EE 332: Devices and Circuits II

Lecture 3: Single-stage Amplifiers (Part 2)

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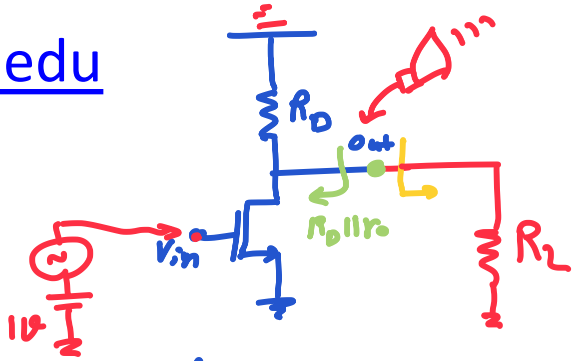

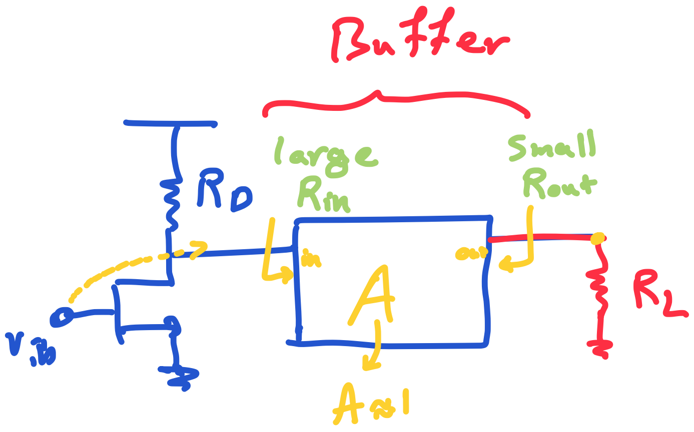

$$\frac{V_{out}}{V_{in}} = -g_m (r_o || R_D) \rightarrow R_D || R_L$$

Output open

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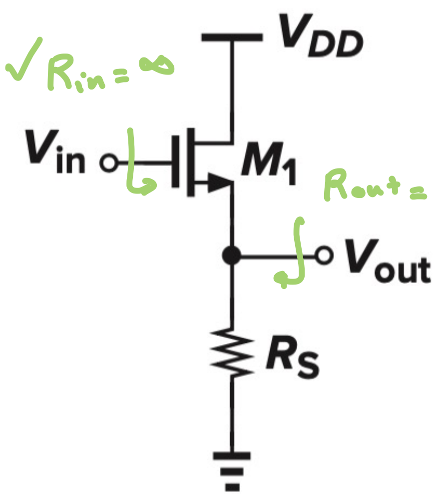
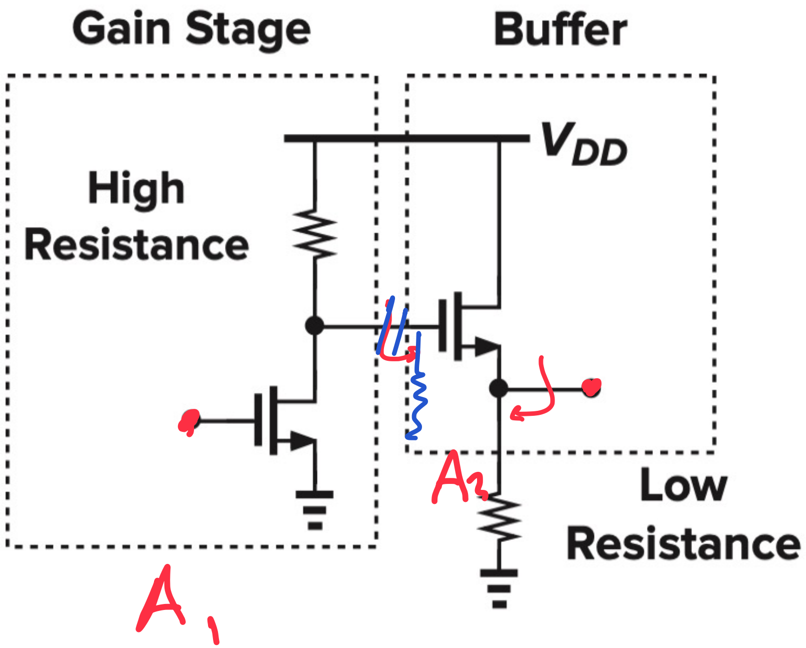
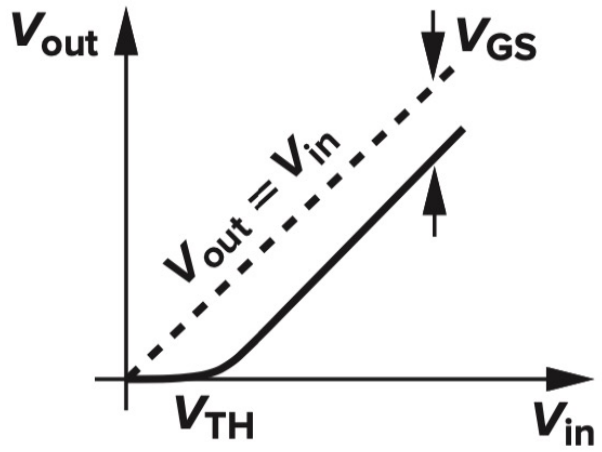
Source Follower

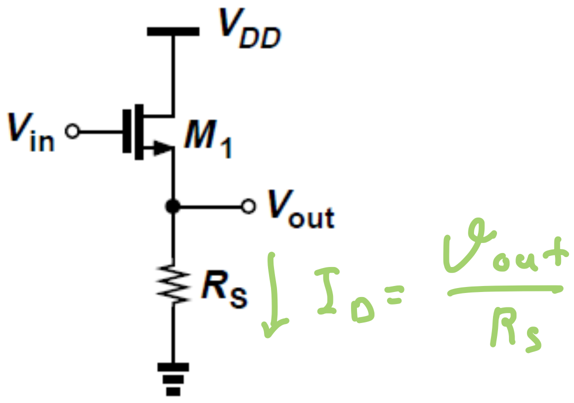
- Source follower (also called “common-drain” stage) senses the input at the gate and drives load at the source
- It presents a high input impedance, allowing source potential to “follow” the gate voltage
- Acts as a voltage buffer

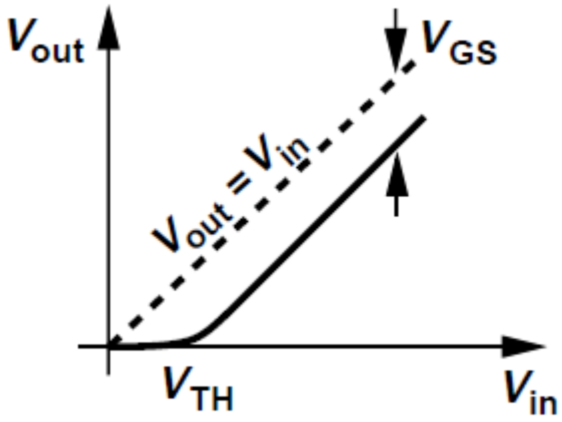






Source Follower



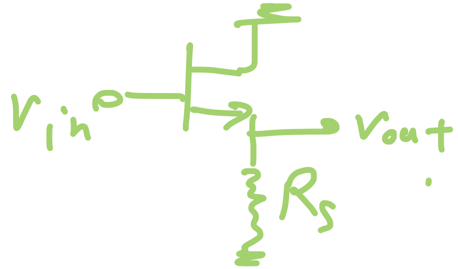


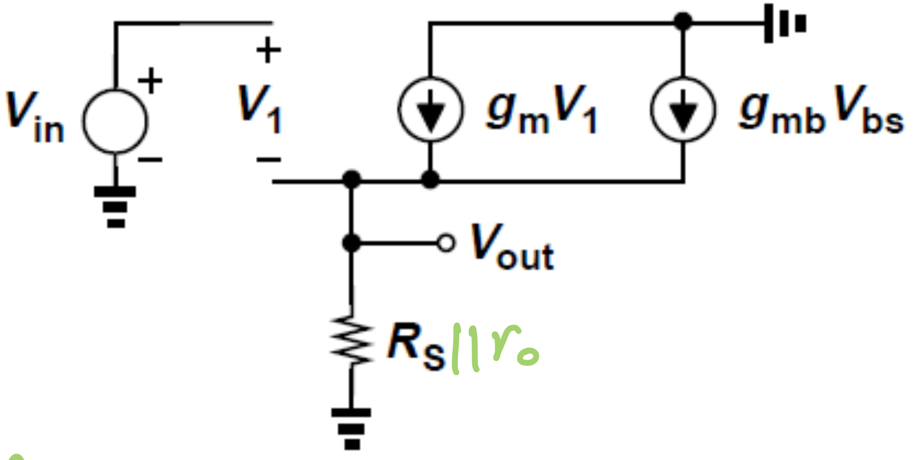
- For $V_{in} < V_{TH}$, M_1 is off and $V_{out} = 0$
- As V_{in} exceeds V_{TH}, M_1 turns on in saturation since $V_{DS} = V_{DD}$ and $V_{GS} - V_{TH} \approx 0$ and I_{D1} flows through R_S
- As V_{in} increases further, V_{out} follows the input with a difference (level shift) equal to V_{GS}
-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

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

Source Follower

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





- We have,
  - KVL: $V_{in} - V_1 = V_{out}, V_{bs} = -V_{out}$
  - KCL: $g_m V_1 - g_{mb} V_{out} = V_{out}/R_S$

$\rightarrow \frac{V_{out}}{V_{in}} = A_v = \ldots$

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

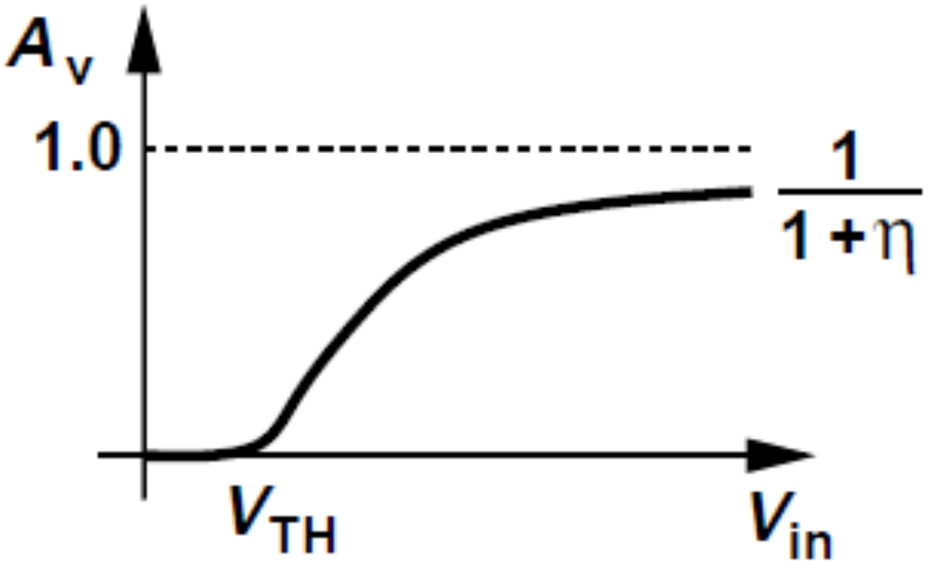
$A_v > 0$

$A_v < 1$

Source Follower

large

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



$g_{mb} = \eta g_m$

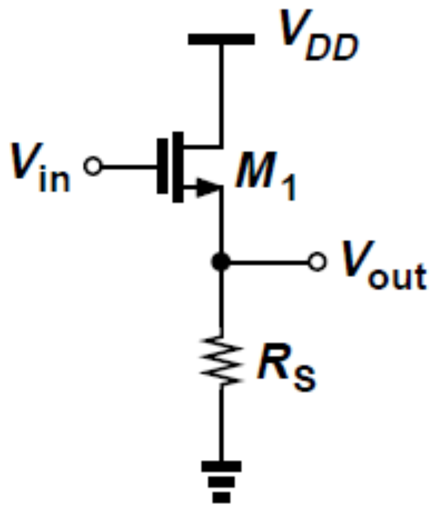
- Voltage gain begins from zero for $V_{in} \approx V_{TH}$ ($g_m \approx 0$), and monotonically increases
- As drain current and g_m increase, A_v approaches

$$g_m/(g_m+g_{mb}) = 1/(1+\eta)$$

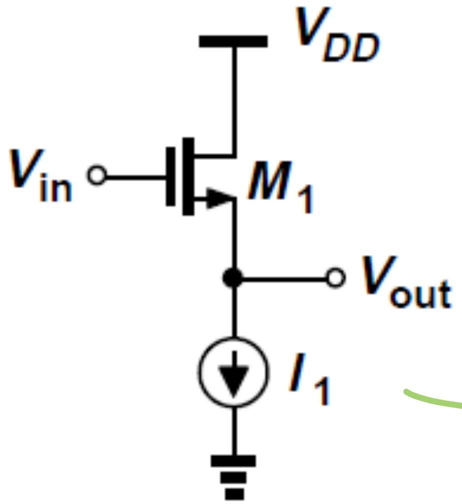
- Even if $R_S = \infty$, voltage gain of a source follower is not equal to one

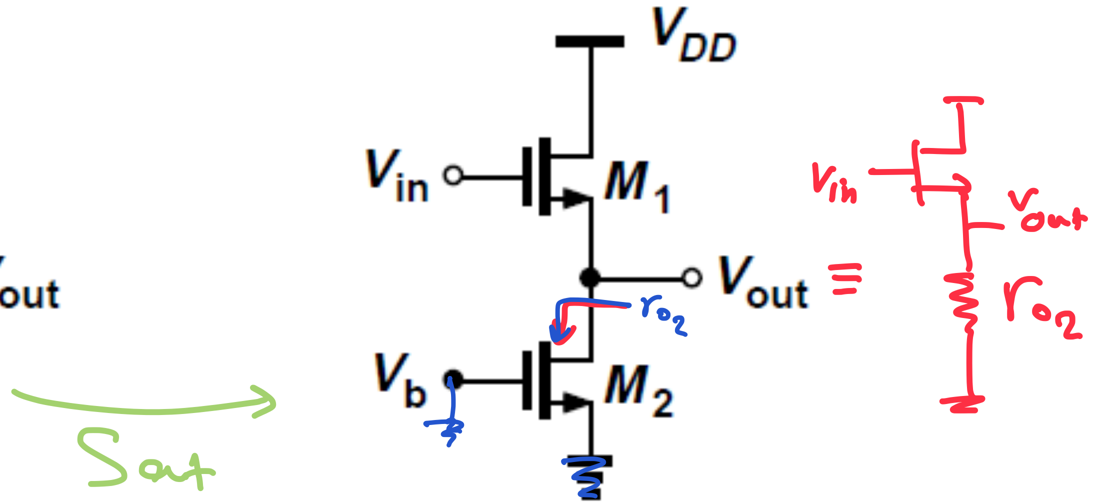
Source Follower

$$A_v = \frac{g_m r_{o2}}{1 + g_m r_{o2}}$$



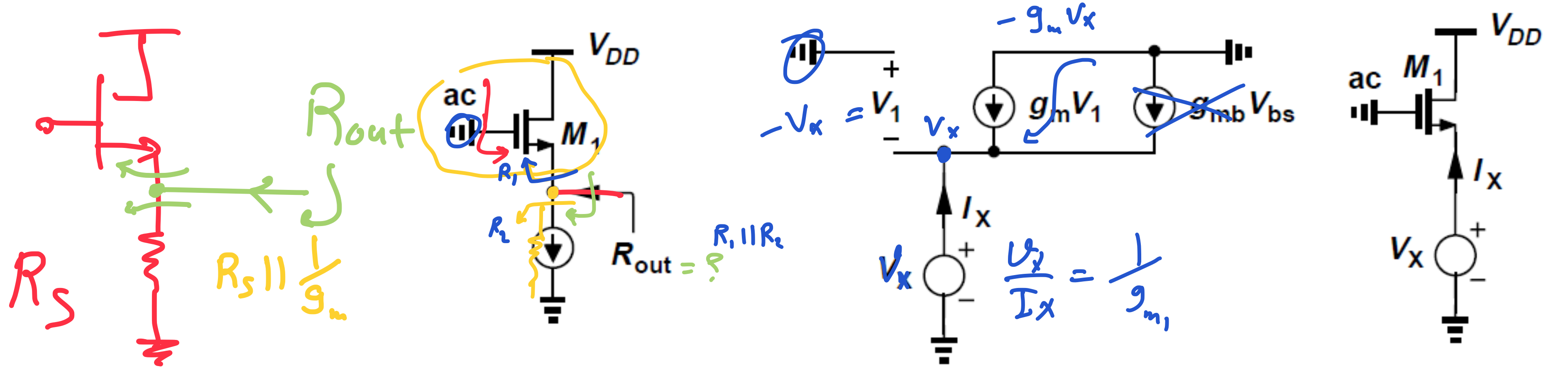
$$\frac{1}{2}\mu_n C_{ox}\frac{W}{L}(V_{in} - V_{TH} - V_{out})^2 R_S = V_{out}$$





- 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 itself is implemented as an NMOS transistor operating in the saturation region

Source Follower: output impedance



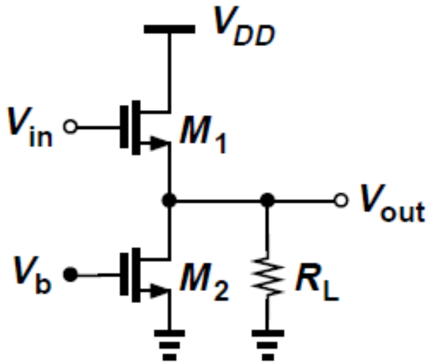
- From small-signal equivalent circuit,
- It follows that $I_X - g_m V_X - g_{mb} V_X = 0$ and $V_X = -V_{bs}$

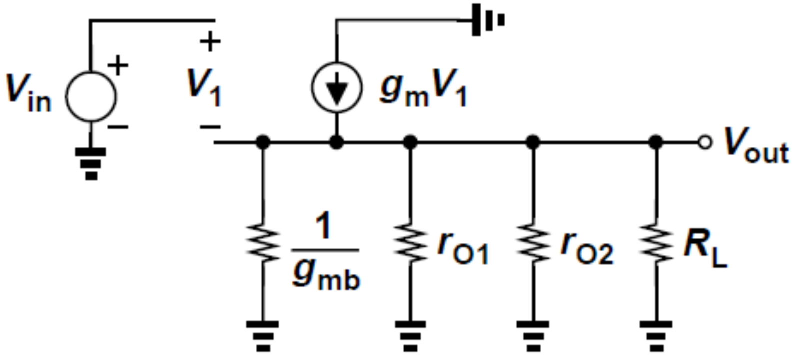
$$\boxed{R_{out} = \frac{1}{g_m + \cancel{g_{mb}}}}$$

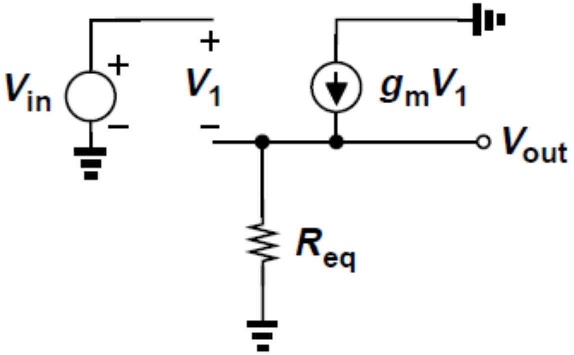
- Body effect decreases output resistance of source followers
- If V_X decreases by ΔV so the drain current increases
  - w/o body effect, V_{GS} increases by ΔV
  - with body effect, V_{TH} decreases as well, thus $(V_{GS}-V_{TH})^2$ and I_{D1} increase by a greater amount, hence lower output impedance

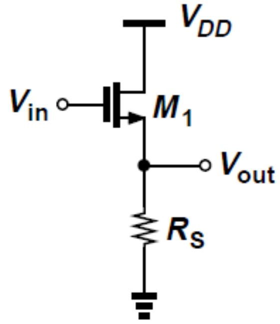
Source Follower

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





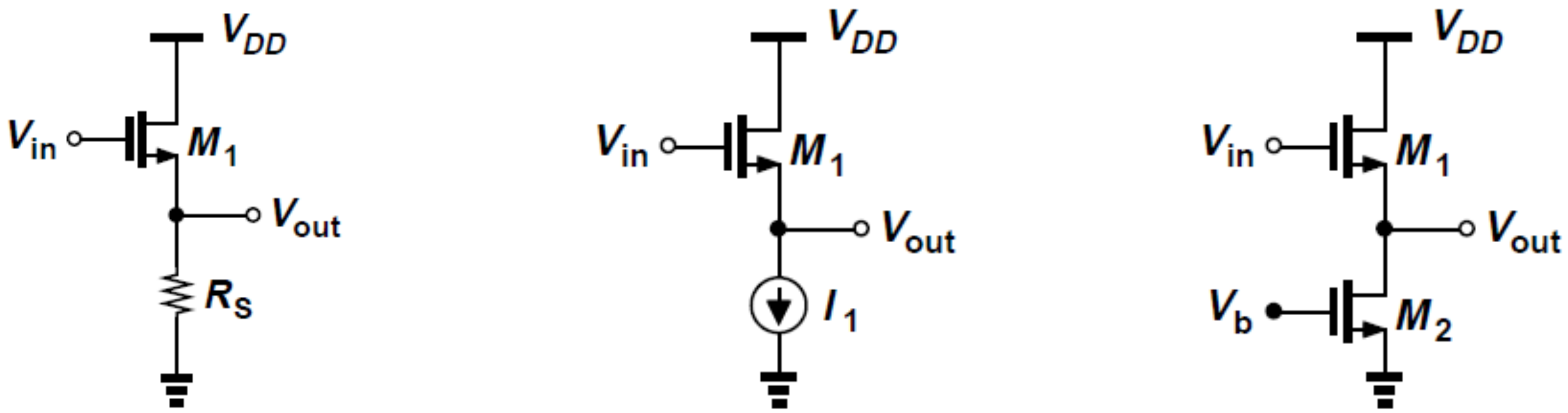




- Recall that gain for R_s was $$A_v = \frac{g_m R_S}{1 + (g_m + g_{mb}) R_S}$$

- Gain = ?

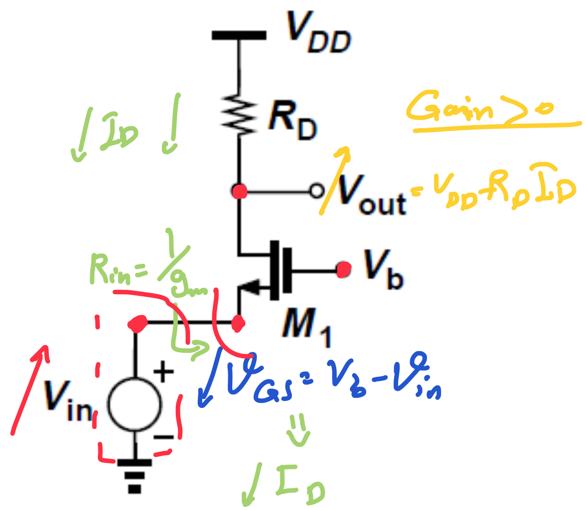
Issues with Source Follower

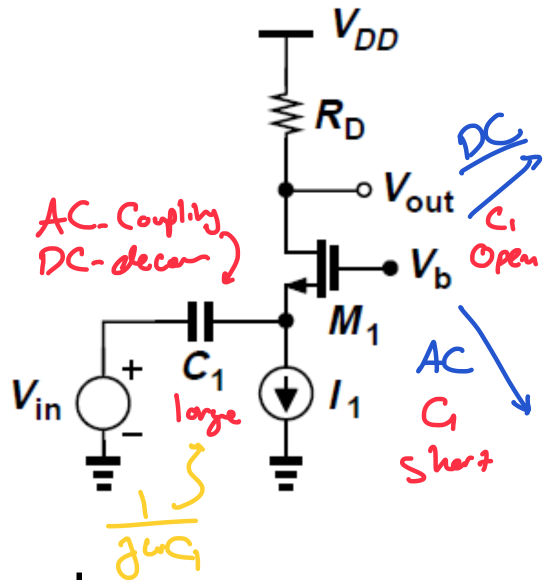


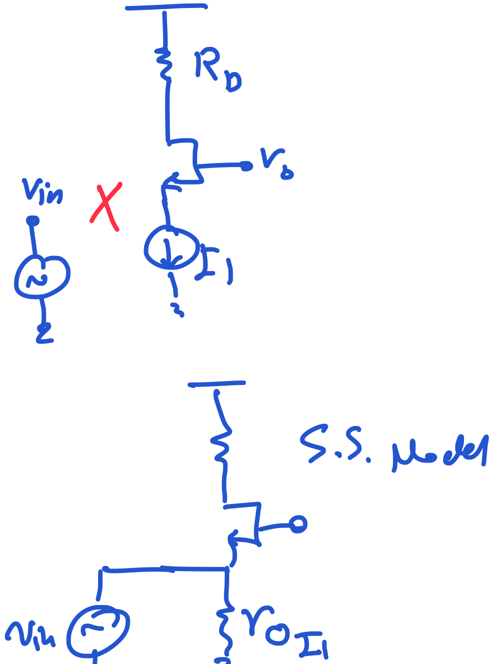
- Source followers exhibit high input impedance and moderate output impedance, but at the cost of
  - Nonlinearity
  - Voltage headroom limitation → $V_{sw,pp}$ small!
- Even when biased by ideal current source, there is input-output nonlinearity due to nonlinear dependence of V_{TH} on the source potential

Common-Gate Stage

- A common-gate (CG) stage senses the input at the source and produces the output at the drain
- Gate is biased to establish proper operating conditions

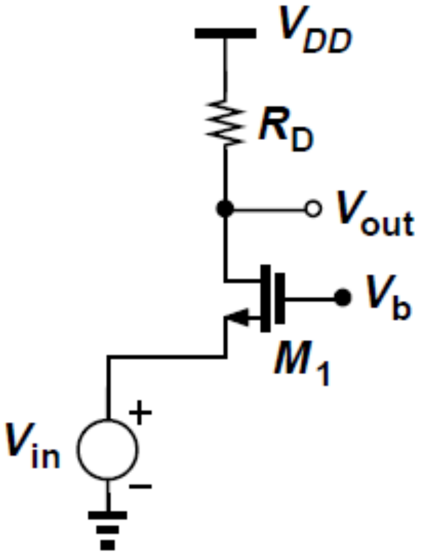






- Bias current of M_1 flows through the input signal source
- Alternatively, M_1 can be biased by a constant current source, with the signal capacitively coupled to the circuit

Common-Gate Stage: Large-signal behavior



- Assume V_{in} decreases from a large positive value and that $\lambda=0$
- For $V_{in} \geq V_b - V_{TH}$, M_1 is off and $V_{out} = V_{DD}$
- For lower values of V_{in}, if M_1 is in saturation,

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

- As V_{in} decreases further, so does V_{out} driving M_1 into the triode region if

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

- In the region where M_1 is saturated, we can express the output voltage as

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

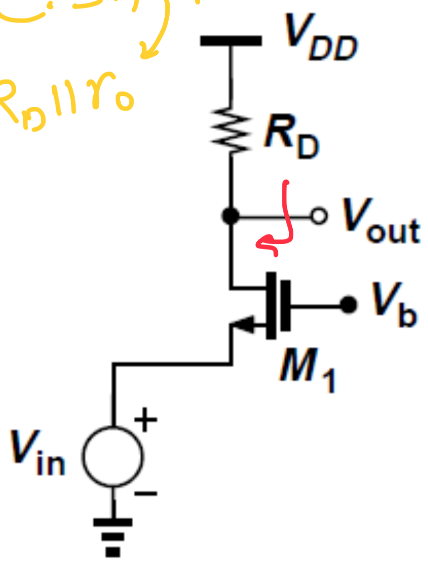
Common-Gate Stage: Input-output characteristic

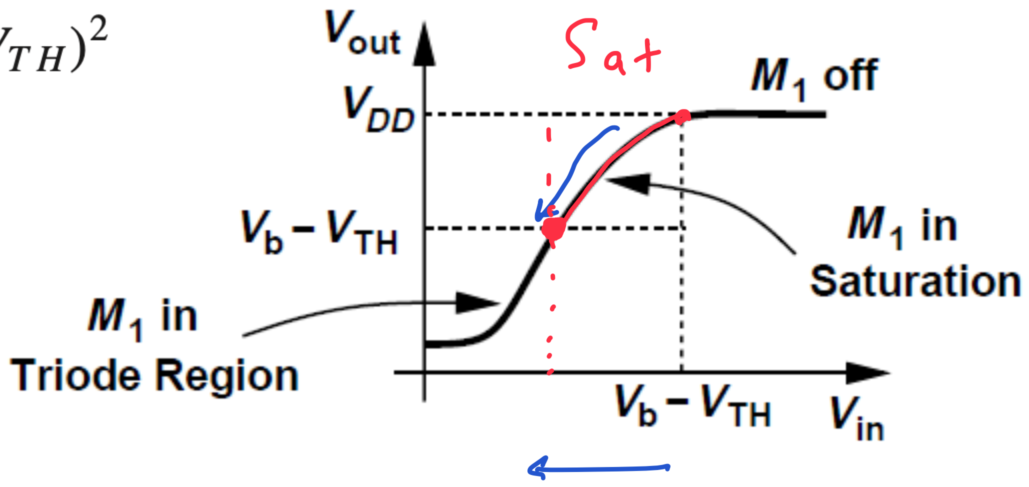
- For M_1 in saturation, $I_D = \frac{1}{2}\mu_n C_{ox}\frac{W}{L}(V_b - V_{in} - V_{TH})^2$
  - V_{out} = ?
- Small-signal gain: $g_m(1+\eta)R_D$

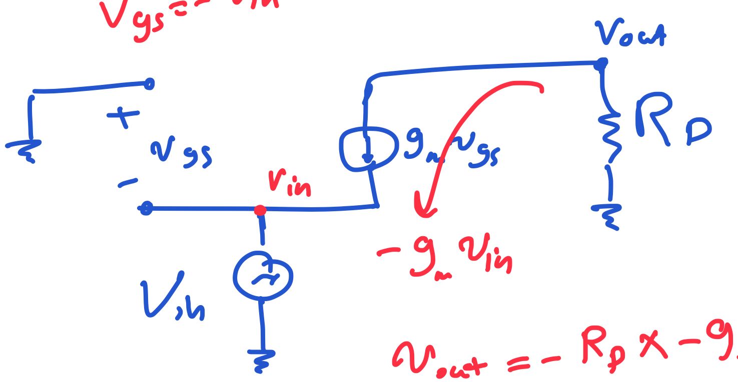
body effect.

Similar to C.S. Amp

$R_{out} = R_D \| r_o$

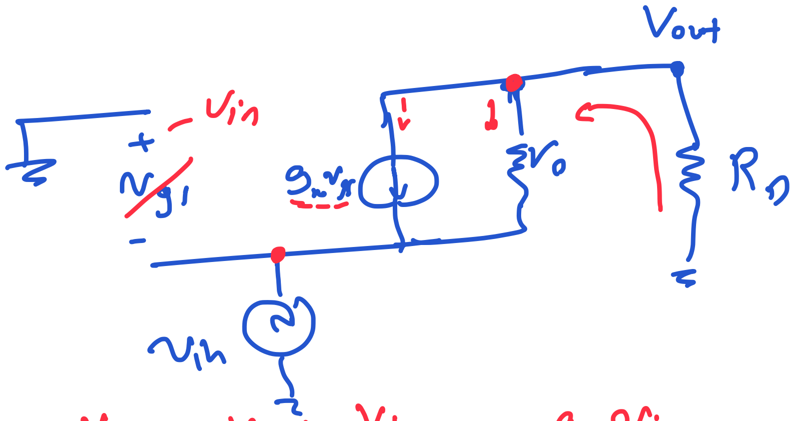






$v_{out} = -R_D \times -g_m v_{in}$

$\Rightarrow \boxed{A_v = g_m R_D}$



$\frac{-V_{out}}{R_D} = \frac{V_{out} - V_{in}}{r_o} + -g_m V_{in}$

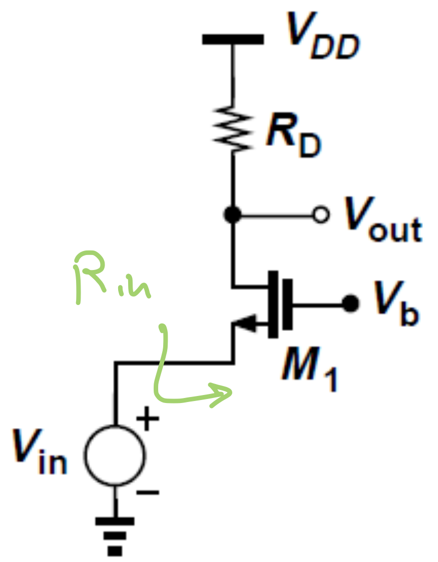
$\Rightarrow V_{out}/V_{in} = \ldots$

Common-Gate Stage

- Gain of the common-gate (CG) stage is positive
- Body effect increases the effective transconductance of the stage
- The minimum allowable value of V_{out} is V_b-V_{TH}
    - Min of V_b = ? $V_{in,DC} + V_{th}$

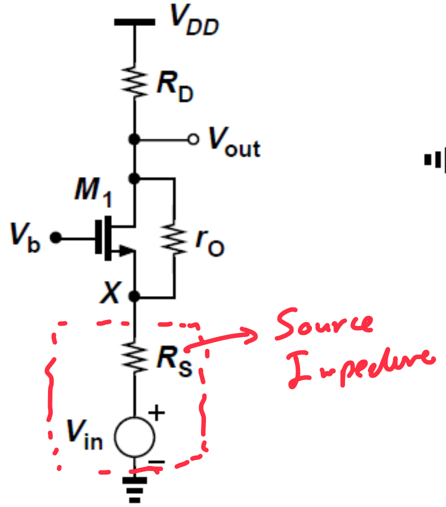
$V_{out,min} = V_b - V_{th}$

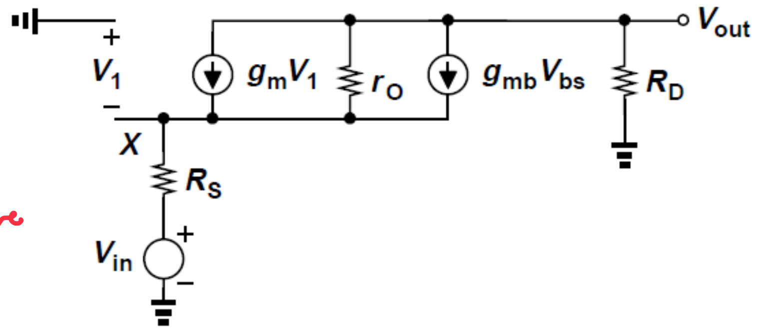
$V_{out,Max} = V_{DD}$



Common-Gate Stage (with r_o & R_s)

- Consider output impedance of transistor (r_o) and impedance of the signal source (R_s):





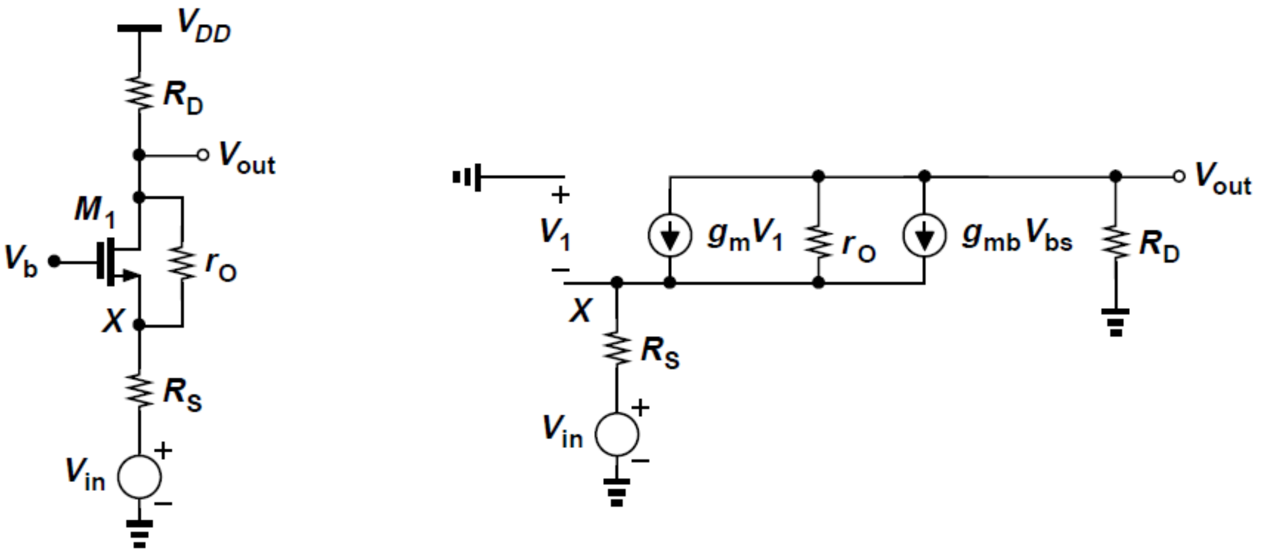
- In small-signal equivalent circuit, since current flowing R_S is $-V_{out}/R_D$,

$$V_1 - \frac{V_{out}}{R_D} R_S + V_{in} = 0 \qquad (1)$$

- Moreover, since current through r_O is $-V_{out}/R_D - g_m V_1 - g_{mb} V_1$

$$r_O \left(\frac{-V_{out}}{R_D} - g_m V_1 - g_{mb} V_1 \right) - \frac{V_{out}}{R_D} R_S + V_{in} = V_{out} \qquad (2)$$

Common-Gate Stage



- Substituting V_1 from (1) in (2),

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

- Therefore,

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

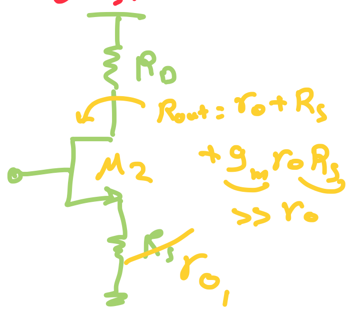
- The voltage gain expression is similar to that of a degenerated CS stage

Cascode Stage

G_m $\underbrace{R_{out}}_{\sim (g_{m2} r_{o2}) r_{o1}}$

g_{m1}

Cascode gain boost

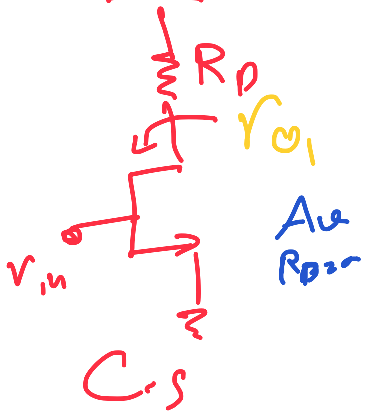


$R_{out} \approx g_{m2} r_{o2} r_{o1}$

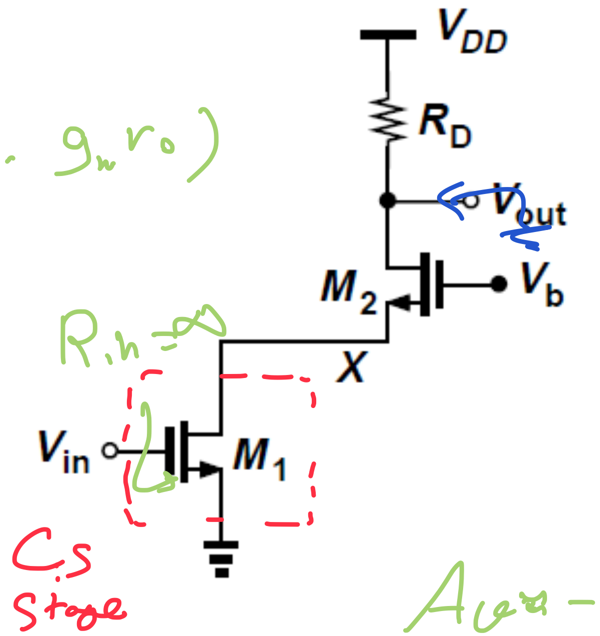
- The cascade of a CS stage and a CG stage is called a cascode topology

× lower V_{sw}

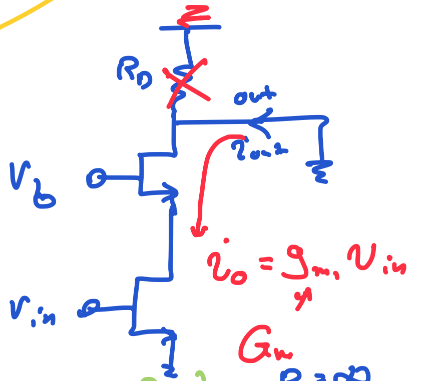
✓ larger gain $((g_m r_o)^2$ vs. $g_m r_o)$



$A_v \xrightarrow{R_D \to \infty} g_m r_o$



C.G Stage



$i_o = g_{m1} v_{in}$

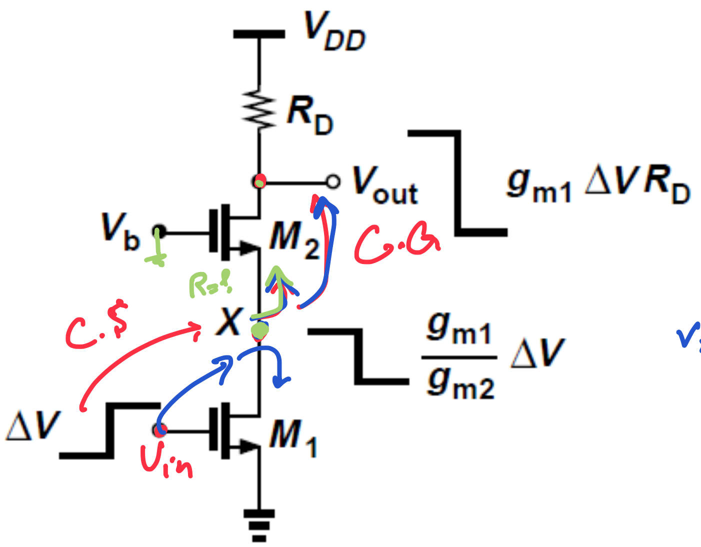
G_m

$A_v \approx -g_{m1} \times (g_{m2} r_{o2} r_{o1} \| R_D) \xrightarrow{R_D \to \infty} A_v \sim (g_m r_o)^2$

- M_1 generates a small-signal drain current proportional to the small-signal input V_{in} and M_2 simply routes the current to R_D
- M_1 is called the input device and M_2 the cascode device
- M_1 and M_2 in this example carry equal bias and signal currents

Cascode Stage: Qualitative Analysis

- Assume both transistors are in saturation and $\lambda = \gamma = 0$
- If V_{in} rises by ΔV, then I_{D1} increases by $g_{m1}\Delta V$
  - This change in current flows through the impedance seen at X, i.e., the impedance seen at the source of M_2, which is equal to $1/g_{m2}$
  - Thus, V_X falls by an amount given by $g_{m1}\Delta V\cdot(1/g_{m2})$
  - This change in I_{D1} also flows through R_D, producing a drop of $g_{m1}\Delta V R_D$ in V_{out}, just as in a simple CS stage



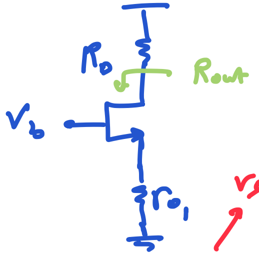
$$A_v = \frac{v_{out}}{v_{in}} = \frac{v_{out}}{V_x} \times \frac{V_x}{V_{in}}$$

C.G gain

C.S gain

$-g_{m1}\left(r_{o1} \| \frac{1}{g_{m2}}\right)$

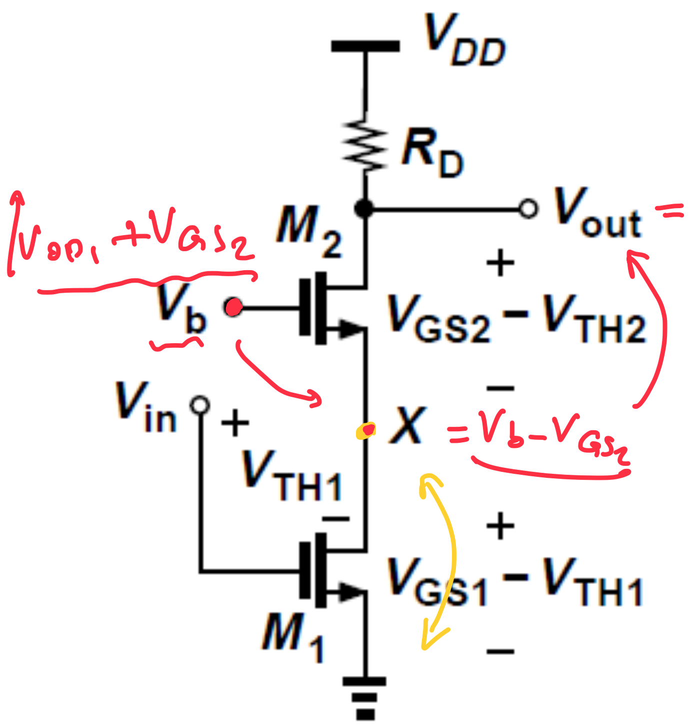
$\approx -\frac{\cancel{g_{m1}}}{\cancel{g_{m2}}}$



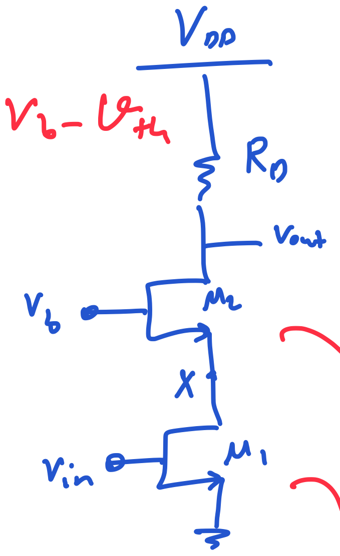
$\cancel{r_{o1}+r_{o2}}+g_m r_{o1} r_{o2}$

$\cancel{g_{m2}} \times (R_{out} \| R_D)$

Cascode Stage: Bias Conditions



- For M_1 & M_2 to operate in saturation, we must have ?



$V_{out,max} = V_{DD}$

$V_{out,min} = V_b - V_{th}$

$V_{b,min} = V_X + V_{th}$

$V_{X,min} = V_{in} - V_{th} = V_{OD1}$

for min V_b

$V_{out,min} = V_{OD1} + V_{OD2}$

$$\begin{cases} V_b - \cancel{V_X} - V_{th} < V_{out} - \cancel{V_X} \\ V_b > V_X + V_{th} \end{cases}$$

$$\begin{cases} V_{in} - V_{th} < V_X \\ V_{in} > V_{th} \end{cases}$$

- Minimum output level for which both transistors are in saturation is equal to the sum of overdrives of M_1 and M_2
- Addition of M_2 to the circuit reduces the output voltage swing by at least its overdrive voltage (compared with a basic CS amplifier)

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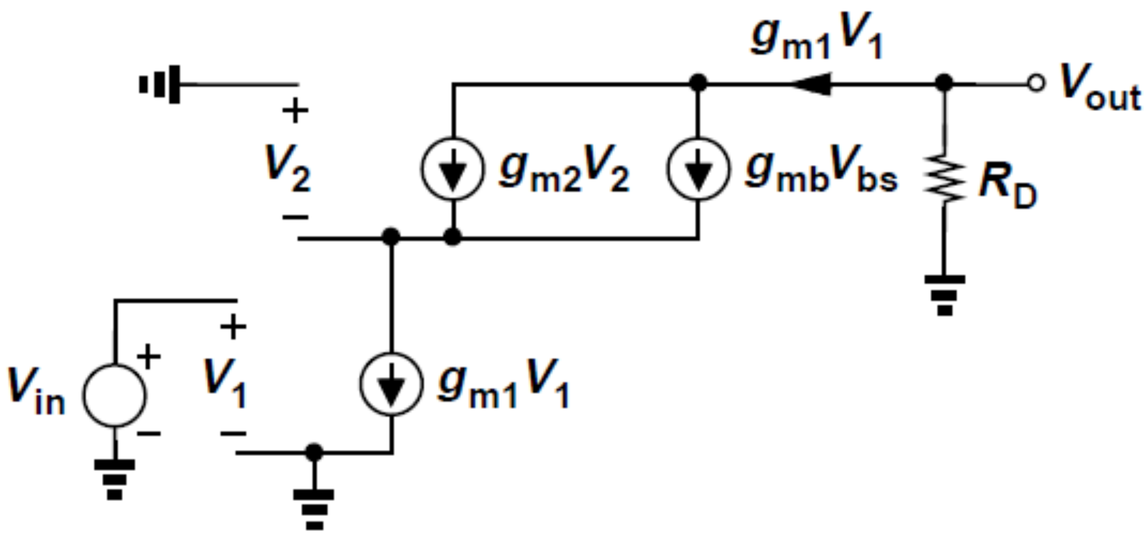
Cascode Stage: Small-signal characteristics

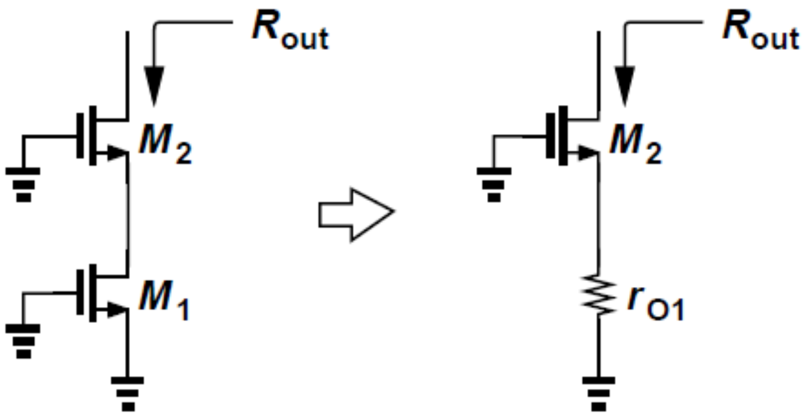


- Assume both transistors operate in saturation and λ=0
- Voltage gain is equal to that of a common-source stage because the drain current produced by the input device must flow through the cascode device (M_2): (G_m=g_{m1})
- This result is independent of the transconductance and body effect of M_2
- Can be verified using $A_v = -G_m R_{out}$

ELECTRICAL & COMPUTER ENGINEERING

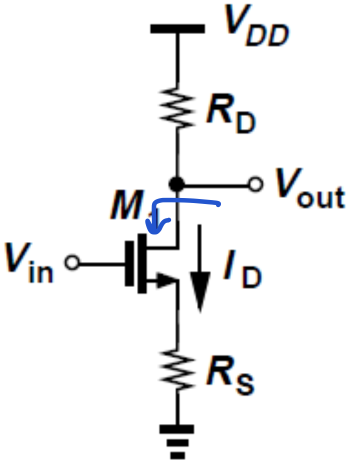
Cascode Stage: Output Impedance

- Important property of the cascode structure is its high output impedance



$$R_{out} = [1 + (g_m + \cancel{g_{mb}})R_S]r_O + R_S$$
$$= \underline{[1 + (g_m + \cancel{g_{mb}})r_O]R_S + r_O}$$
$$= r_{o2} + g_{m2} r_{o2} R_S + R_S$$

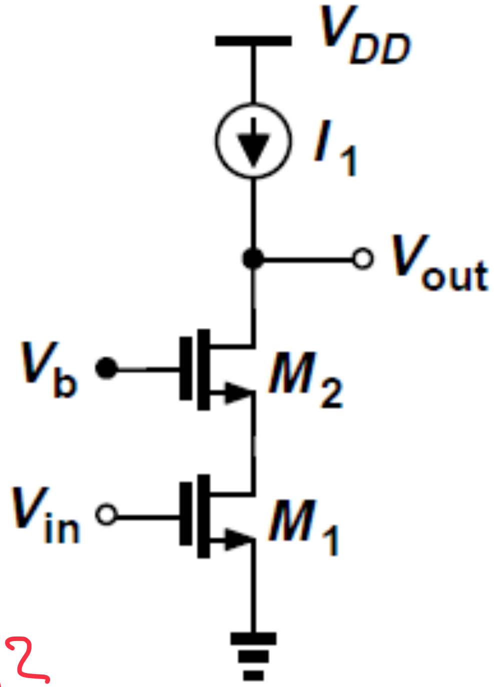
in here if $R_S = r_{o1}$



- For calculation of R_{out}, the circuit can be viewed as a common-source stage with a degeneration resistor equal to r_{O1}
- Thus, $R_{out} = [1 + (g_{m2} + g_{mb2})r_{O2}]r_{O1} + r_{O2}$
- Assuming $g_m r_O$>>1, we have $R_{out} \approx (g_{m2} + g_{mb2})r_{O2}r_{O1}$
- M2 boosts the output impedance of M1 by a factor of $(g_{m2}+g_{mb2})r_{O2}$

Cascode stage with current source load

- Voltage gain can be maximized by maximizing G_m and/or R_{out}
- Since G_m is typically determined by the transconductance of a transistor and has trade-offs with the bias current and device capacitances, it is desirable to increase voltage gain by maximizing R_{out}



- If both M_1 and M_2 operate in saturation, $G_m \approx g_{m1}$ and yielding

$$R_{out} \approx (g_{m2} + g_{mb2}) r_{O2} r_{O1}$$

- Maximum gain is roughly equal to the square of the intrinsic gain of the transistors

$$\underline{A_v = (g_{m2} + g_{mb2}) r_{O2} g_{m1} r_{O1}} \approx (g_m r_o)^2$$

ELECTRICAL & COMPUTER ENGINEERING

Summary of Amplifier Designs