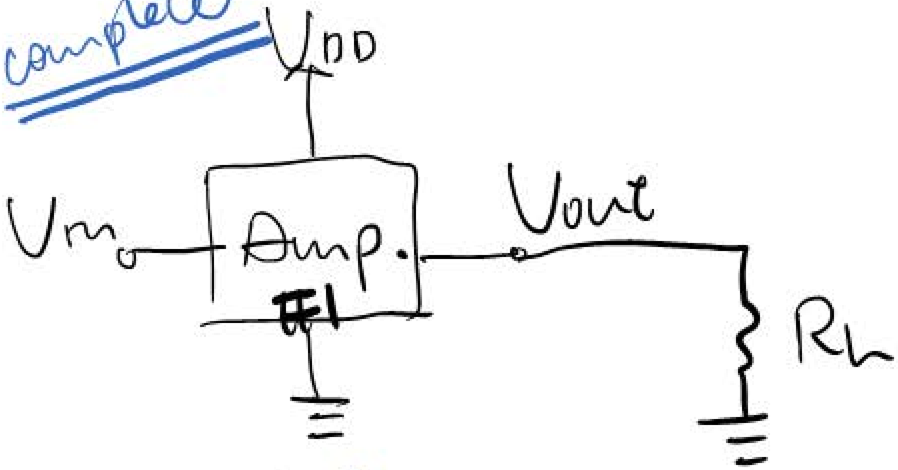
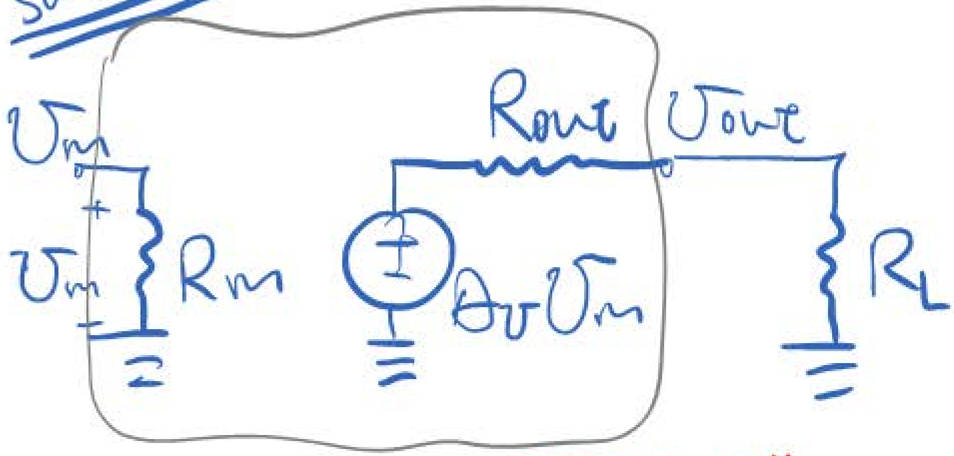
Common-Drain

Source Follower (Buffer)

complete



small-signal

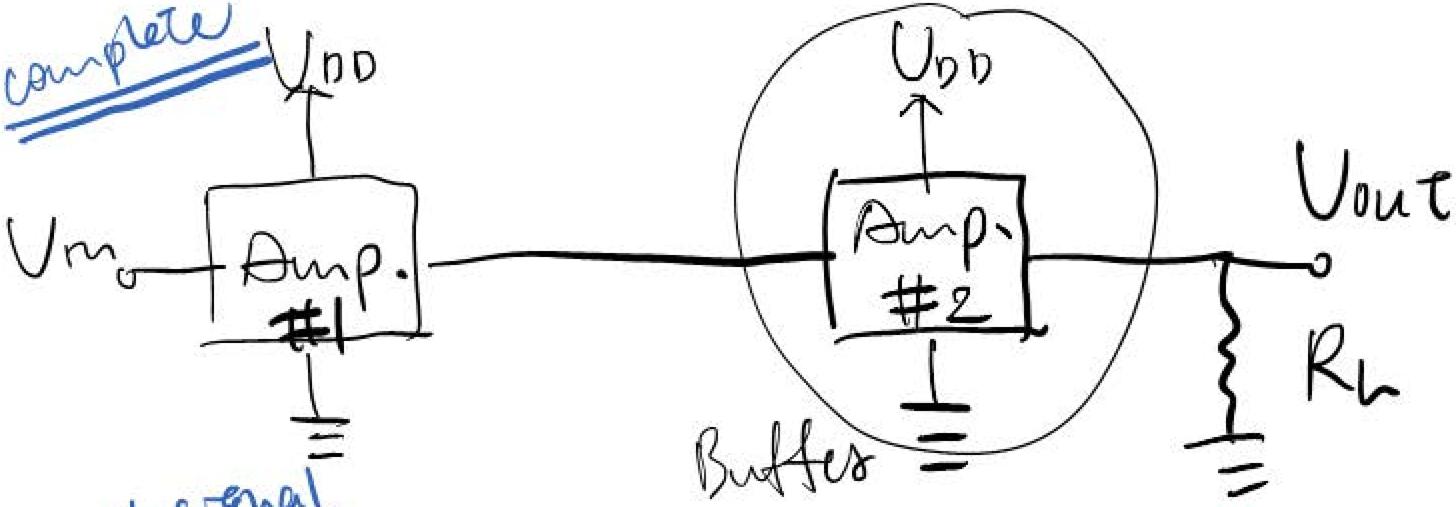


small

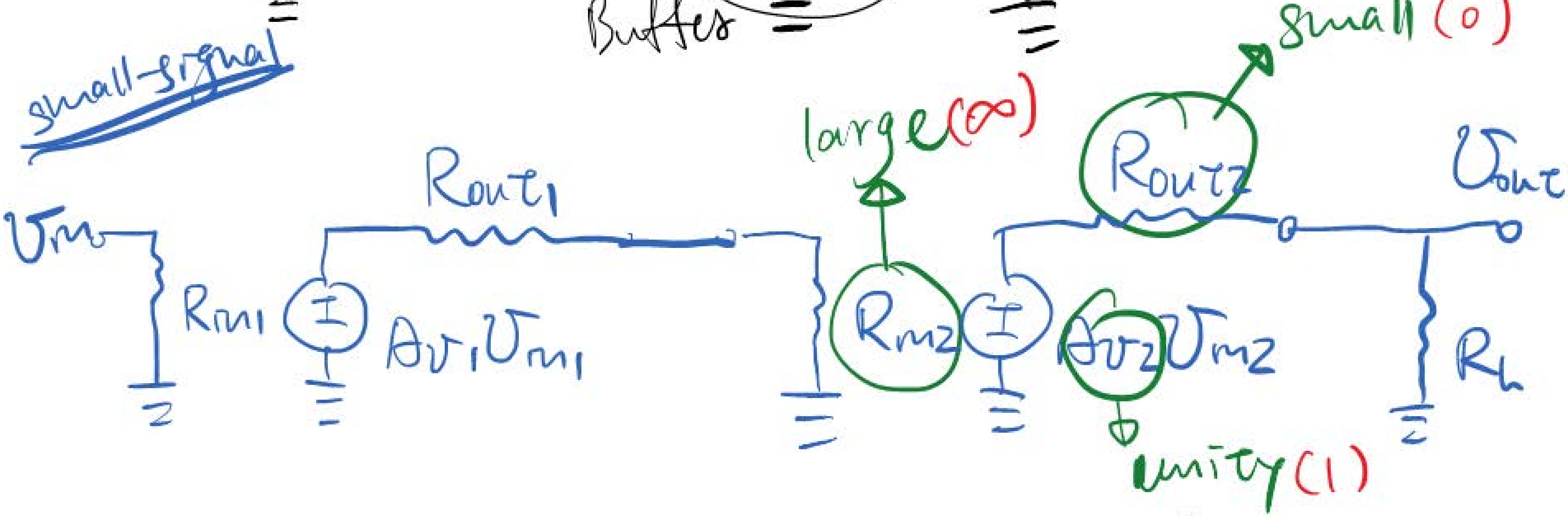
$$\frac{V_{out}}{V_{in}} = A_v \cdot \frac{R_L}{R_{out}+R_L} \Rightarrow A_v \text{ consumed by the factor } \frac{R_L}{R_{out}+R_L}$$

large

complete

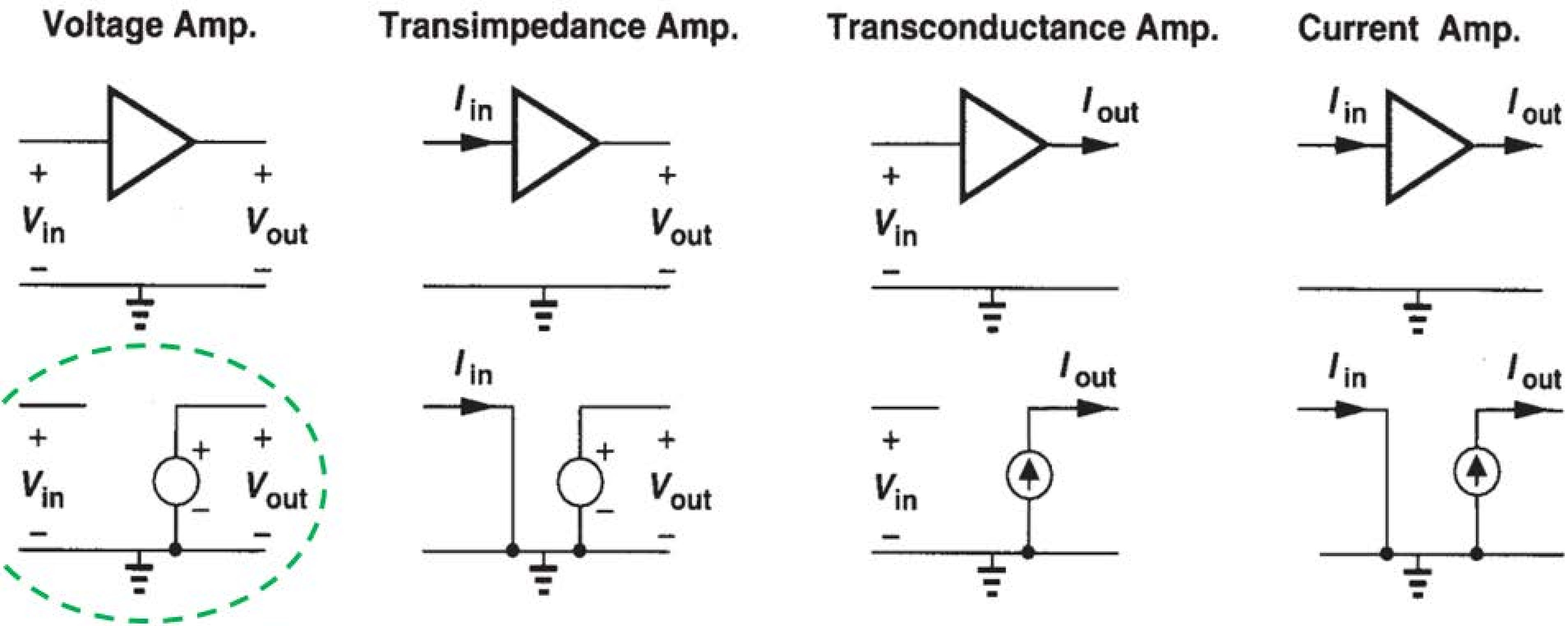


small-signal



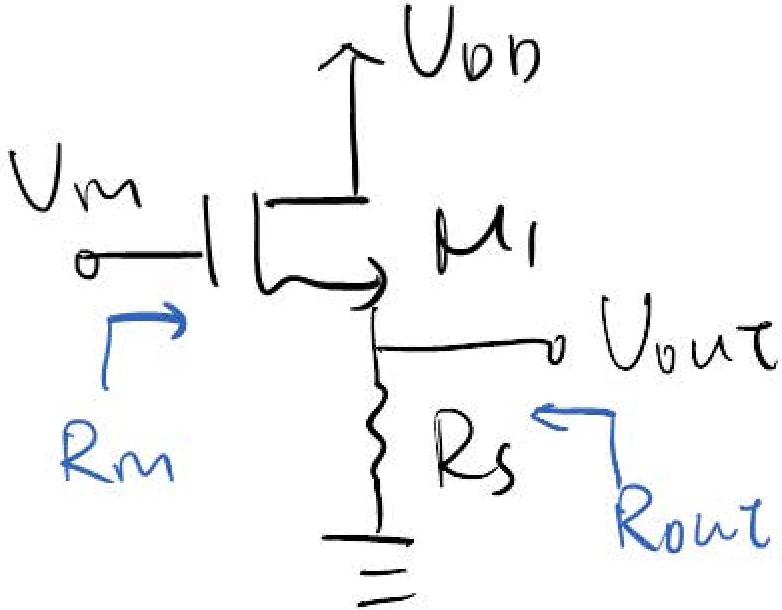
$$\frac{V_{out}}{V_{in}} = A_{v1}\frac{R_{in2}}{\underbrace{R_{out1}}_{\text{large}}+R_{in2}}\,A_{v2}\frac{\overbrace{R_L}^{\text{small}}}{R_{out2}+R_L}$$

Ideal Amplifier



CS + Source Follower

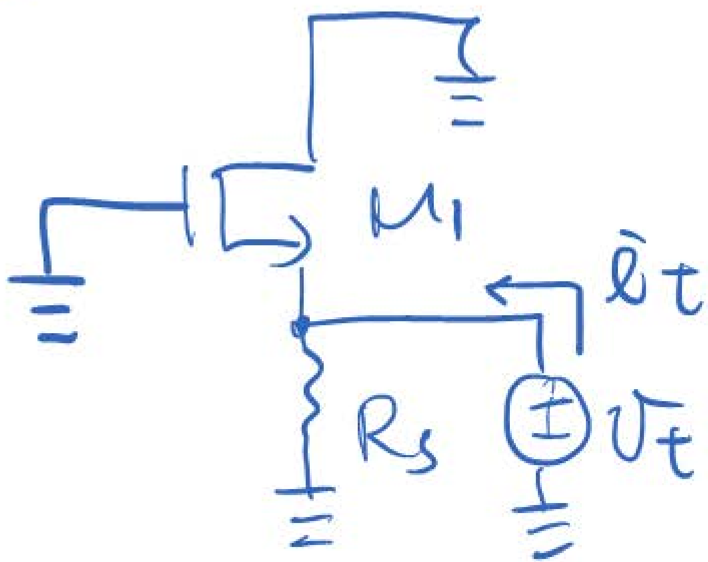
- For driving a low impedance load, source follower, as a buffer, provides **no gain** but **large input impedance** and **low output impedance**.



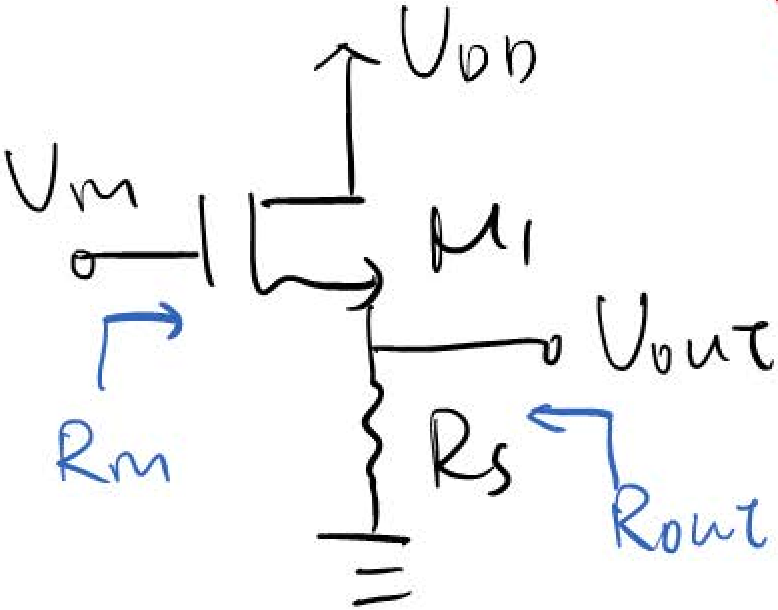
$$R_{in} = \infty$$

$$R_{out} = R_S \,//\, r_{o1} \,//\, \left(\frac{1}{g_{m1} + g_{mb1}}\right)$$

small-signal



$$R_{out} = \frac{v_t}{i_t}$$



$\lambda \neq 0,\ \gamma \neq 0$

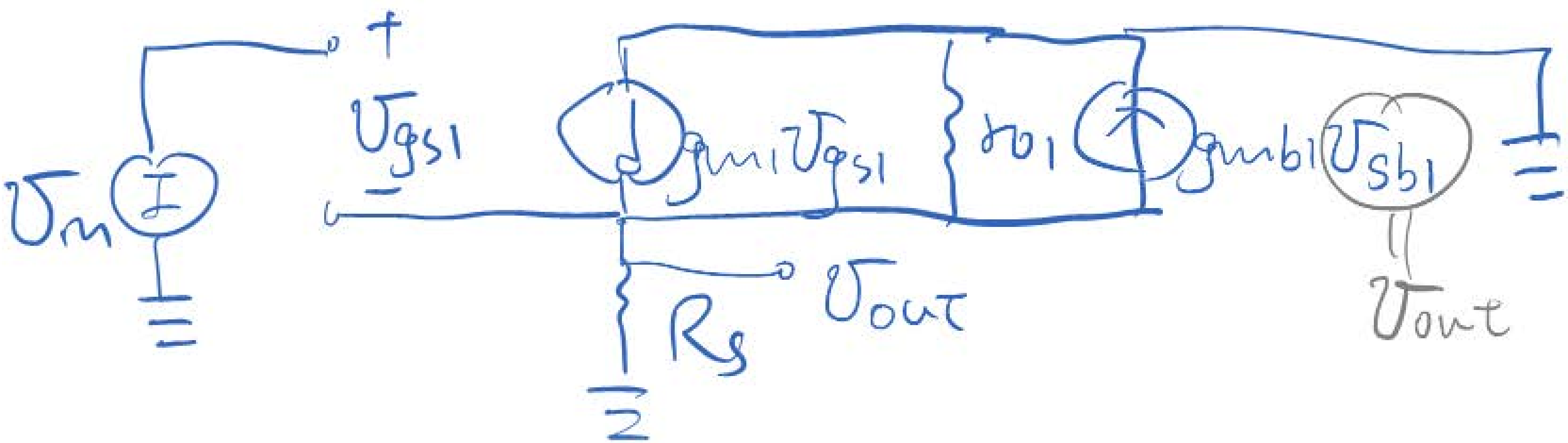
$$R_{in} = \infty$$

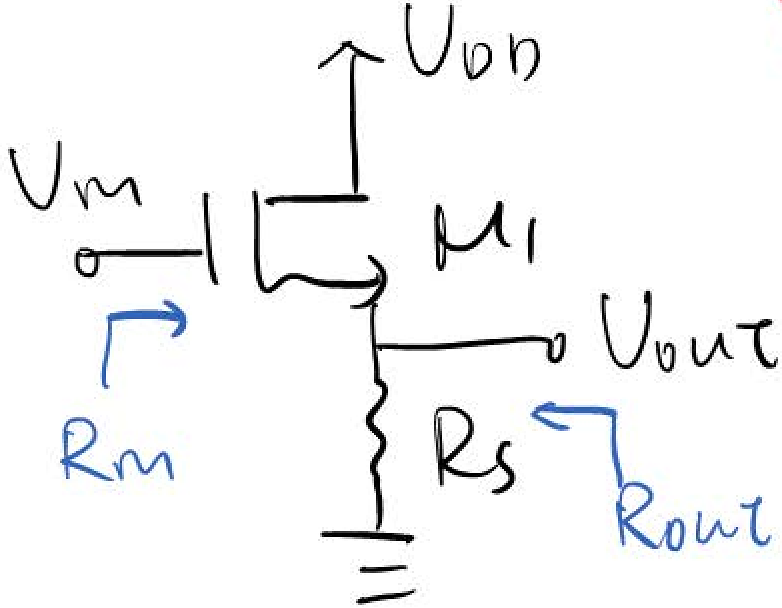
$$R_{out} = R_S \parallel r_{o1} \parallel \left(\frac{1}{g_{m1}+g_{mb1}}\right)$$

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

small-signal

$$\frac{v_{out}}{R_S} + (v_{out} - v_{in})g_{m1} + \frac{v_{out}}{r_{o1}} + g_{mb1}v_{out} = 0$$



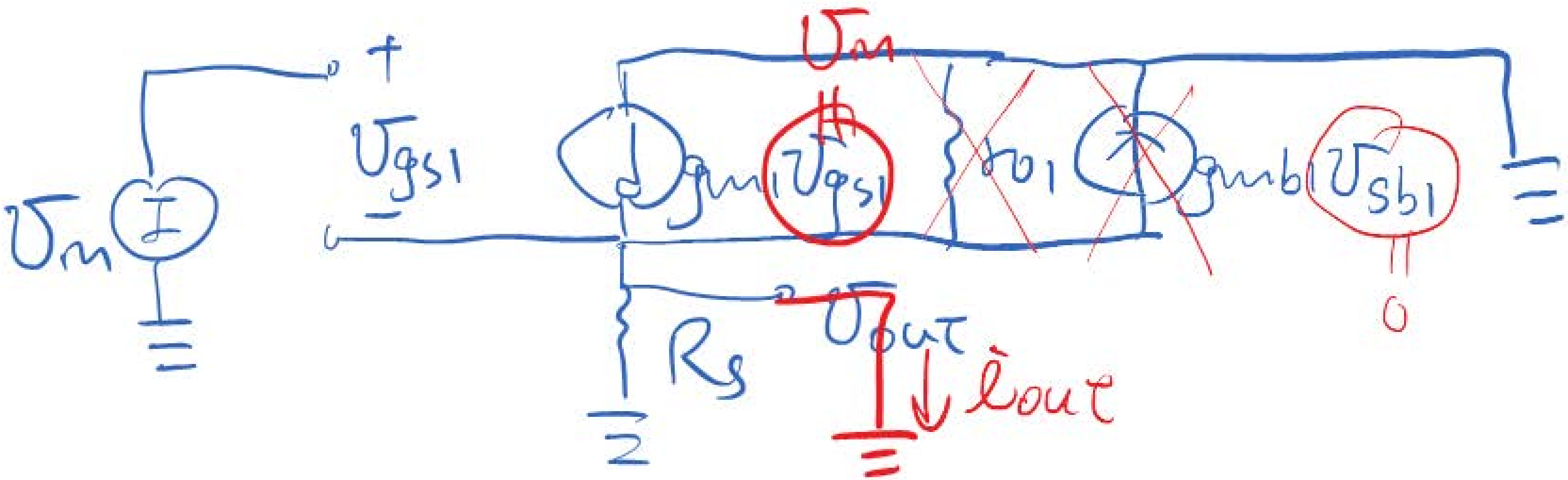


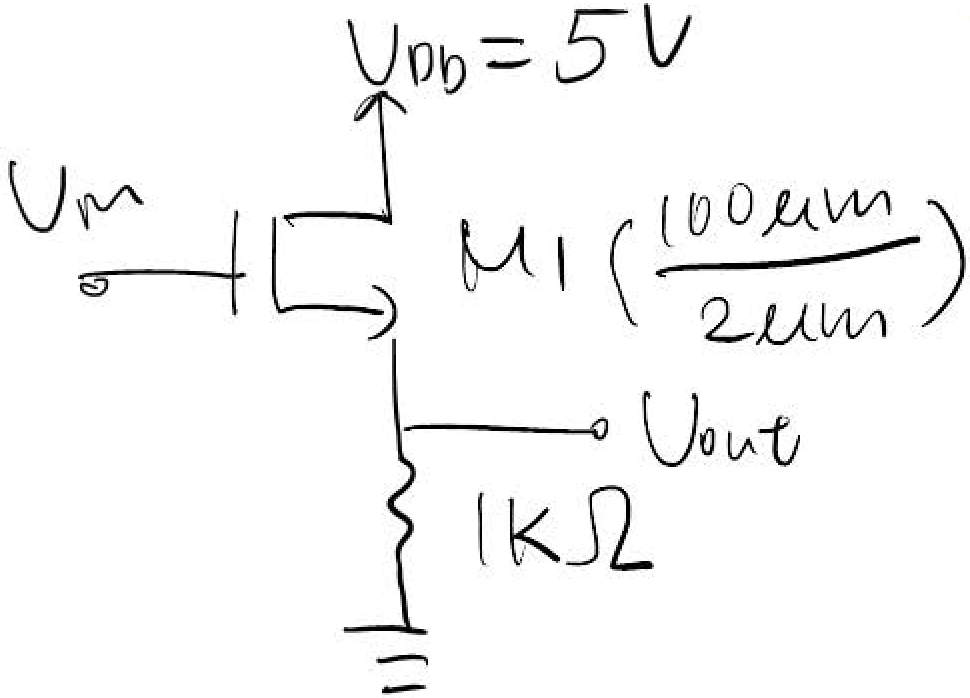
$\lambda \neq 0,\ \gamma \neq 0$

$$G_m = ? = \frac{i_{out}}{v_{in}} = g_{m1}$$

$$i_{out} = g_{m1} v_{in}$$

small-signal





$V_{in} = 3 + 0.001\sin(2\pi 100t)$

$V_{out} = ?$

$\lambda \neq 0, \gamma \neq 0$

1° $V_{OUT} = ?$

DC biasing analysis.

M1 must be in sat.

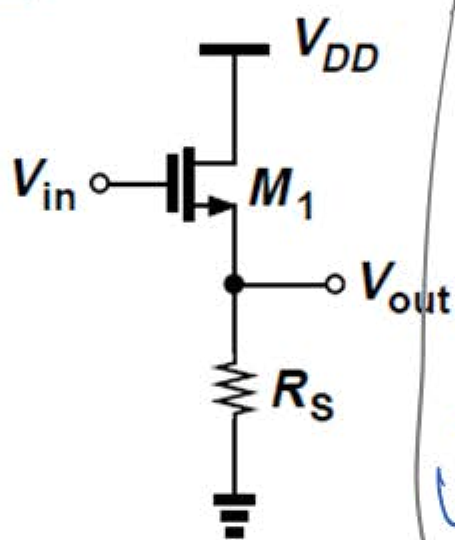
$$\frac{V_{OUT}}{1k} = \frac{1}{2}\mu_n C_{ox}\left(\frac{W}{L_{eff}}\right)\cdot(3 - V_{OUT} - V_{TH})^2 \cdot [1 + \lambda(5 - V_{out})]$$

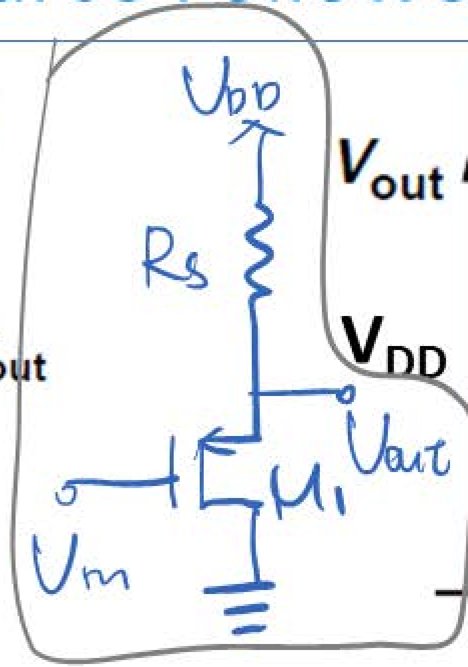
Source Follower

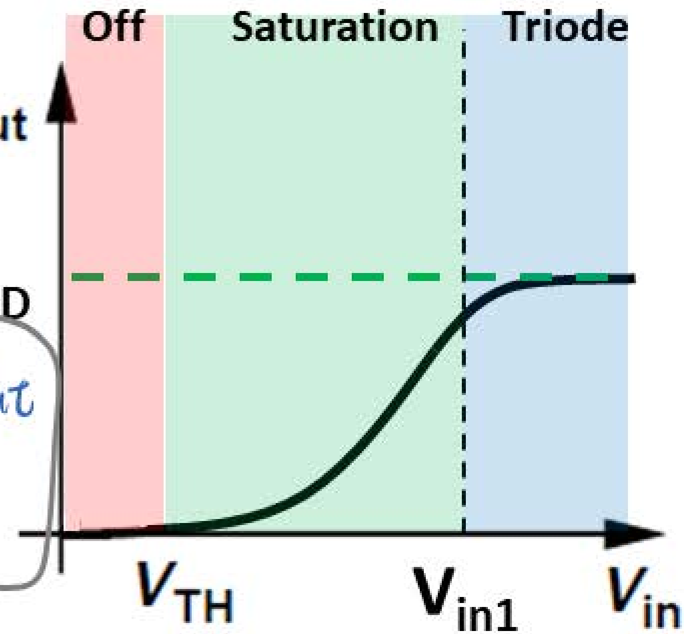
DC Analysis

$\lambda = 0$

$\gamma \neq 0$







- $V_{in} < V_{TH}$ → M_1 Off

$$V_{out} = 0$$

- $V_{in1} > V_{in} > V_{TH}$ → M_1 in Saturation

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

- $V_{in} > V_{in1}$ → M_1 in Triode

$$R_S \mu_n C_{ox} \frac{W}{L_{eff}} \left[(V_{in} - V_{out} - V_{TH})(V_{DD} - V_{out}) - \frac{1}{2} (V_{DD} - V_{out})^2 \right] = V_{out}$$

$$V_{DD} - V_{out} = V_{in1} - V_{out} - V_{TH}$$

$$\rightarrow V_{in1} = V_{DD} + V_{TH}$$

Source Follower

DC Analysis

$Vout = V_{SB}.$

$\lambda = 0$

$\gamma \neq 0$

- **$V_{in1} > V_{in} > V_{TH} \rightarrow M_1$ in Saturation**

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

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

$$R_S \underbrace{\boxed{\mu_n C_{ox}\frac{W}{L}(V_{in} - V_{out} - V_{TH})}}_{= gm}\left(1 - \frac{\partial V_{out}}{\partial V_{in}} - \underbrace{\frac{\partial V_{TH}}{\partial V_{out}}}_{= \eta = \frac{\gamma}{2\sqrt{2\Phi_F + V_{SB}}}}\frac{\partial V_{out}}{\partial V_{in}}\right) = \frac{\partial V_{out}}{\partial V_{in}}$$

$\frac{\partial V_{TH}}{\partial V_{SB}}$

$$A_v = \frac{gmR_S}{1 + gmR_S(1+\eta)} = \frac{gmR_S}{1 + (gm + gmb)R_S} \approx \frac{1}{1+\eta}$$

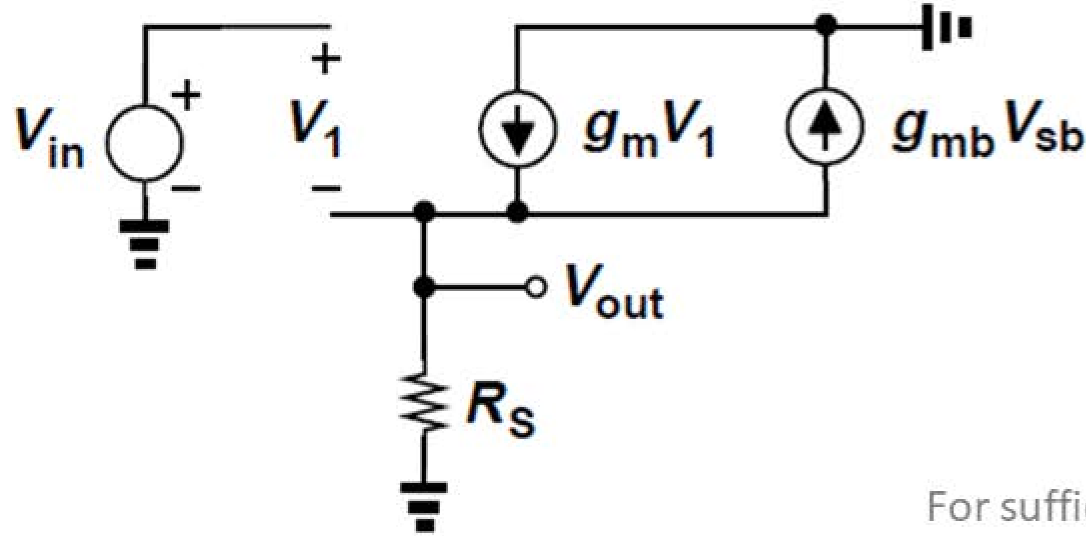
If $(gm + gmb)R_S >> 1$

Source Follower

Small-signal Analysis

$\lambda = 0$

$\gamma \neq 0$



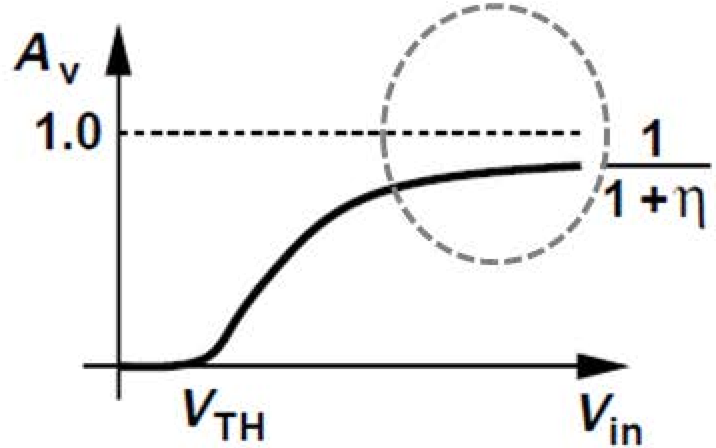
$$G_m = gm$$

$$R_{out} = R_S \parallel \left(\frac{1}{gm + gmb}\right)$$

$$\boxed{A_v = \frac{gmR_S}{1 + (gm + gmb)R_S} \approx \frac{1}{1 + \eta}}$$

If $(gm + gmb)R_S >> 1$

For sufficiently large V_{in}, I_D and thus gm.

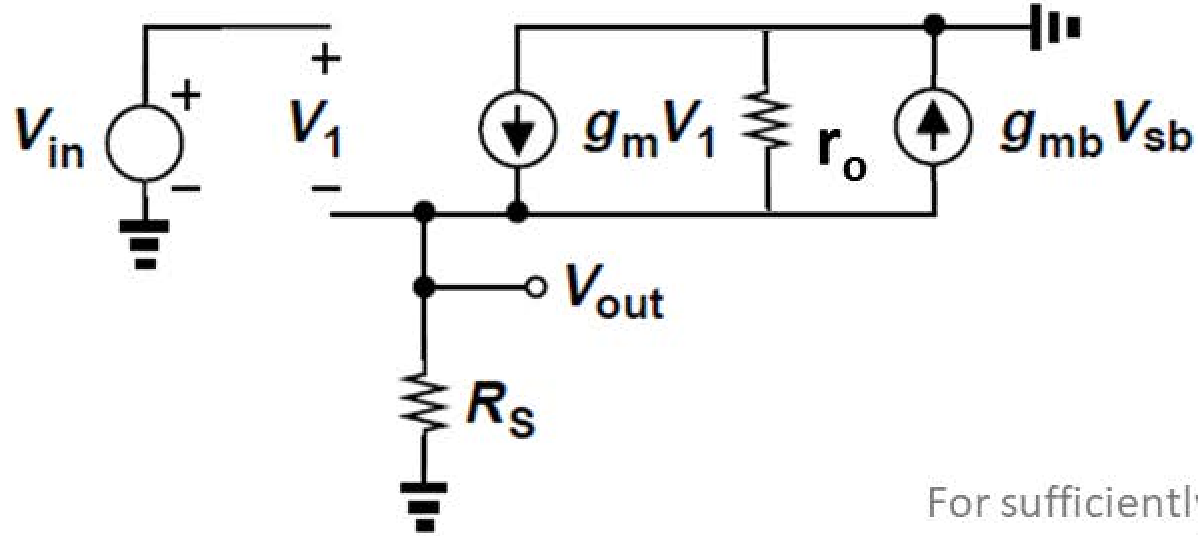


Source Follower

Small-signal Analysis

$\lambda \neq 0$

$\gamma \neq 0$



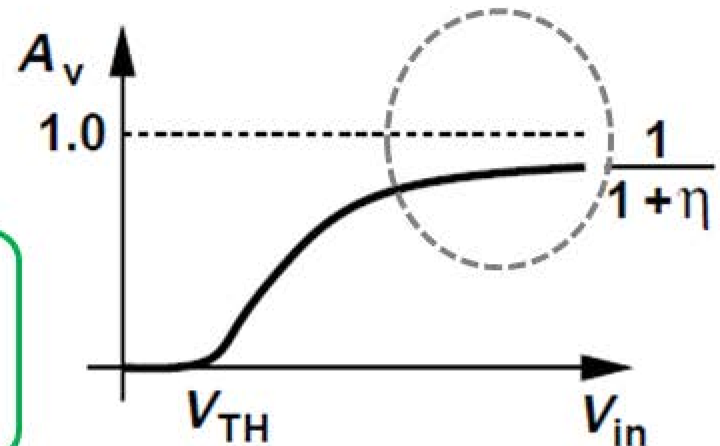
$$G_m = gm$$

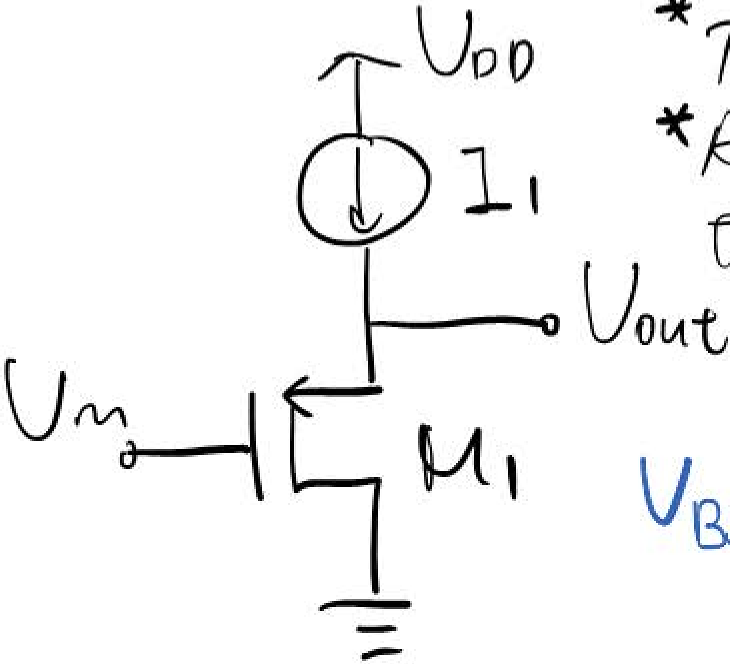
$$R_{out} = r_o \parallel R_S \parallel \left(\frac{1}{gm + gmb}\right)$$

$$\boxed{A_v = \frac{gmr_oR_S}{r_o + R_S + (gm + gmb)r_oR_S} \approx \frac{1}{1 + \eta}}$$

If $(gm + gmb)r_oR_S >> r_o$ and R_S

For sufficiently large V_{in}, I_D and thus gm.





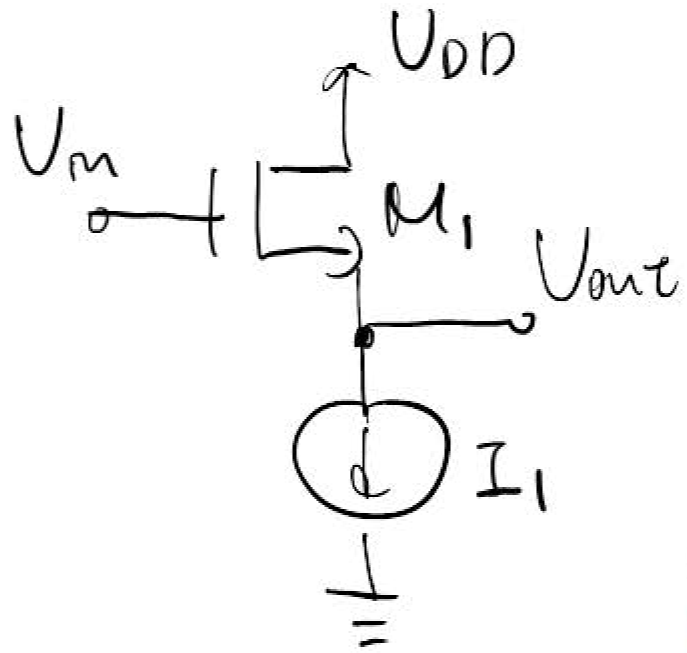
* $\lambda = \gamma = 0$

* Assume all transistors in sat.

$V_{BS1} > 0 \not\Rightarrow |V_{THP}| > 0.8$ if $\gamma \neq 0$

$$\frac{1}{2}\mu_p C_{ox}\left(\frac{W}{L_{eff}}\right)_1 \left(V_{out} - V_{in} - |V_{THP}|\right)^2 = I_1$$

constants



$\lambda \neq 0, \gamma \neq 0$

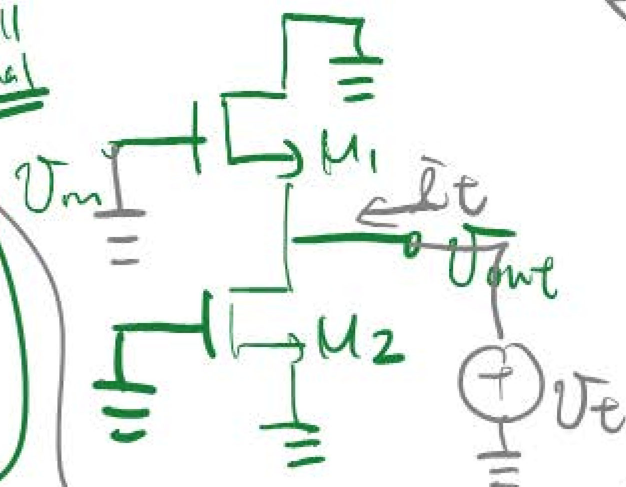
All transistors operate in sat.

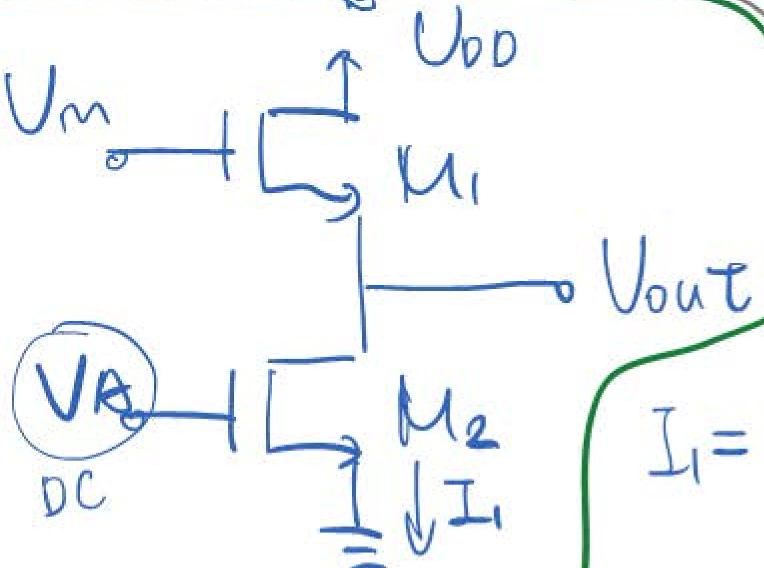
$R_{in} = ?$ $R_{out} = ?$ $A_v = ?$

$R_{in} = \infty$

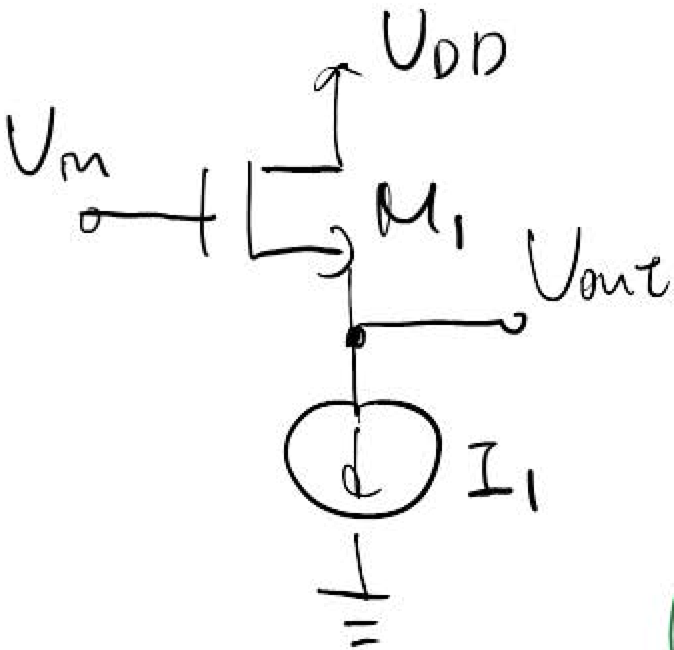
$R_{out} = r_{o2} // r_{o1} // \left(\frac{1}{g_{m1} + g_{mb1}}\right)$

small signal





$$I_1 = \frac{1}{2} \mu_n C_{ox} \left(\frac{W}{L_{eff}}\right)(V_A - 0.7)^2 (1 + \lambda V_{OUT})$$



$\lambda \neq 0,\ \gamma \neq 0$

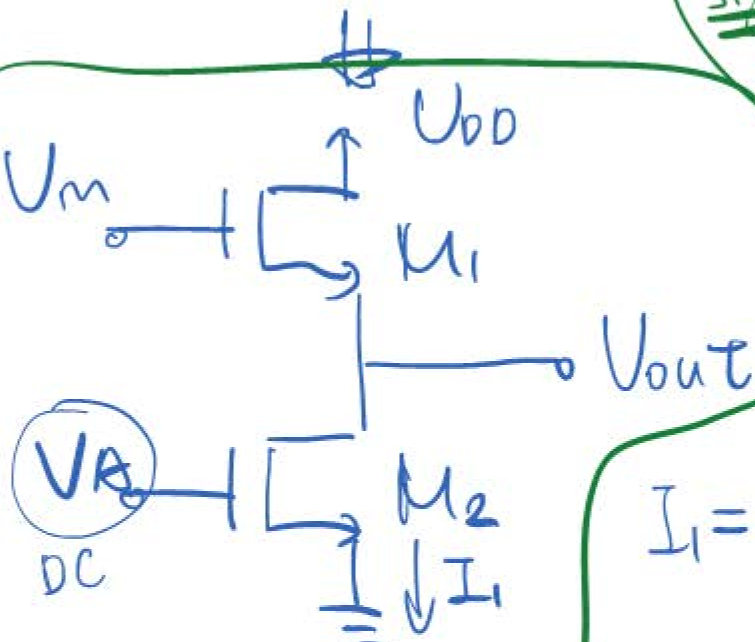
All transistors operate in sat.

$R_{in} = ?$ $R_{out} = ?$ $A_v = ?$

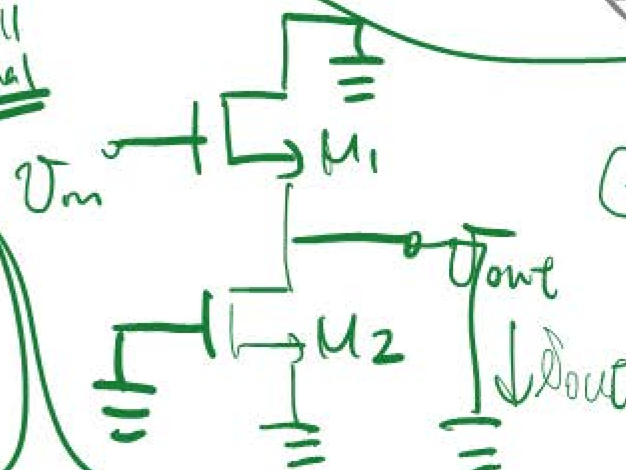
$= G_m R_{out}$

$R_{in} = \infty$

$R_{out} = r_{o2} // r_{o1} // \left(\frac{1}{g_{m1} + g_{mb1}}\right)$



small signal



$G_m = g_{m1}$

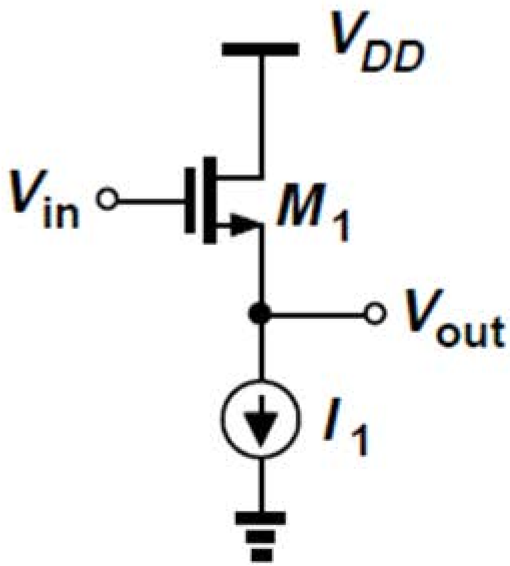
$I_1 = \frac{1}{2} \mu_n C_{ox} \left(\frac{W}{L_{eff}}\right)(V_A - 0.7)^2 (1 + \lambda V_{OUT})$

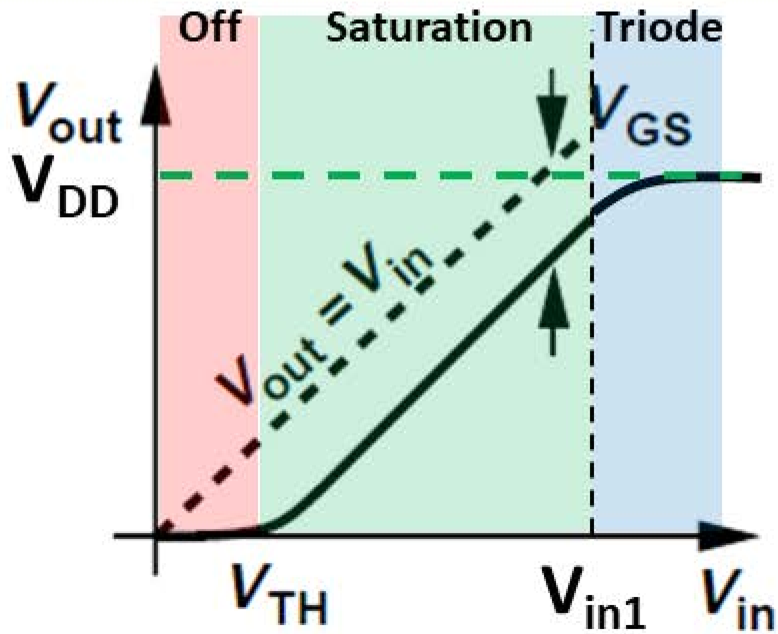
Source Follower with Current Source

DC Analysis

$\lambda = 0$

$\gamma \neq 0$





$$\frac{1}{2}\mu_n C_{ox}\frac{W}{L}(V_{in} - V_{out} - V_{TH})^2 = I_1$$

$$\frac{1}{2}\mu_n C_{ox}\frac{W}{L}2(V_{in} - V_{out} - V_{TH})\left(1 - \frac{\partial V_{out}}{\partial V_{in}} - \frac{\partial V_{TH}}{\partial V_{in}}\right) = 0$$

$$\underbrace{\boxed{\mu_n C_{ox}\frac{W}{L}(V_{in} - V_{out} - V_{TH})}}_{= gm}\left(1 - \frac{\partial V_{out}}{\partial V_{in}} - \underbrace{\boxed{\frac{\partial V_{TH}}{\partial V_{out}}}}_{= \eta}\frac{\partial V_{out}}{\partial V_{in}}\right) = 0$$

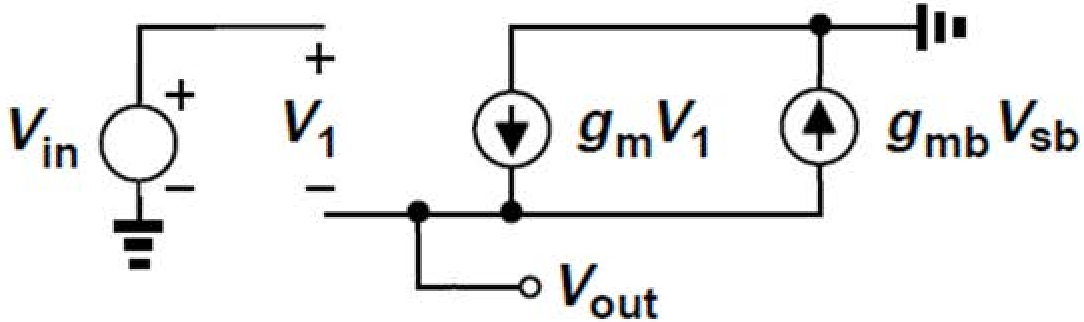
$$\boxed{A_v = \frac{1}{1+\eta} \qquad \text{If } \gamma = 0,\ A_v = 1.}$$

Source Follower with Current Source

Small-signal Analysis

λ = 0

γ ≠ 0

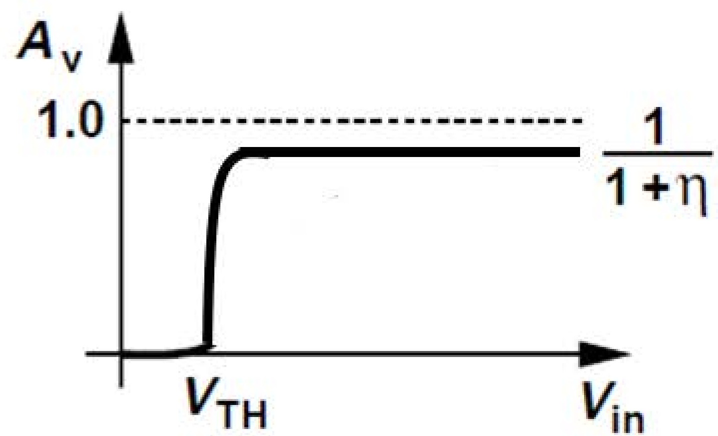


$$G_m = gm$$

$$R_{out} = \frac{1}{gm + gmb}$$

$$A_v = \frac{1}{1+\eta}$$

If $\gamma = 0$, $A_v = 1$.

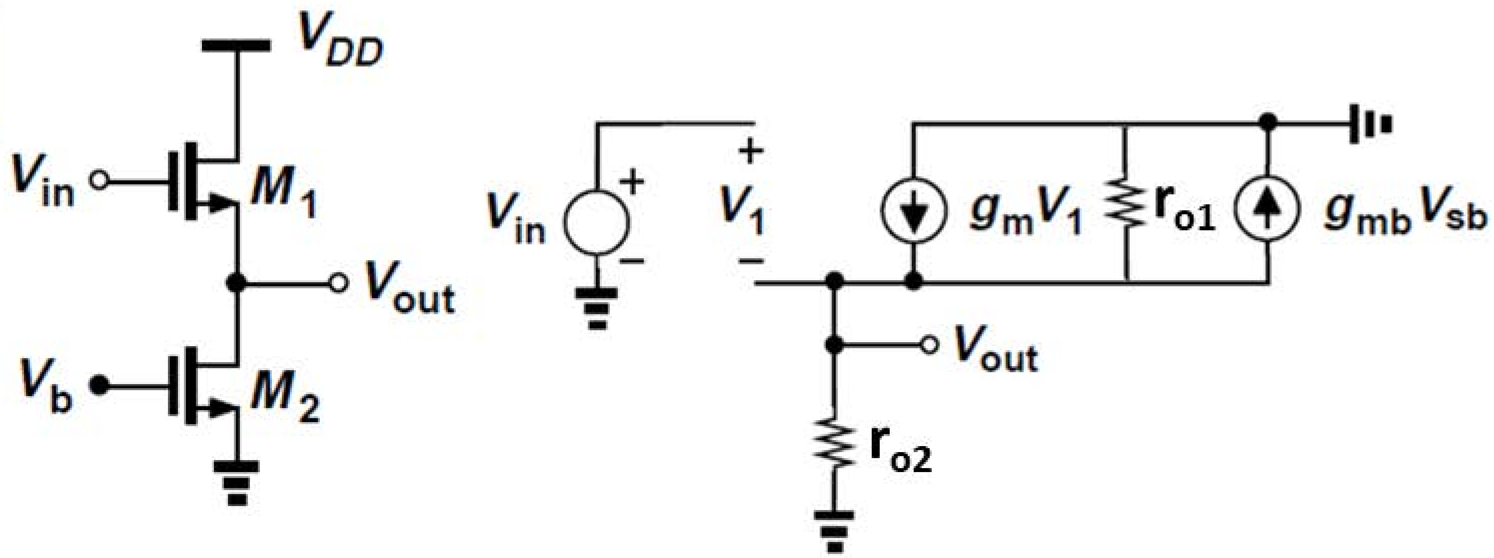


Source Follower with Current Source

Small-signal Analysis

$\lambda \neq 0$

$\gamma \neq 0$



$$G_m = gm_1$$

$$R_{out} = r_{o1} \parallel r_{o2} \parallel \left(\frac{1}{gm_1 + gmb_1}\right)$$

$$\boxed{A_v = \frac{gm r_{o1} r_{o2}}{r_{o1} + r_{o2} + (gm + gmb) r_{o1} r_{o2}}}$$

If r_{o1} and r_{o2} large, A_v is linear.

Source Follower with Current Source ($V_{BS} = 0$)

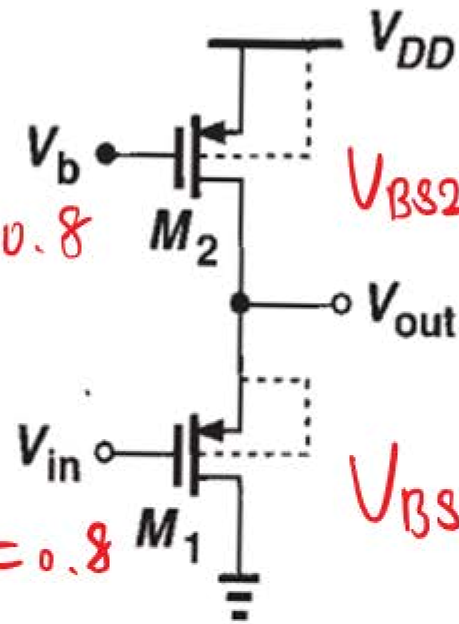
Small-signal Analysis

$\lambda \neq 0$

$\gamma \neq 0$

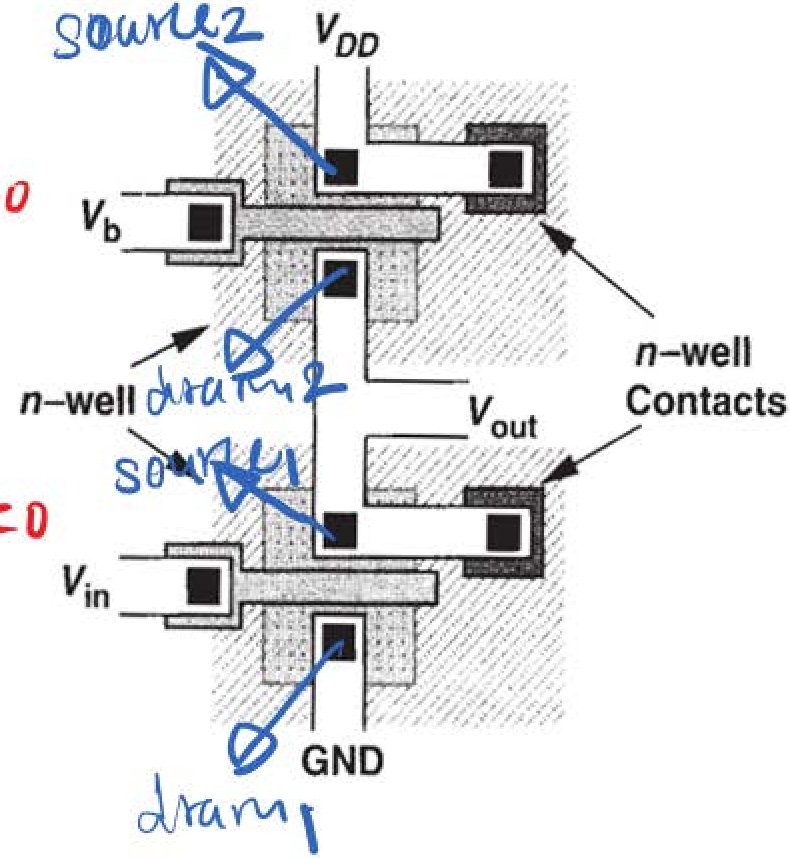
$|V_{TH2}| = 0.8$

$|V_{TH1}| = 0.8$



$V_{BS2} = 0$

$V_{BS1} = 0$



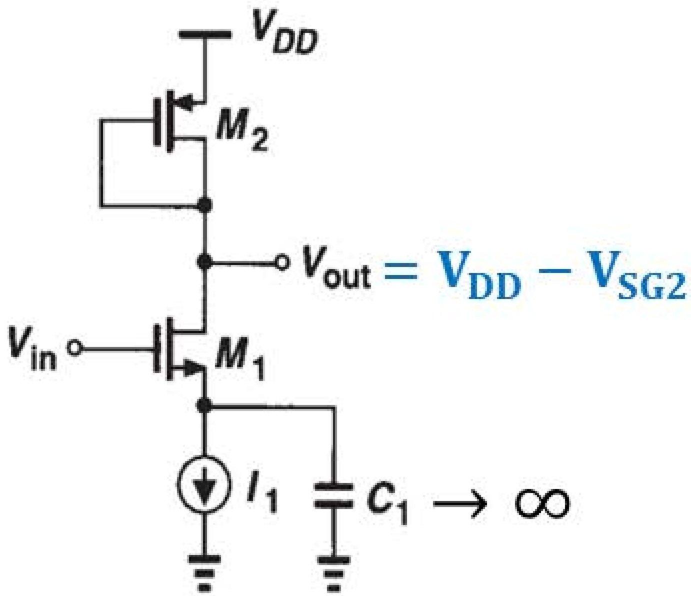
$$G_m = gm_1$$

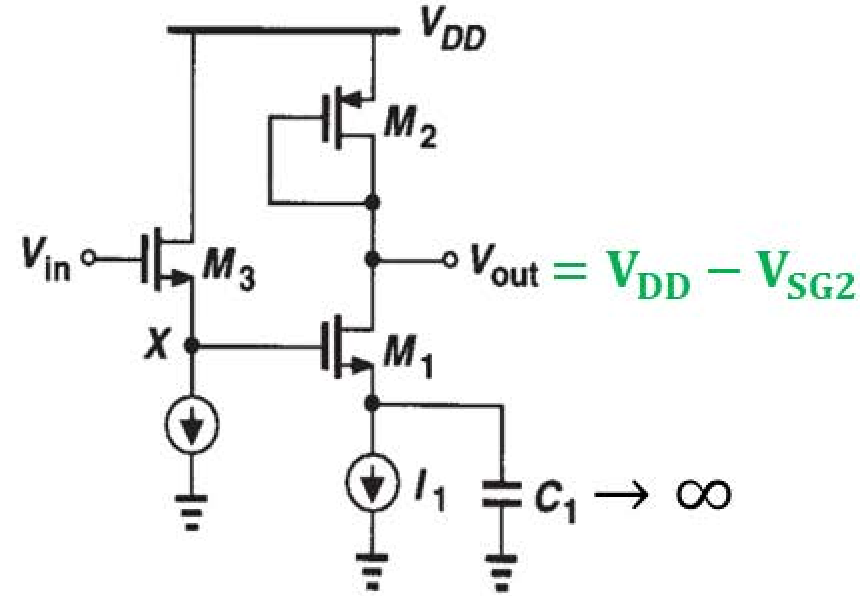
$$R_{out} = r_{o1} \parallel r_{o2} \parallel \frac{1}{gm_1}$$

$$\boxed{A_v = \frac{gm_1 r_{o1} r_{o2}}{r_{o1} + r_{o2} + gm_1 r_{o1} r_{o2}}}$$

- The sacrifice here is the higher output impedance due to smaller mobility of holes relative to electrons.

Source Follower as Level Shifter





$$V_{in} \le V_{DD} - V_{SG2} + V_{TH1}$$

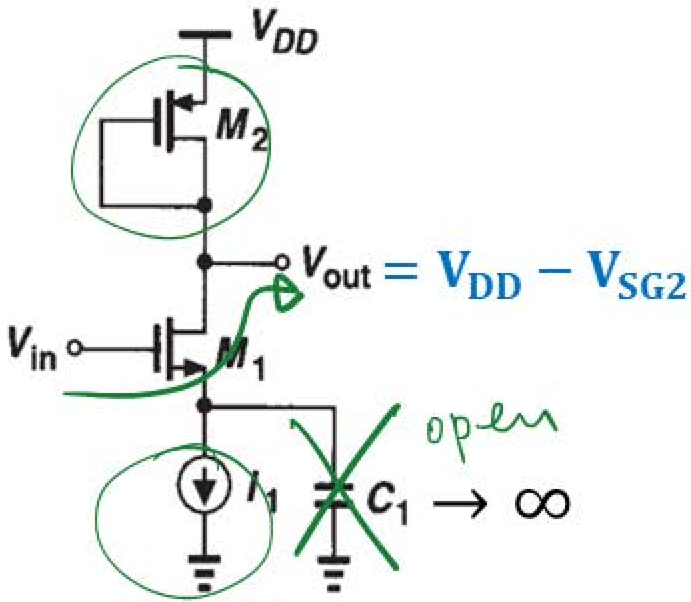
$$V_{in} - V_{GS3} \le V_{DD} - V_{SG2} + V_{TH1}$$

$$\begin{cases} G_m = -gm_1 \\ R_{out} = r_{o1} \parallel r_{o2} \parallel \dfrac{1}{gm_2} \end{cases}$$

$$\begin{cases} G_{m(left)} = gm_3 \\ R_{out(left)} = r_{o3} \parallel \dfrac{1}{gm_3 + gmb_3} \end{cases}$$

$$\begin{cases} R_{in(right)} = \infty \\ G_{m(right)} = -gm_1 \\ R_{out(right)} = r_{o1} \parallel r_{o2} \parallel \dfrac{1}{gm_2} \end{cases}$$

Source Follower as Level Shifter



$$V_{in} \le \underbrace{\boxed{V_{DD} - V_{SG2}}}_{V_{OUT}} + V_{TH1}$$

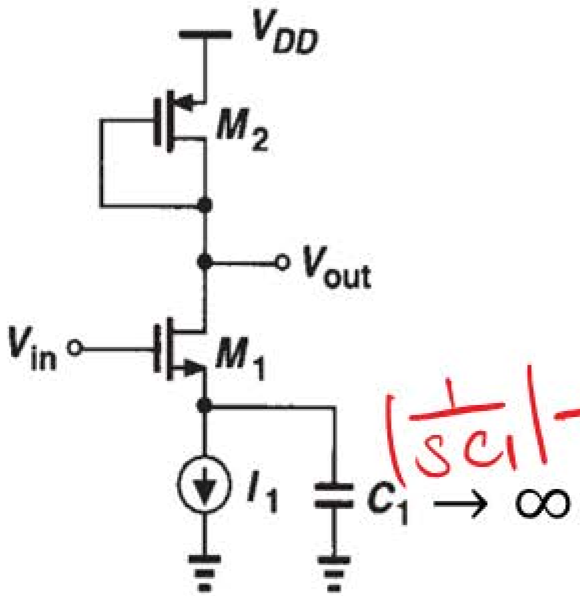
When V_{in} higher than $V_{OUT} + V_{TH1}$, M_1 will be driven into triode.

1° DC biasing analysis

$$I_1 = \frac{1}{2}\mu_p C_{ox}\left(\frac{W}{L_{eff}}\right)_2 \cdot \left(V_{DD} - V_{OUT} - \underbrace{|V_{TH2}|}_{0.8}\right)^2 \cdot \left[1 + \lambda(V_{DD} - V_{OUT})\right]$$

$V_{OUT} = ?$

Source Follower as Level Shifter



2° small signal analysis

$$\begin{cases} G_m = -gm_1 \\ R_{out} = r_{o1} \parallel r_{o2} \parallel \dfrac{1}{gm_2} \\ R_{in} = \infty \end{cases}$$

$\Downarrow$

small signal