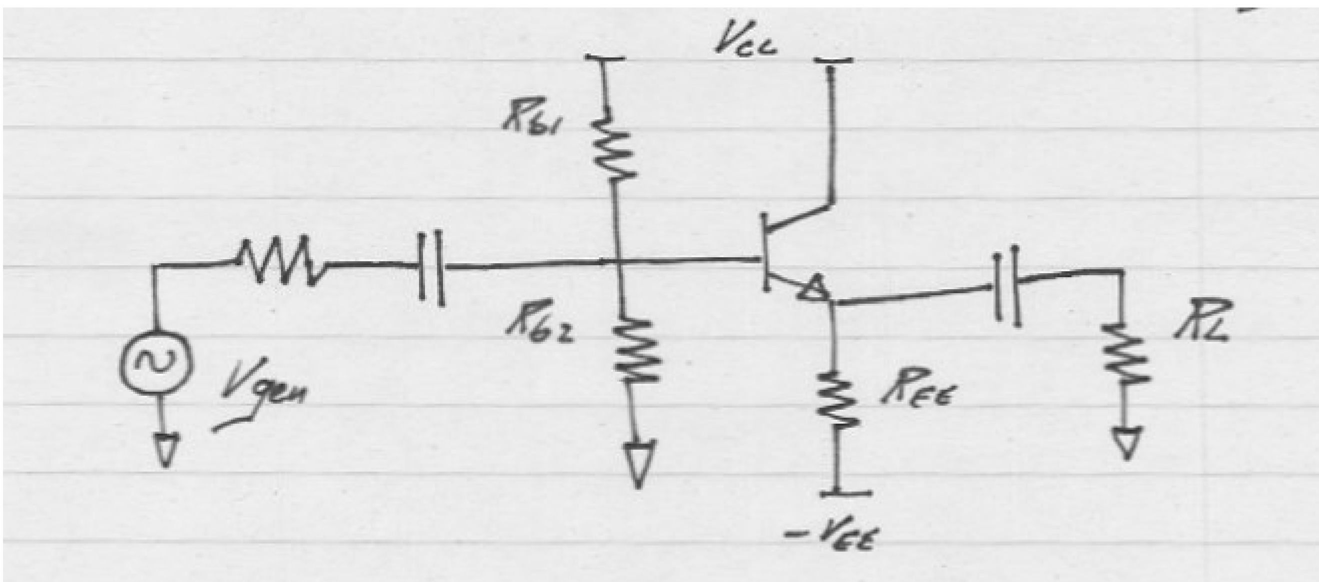
ECE137A, notes set 5: Source Follower, Emitter Follower

Mark Rodwell,
Doluca Family Chair, ECE Department
University of California, Santa Barbara
rodwell@ece.ucsb.edu

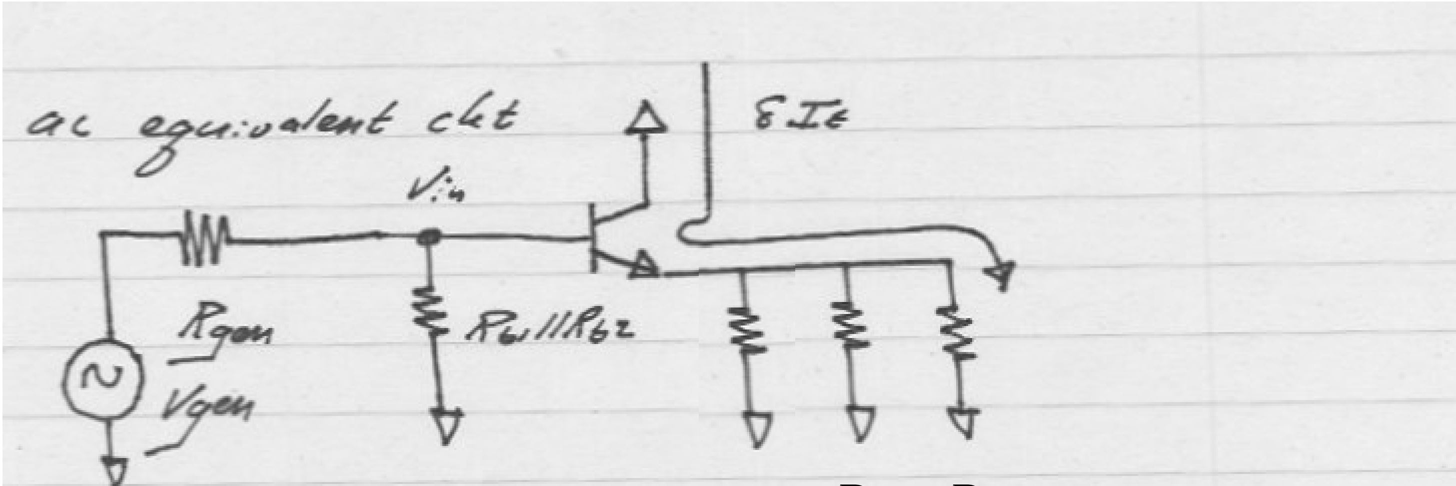
Emitter Follower, Source Follower

Both used when:

- driving a low load resistance
  - small output impedance required.
- operating from a high generator resistance
  - high input impedance required.



Analysis



$$R_{CE} \quad R_{EE} \quad R_L$$

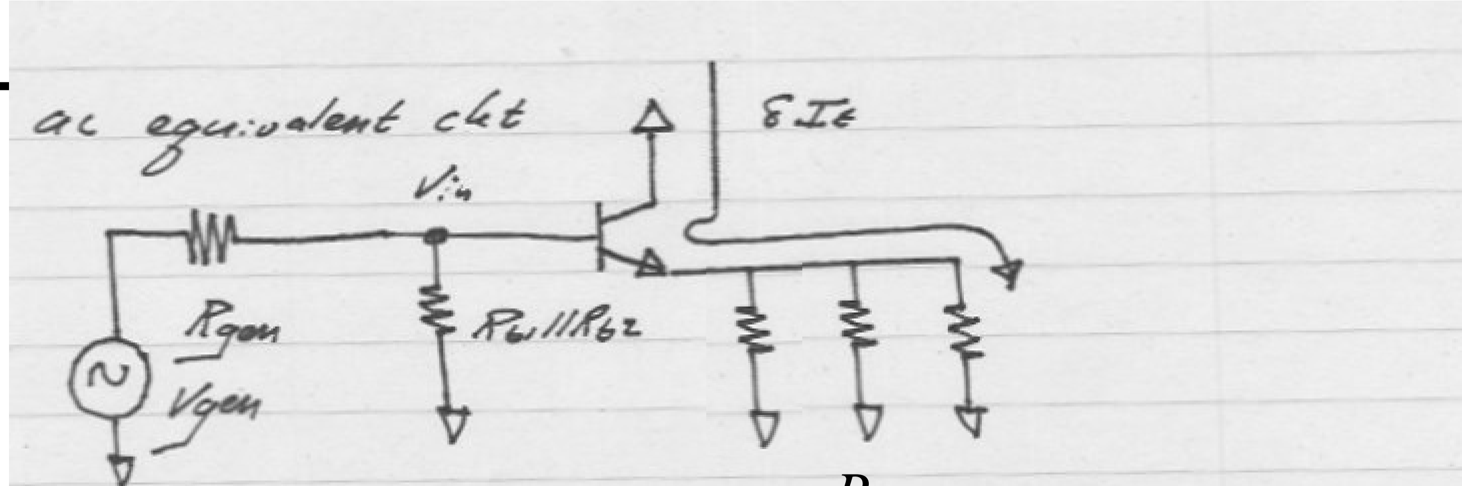
$$R_{CE} \parallel R_{EE} \parallel R_L = R_{L,eq}$$

given δI_E:

$$\delta V_{emitter} = \delta V_{out} = R_{Leq} \cdot \delta I_E$$

$$\delta V_{be} = r_e \cdot \delta I_E \quad \text{because} \quad r_e^{-1} = g_m \triangleq \frac{\partial I_E}{\partial V_{be}}$$

Analysis



$R_{L,eq}$

so: $\delta V_{in} = \delta V_{BE} + \delta V_E$

$$= \delta I_E (R_{Leq} + r_e) = R_{Leq} \cdot \delta I_E \left(\frac{R_{Leq} + r_e}{R_{Leq}} \right)$$

$$\delta V_{in} = \delta V_{out} \left(\frac{R_{Leq} + r_e}{R_{Leq}} \right)$$

Small signal gain: $\dfrac{v_{out}}{v_{in}} = \dfrac{R_{Leq}}{R_{Leq} + r_e}$

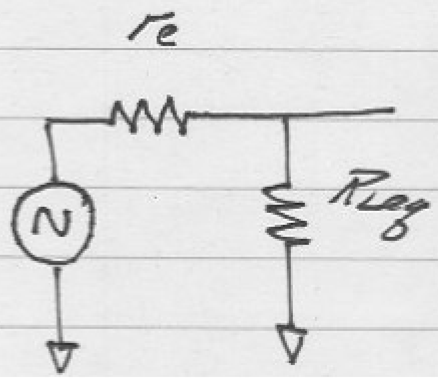
$r_e = 1/g_m$

Emitter Follower Voltage Gain

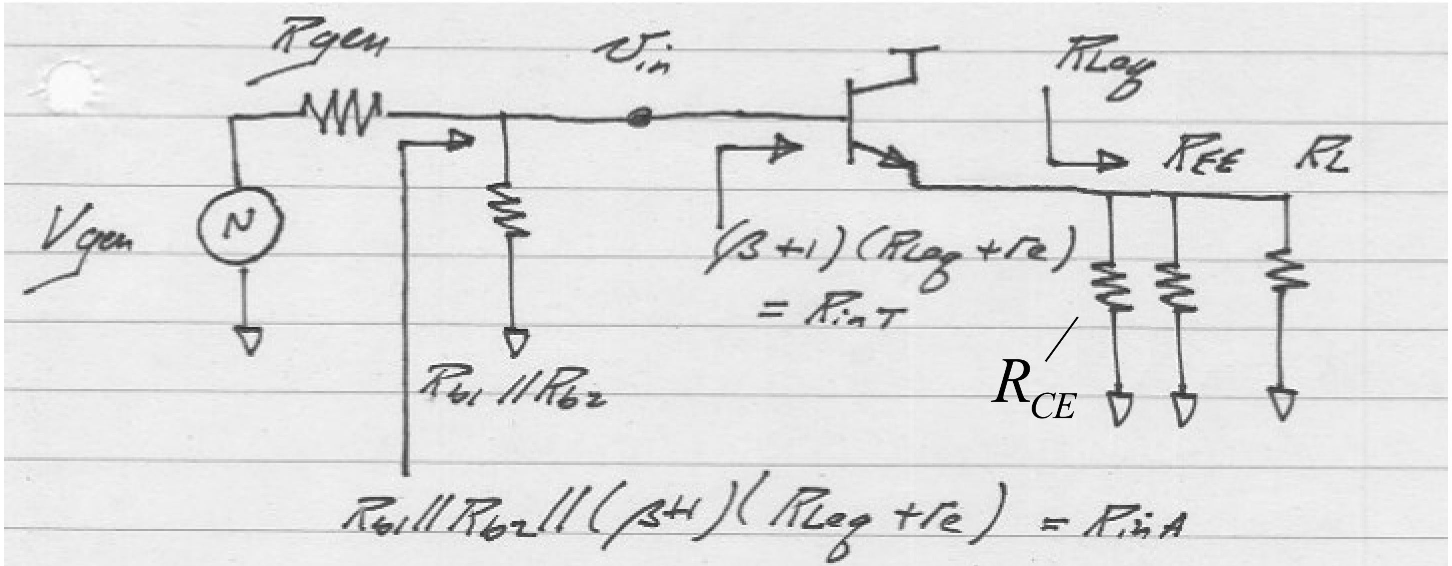
small signal gain: $\dfrac{v_{out}}{v_{in}} = \dfrac{R_{Leq}}{R_{Leq} + r_e}$

$r_e = 1/g_m$

this is similar to a voltage divider between r_e and R_{Leq}:

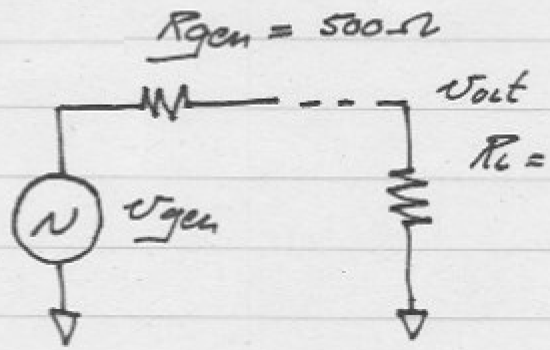


Impedances in the Emitter Follower



Follows from formulas earlier derived for emitter - degeneration.

Emitter Follower: Example (1)

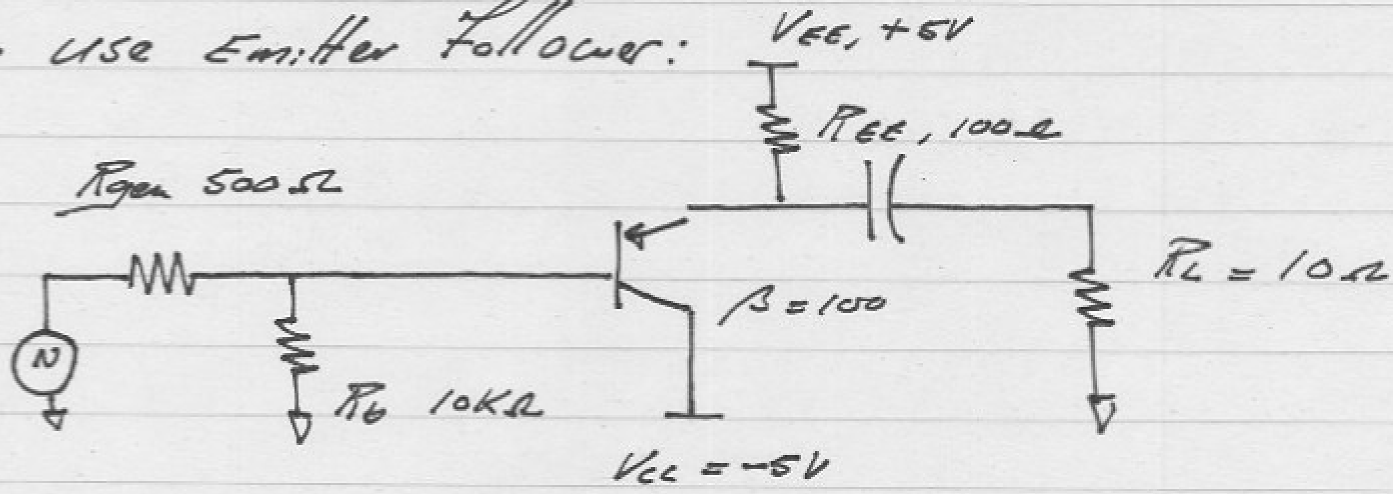


$$\frac{v_{out}}{v_{gen}} = \frac{10}{510} \cong 0.02$$

most of signal amplitude lost!

Emitter Follower: Example (2)

⇒ use Emitter Follower:



bias: guess $I_B \sim 0 \Rightarrow V_b = 0,\ V_E = 0.7$ Volts

$\Rightarrow I_E = (5-0.7)\text{V}/100\Omega = 43\text{ mA}$

hence $I_b = 43\text{mA}/100 = 430\ \mu\text{A}$

Repeat calculation:

$V_b = 430\mu\text{A}\cdot(500\Omega \| 10\text{k}\Omega) = 0.143\text{V}$

$V_E = 0.143 + 0.7 = 0.843\text{ V}$

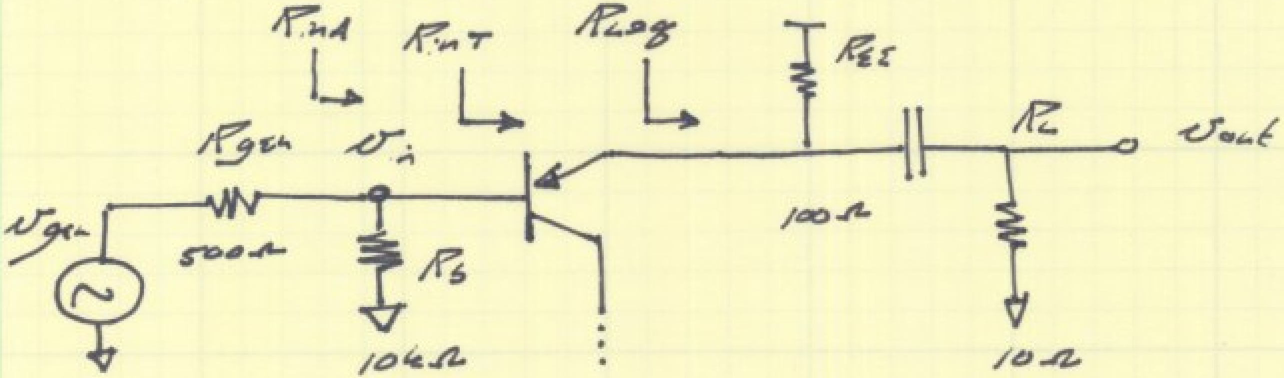
$I_E = (5-0.843)\text{V}/100\Omega = 41.6\text{ mA}$

$I_B = 416\ \mu\text{A}$

Emitter Follower: Example (3)

small signal analysis

$r_e = 1/g_m = 26\,mV/41.6\,mA = 0.63\,\Omega$



$R_{Leq} = 10\,\Omega \,\|\, 100\,\Omega = 9.09\,\Omega$

$v_{out}/v_{in} = R_{Leq}/(r_e + R_{Leq}) = 0.94$, with $r_e = 0.63\,\Omega$, $R_{Leq} = 9.09\,\Omega$

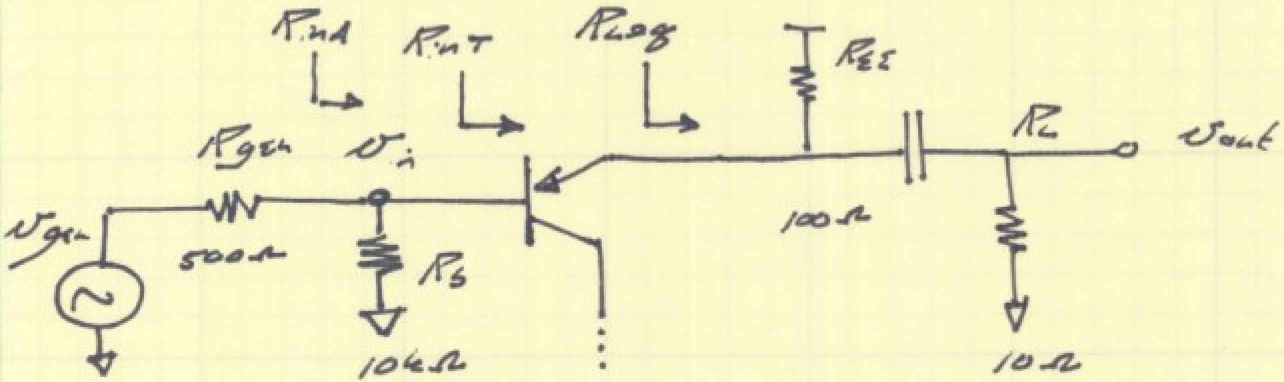
$R_{inT} = \beta(r_e + R_{Leq}) = 982\,\Omega$, with $\beta = 100$, $r_e = 0.63\,\Omega$, $R_{Leq} = 9.09\,\Omega$

$R_{inA} = R_b \,\|\, R_{inT} = 894\,\Omega$, with $R_b = 10\,k\Omega$, $R_{inT} = 982\,\Omega$

Emitter Follower: Example (4)

small signal analysis

$r_E = 1/g_m = 26\text{mV}/41.6\text{mA} = 0.63\ \Omega$



$v_{in}/v_{gen} = R_{inA}/(R_{inA} + R_{gen}) = 0.64$

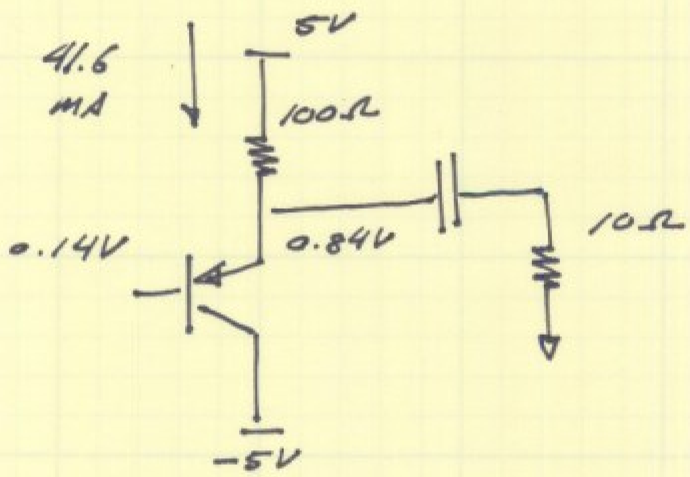
(R_{gen} = 500Ω)

$v_o/v_{gen} = (v_o/v_{in})\cdot(v_{in}/v_{gen}) = 0.94\cdot 0.64 \cong 0.6$

much more than 0.020

Emitter Follower: Example (5)

Maximum signal swings



Saturation: $V_{CE} \cong 0.5V$

bias : $V_{CE} = 0.84V - (-5V) = 5.84V$

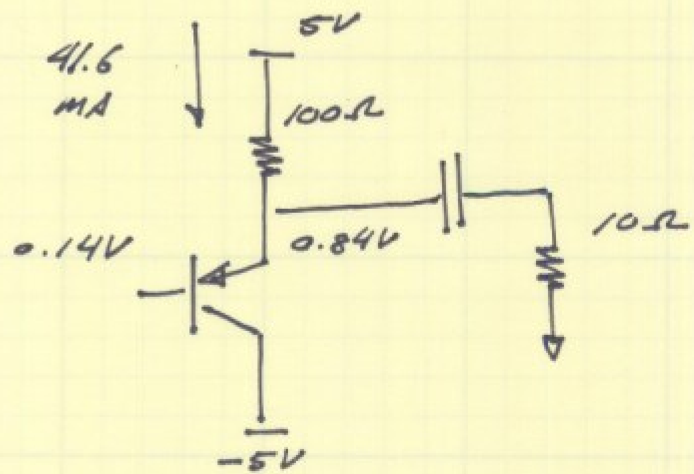
$\Delta V_{CE} = 5.34V = \Delta V_C - \Delta V_E$

(ΔV_C: clearly zero; $\Delta V_E = \Delta V_{out}$)

$\Delta V_{out} = 5.34V \downarrow$

Emitter Follower: Example (6)

Maximum signal swings



bias: $I_c = 41.6\ mA$

cutoff $I_c = 0\ mA$

$\Delta I_c = 41.6\ mA$ (decrease)

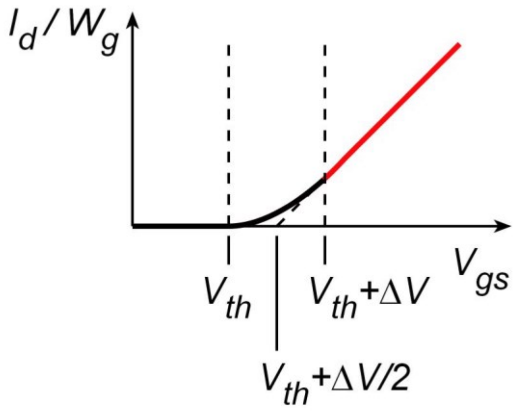
$\Delta V_{out} = \Delta I_c \cdot R_{Leq}$

$= 41.6\ mA \cdot (10\Omega \,||\, 100\Omega)$

$= 0.39V$ ↑

Source Follower Example (1)

Recall FET $I_D - V_{gs}$ characters itics in constant - current region

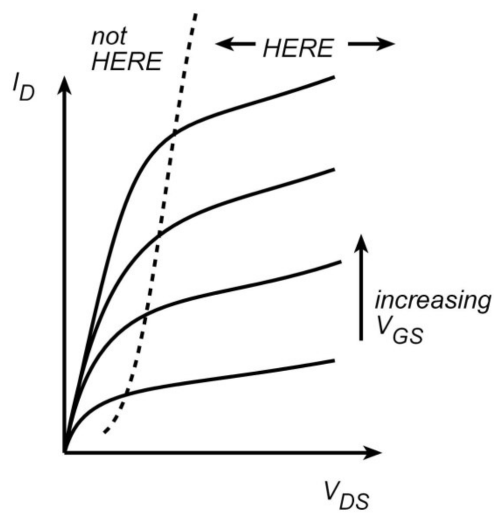


$$I_D \cong K_\mu (V_{gs} - V_{th})^2 (1 + \lambda V_{DS})$$

for $V_{gs} - V_{th} < \Delta V$, where $K_\mu = \mu c_{gs} W_g / 2L_g$

$$I_D \cong K_v (V_{gs} - V_{th} - \Delta V / 2)(1 + \lambda V_{DS})$$

for $V_{gs} - V_{th} > \Delta V$, where $K_v = v_{inj} c_{gs} W_g$



Device model: NMOS @ 15nm gate length

$L_g = 15\text{nm}$

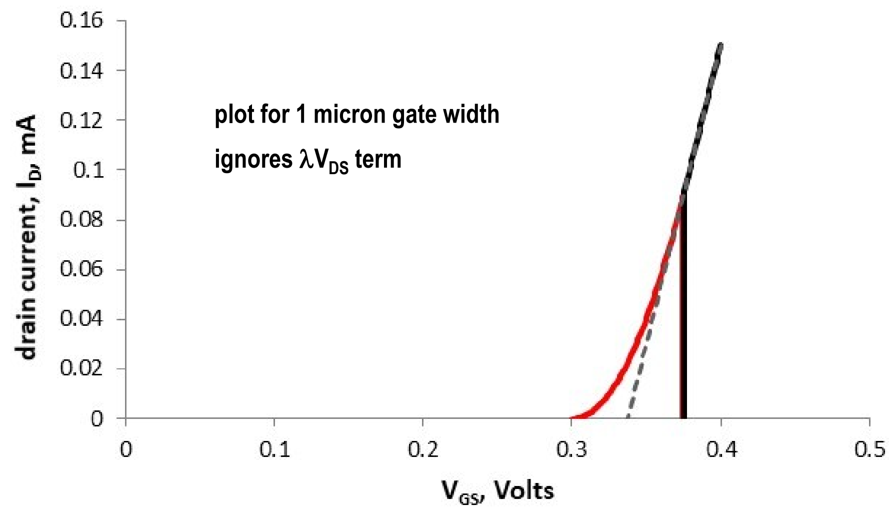
$V_{th} = 0.3\text{ V}$

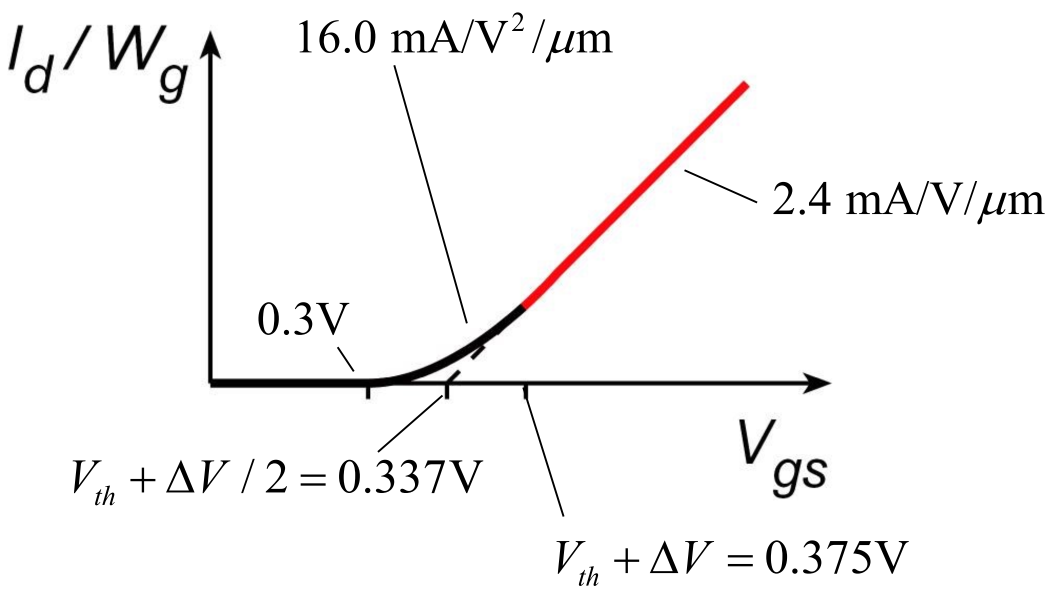
$K_\mu = 16\text{mA/V}^2 \cdot (W_g / 1\mu\text{m})$

$K_v = 2.40\text{mA/V} \cdot (W_g / 1\mu\text{m})$

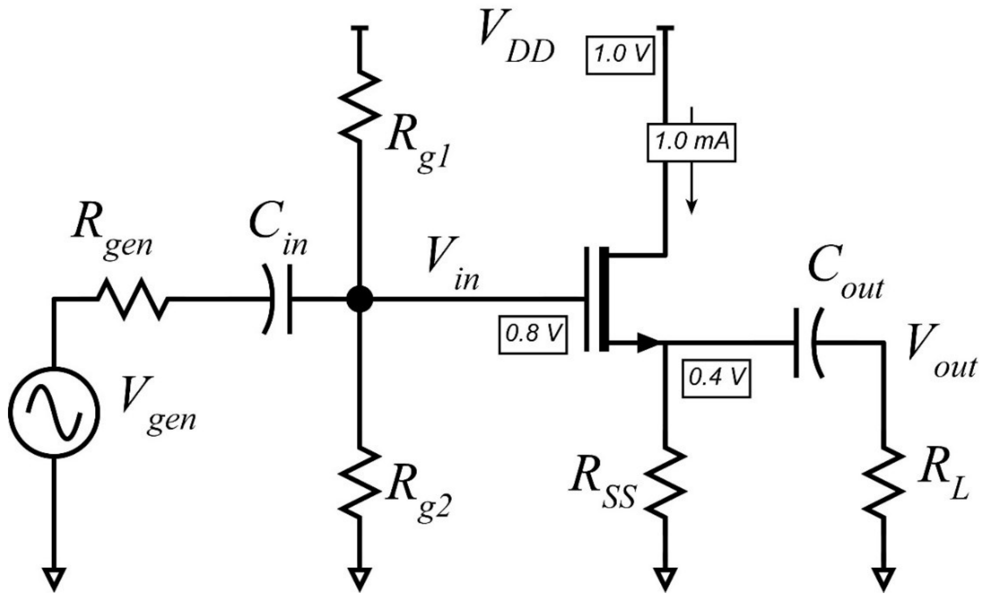
$\Delta V = 75\text{mV}$

$1/\lambda = 5\text{V}$





Source Follower Example (3)



We've chosen to bias the FET @ $V_{gs} - V_{th} = 0.4\text{V} - 0.3\text{V}{=}0.1\text{V}$ and $V_{DS} = 0.6\text{V}$.

Velocity-limited: $I_D = 2.4\text{mA/V} \cdot (W_g / 1\mu\text{m})(V_{gs} - V_{th} - \Delta V / 2)(1 + \lambda V_{DS}) = 1\text{mA}$.

$1\text{mA}{=}2.4\text{mA/V} \cdot (W_g / 1\mu\text{m})(0.1 - 75\text{mV})(1{+}0.6\text{V/5V}) \rightarrow W_g = 14.9\,\mu\text{m}$.

Setting $R_{g1} = 200\text{k}\Omega$ and $R_{g2} = 800\text{k}\Omega$ provides $V_g = 0.8\text{V}$.

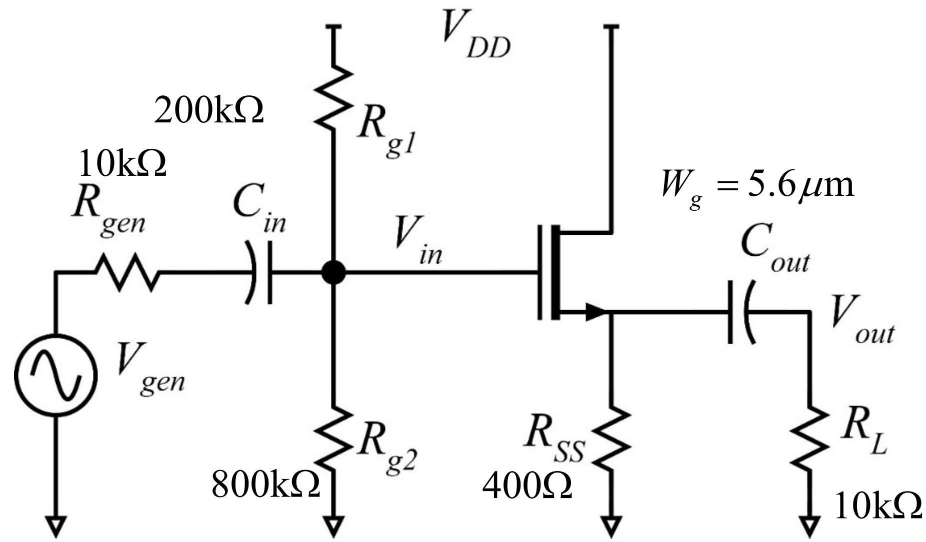
$R_{ss} = 0.4\text{V}/1.0\text{mA}{=}400\Omega$.

Source Follower Example (4)

AC small-signal analysis

$$g_m = K_v(1+\lambda V_{DS})$$
$$= 2.4\text{mA/V}\cdot\left(\frac{14.9\mu\text{m}}{1\mu\text{m}}\right)\left(1+\frac{0.6\text{V}}{5\text{V}}\right)$$
$$= 40\text{mS}.$$

$$R_{DS} \cong 1/\lambda I_D = 5\text{V}/1\text{mA} = 5\text{k}\Omega$$

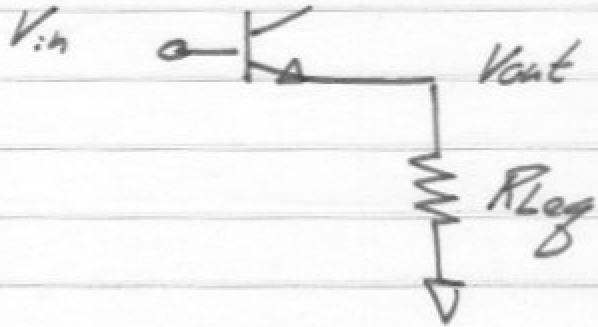


$$R_{Leq} = R_{DS} \,||\, R_{SS} \,||\, R_L = 357\Omega$$
$$V_{out}/V_{in} = R_{Leq}/(R_{Leq}+1/g_m) = 0.93$$

$$R_{in,A} = 200\text{k}\Omega \,||\, 800\text{k}\Omega = 160\text{k}\Omega$$
$$V_{in}/V_{gen} = R_{in,A}/(R_{in,A}+R_{gen}) = 0.94$$

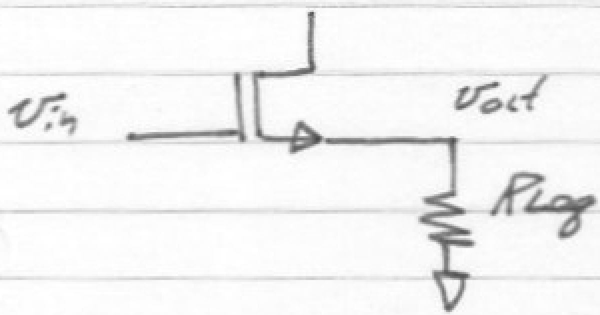
Emitter Followers vs Source Followers

Note that with emitter follower:



$$\frac{v_{out}}{v_{in}} = \frac{R_{Leq}}{R_{Leq} + r_e} = \frac{R_{Leq}}{R_{Leq} + 1/g_m}$$

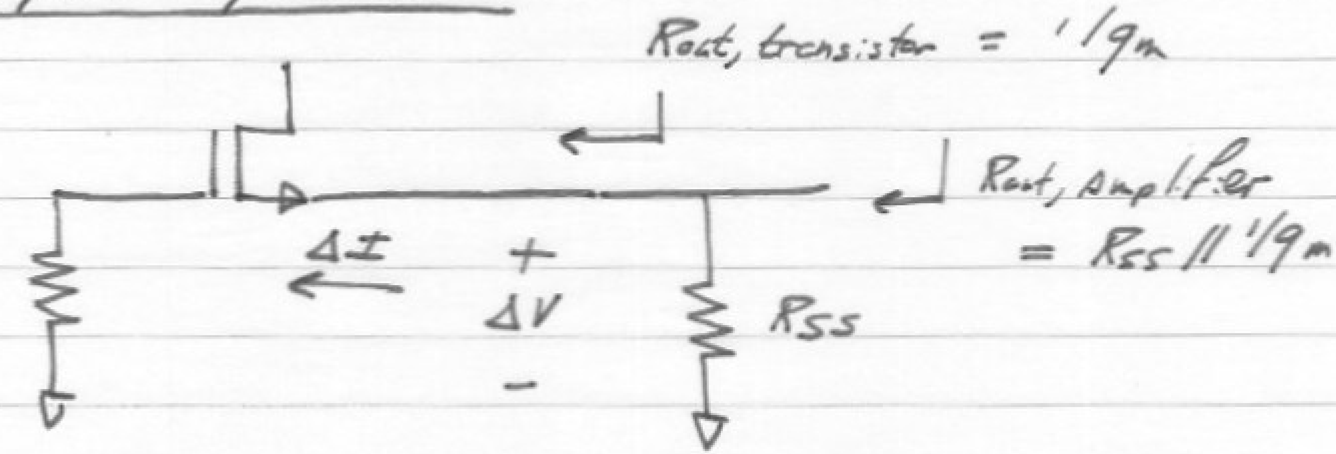
Since the MOSFET has the same s.s. model:



$$\frac{V_{out}}{V_{in}} = \frac{R_{Leq}}{R_{Leq} + 1/g_m}$$

Source Follower Output Impedance

Output impedance:



why is $r_{out,\,transistor} = 1/g_m$??

$$\left(r_{out,\,transistor}\right)^{-1} \triangleq \Delta I/\Delta V = \Delta I_s/\Delta V_{gs}$$

$$= g_m$$

More carefully working from the s.s. model shows that $R_{out,T} = (1/g_m)\,||\,R_{DS}$