude that

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

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



# Source Follower

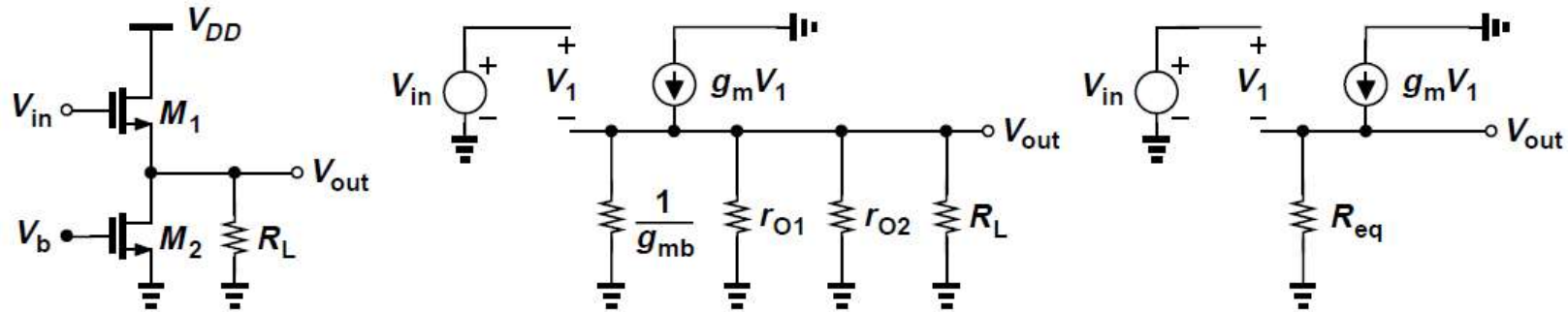


- Modelling effect of  $g_{mb}$  by a resistor helps explain lower than unity gain for  $R_S = \infty$
- From the Thevenin equivalent circuit

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

# Source Follower

- Small-signal equivalent circuit with a finite load resistance and channel-length modulation is shown



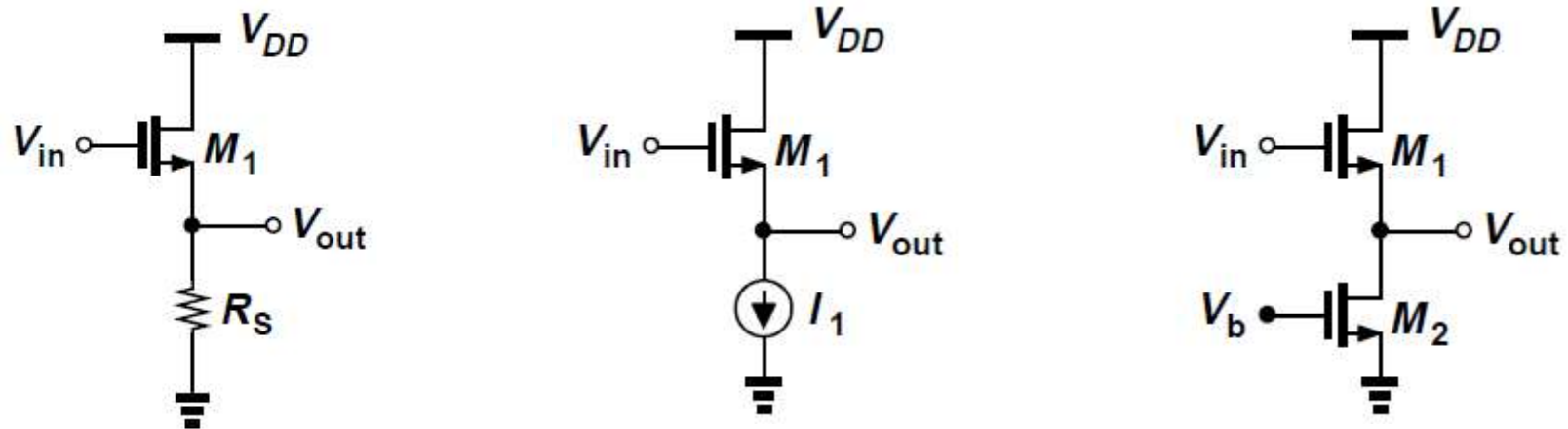
- $1/g_{mb}$ ,  $r_{O1}$ ,  $r_{O2}$  and  $R_L$  are in parallel, therefore,

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

- It follows that

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

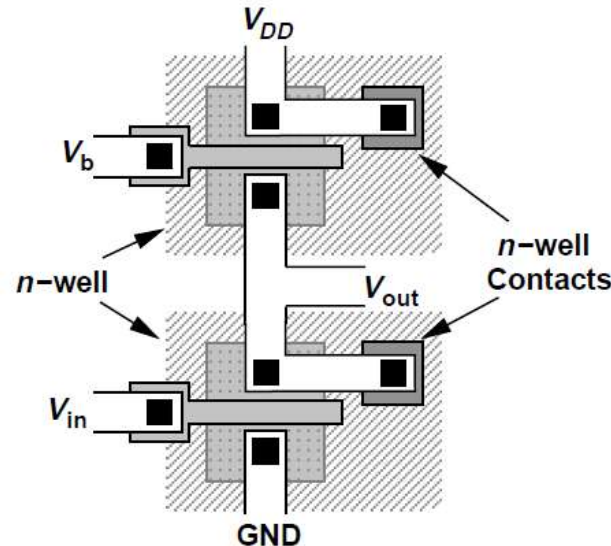
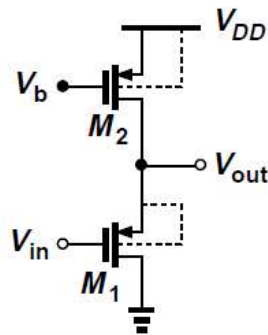
# Issues with Source Follower



- Source followers exhibit high input impedance and moderate output impedance, but at the cost of
  - Nonlinearity
  - Voltage headroom limitation
- Even when biased by ideal current source, there is input-output nonlinearity due to nonlinear dependence of  $V_{TH}$  on the source potential
- In submicron technologies,  $r_o$  changes substantially with  $V_{DS}$  and introduces additional variation in small-signal gain

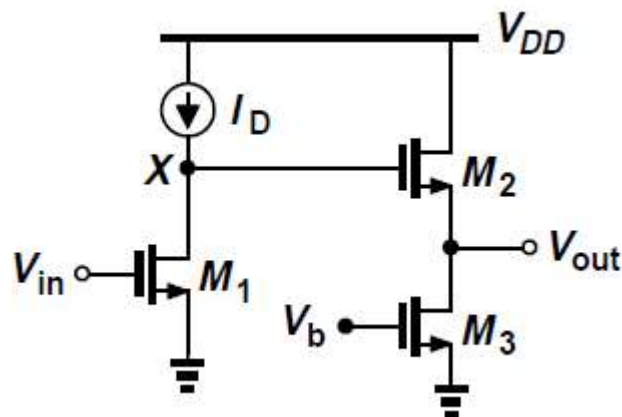
# Issues with Source Follower

- Nonlinearity can be eliminated if the bulk is tied to the source
  - Possible only for PFETs since all NFETs usually share the same substrate
- PMOS source follower employing two separate n-wells can eliminate the body effect of  $M_1$
- Lower mobility of PFETs yields a higher output impedance than that available in the NMOS counterpart



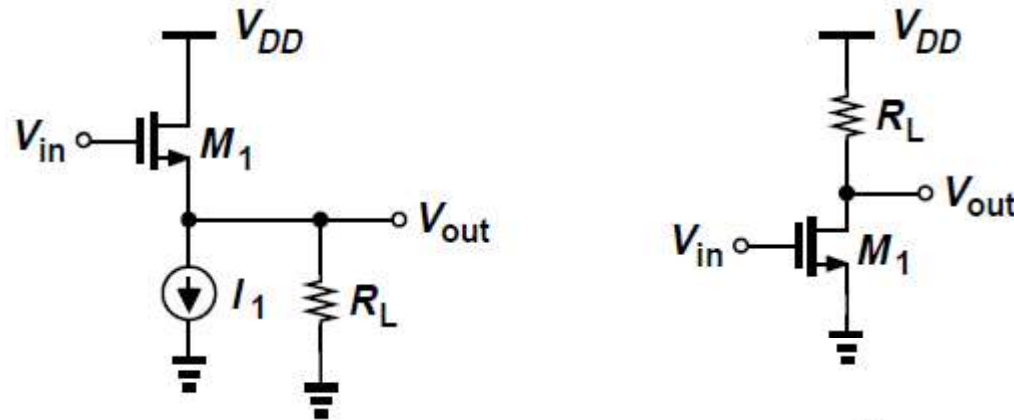
# Issues with Source Follower

- Source followers also shift the dc level of the signal by  $V_{GS}$ , thereby consuming voltage headroom



- In the cascade of CS stage and source follower shown above,
  - w/o source follower, minimum allowable value of  $V_X$  would be  $V_{GS1} - V_{TH1}$  (for  $M_1$  to remain in saturation)
  - with source follower,  $V_X$  must be greater than  $V_{GS2} + (V_{GS3} - V_{TH3})$  so that  $M_3$  is saturated
- For comparable overdrive voltages in  $M_1$  and  $M_3$ , allowable swing at X is reduced by  $V_{GS2}$

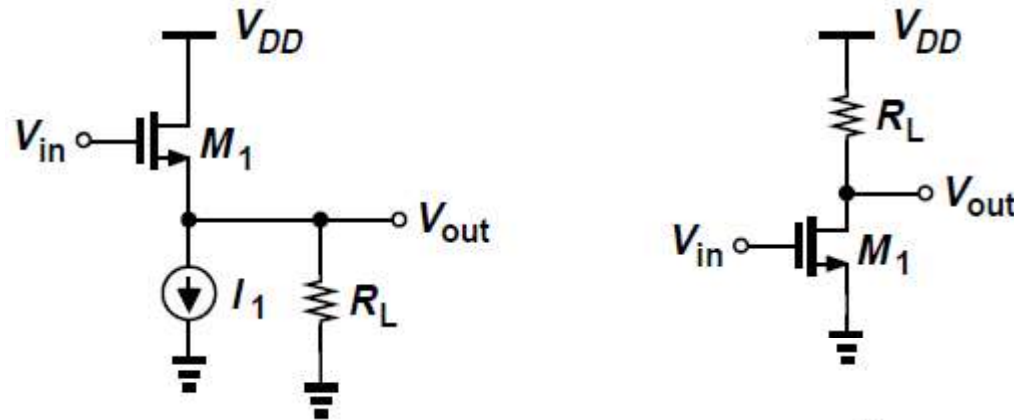
# Comparison of CS stage and Source Follower



- Comparing the gain of source followers and CS stage with a low load impedance
  - E.g., driving an external 50-Ω termination in a high-frequency environment
- When load is driven by a source follower, overall voltage gain is

$$\begin{aligned} \frac{V_{out}}{V_{in}}|_{SF} &\approx \frac{R_L}{R_L + 1/g_{m1}} \\ &\approx \frac{g_{m1}R_L}{1 + g_{m1}R_L} \end{aligned}$$

# Comparison of CS stage and Source Follower



- Load can be included as part of a common-source stage, providing a gain of

$$\frac{V_{out}}{V_{in}}|_{CS} \approx -g_{m1}R_L$$

- Key difference between the two topologies is the achievable voltage gain for a given bias current
- For example, if  $1/g_{m1} \approx R_L$ , source follower exhibits a gain of at most 0.5 whereas the common-source stage provides a gain close to unity
- Thus, source followers are not efficient drivers