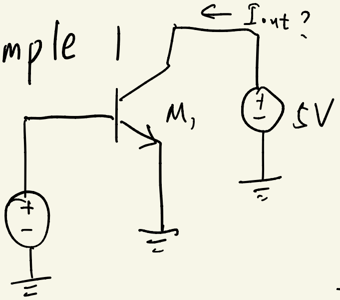
Example 1



$V_{in} = 2 + 0.01 \sin(2\pi 100 t)$

NPN: $I_S = 1e-15$

$\beta = 100$

$V_A = 50$

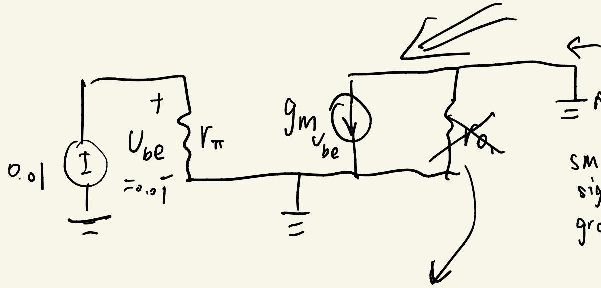
$\Rightarrow I_{out} = I_{OUT} + i_{out}$

$V_{CE} = 5V > V_{BE} = 2V$

check M_1 : FAR

$I_{OUT} = (10^{-15})\left(e^{\frac{2}{0.026}} - 1\right)\left(1 + \frac{5}{50}\right)$

$I_{out} = I_{OUT} + \left(\frac{I_{OUT}}{0.026} 0.01\right) \sin(2\pi 100 t)$

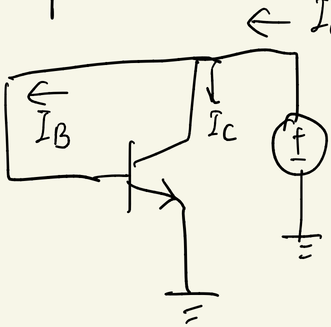


small signal ground

$i_{out} = g_{m1} v_{be1} = \frac{I_{OUT}}{0.026} \times 0.01$

two terminals connects to ground (Ignored!)

Example 2



$I_S = 10^{-15}$, $\beta = 100$, $V_A = 50$

$V_{CE} = V_{BE}$

$\Rightarrow$ FAR

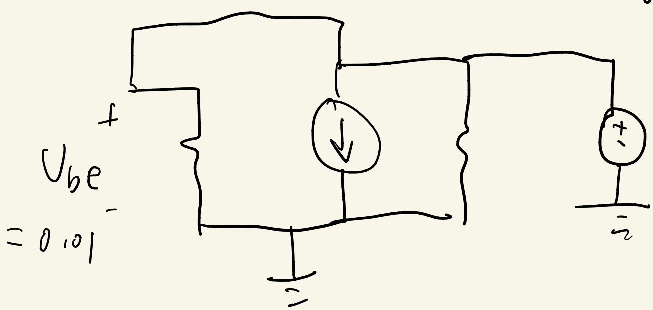
$V_{in} = 2 + 0.01 \sin(2\pi 100 t)$

$I_{out} = I_{OUT} + i_{out}$

$I_{OUT} = (10^{-15})(e^{\frac{2}{0.026}} - 1)(1 + \frac{2}{50})$

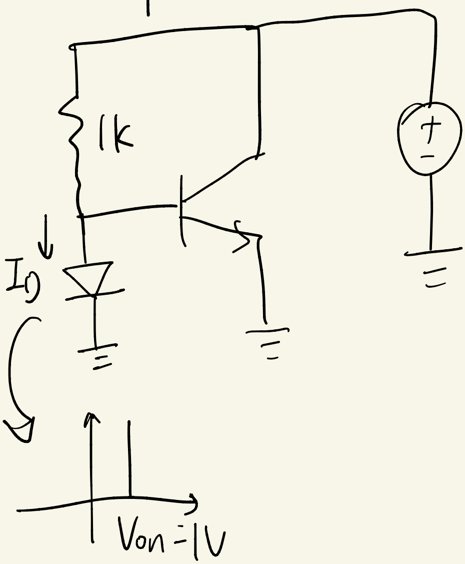
$\Downarrow$

Small-Signal Analysis



$i_{out} = 0.01 \times \left(\frac{1}{r_{\pi_1}} + g_{m_1} + \frac{1}{r_{o_1}}\right)$

Example 3



$I_S = 10^{-15}$, $\beta = \infty$, $V_A = \infty$

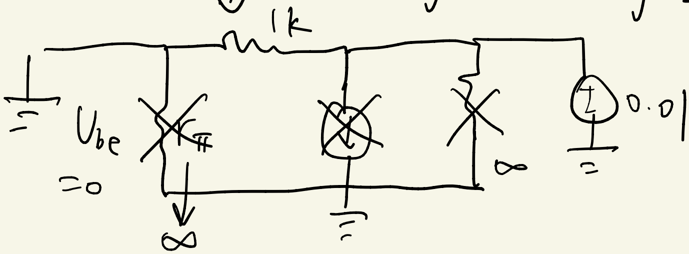
$V_{in} = 2 + 0.01 \sin(2\pi\, 100 t)$

$$I_{out} = I_{OUT} + i_{out}$$

$$= (10^{-15})\left(e^{\frac{1}{0.026}} - 1\right)\left(1 + \frac{2}{\infty}\right)$$

$$I_D = \frac{V_{in} - 1}{1k}$$

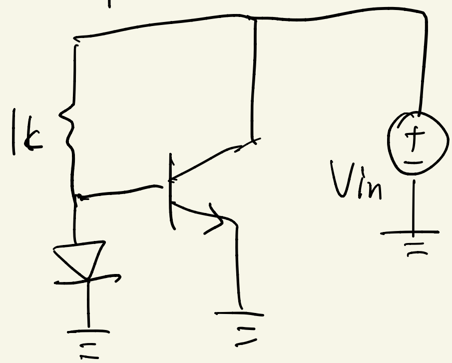
$\Downarrow$ Small-signal Analysis



$\Rightarrow i_{out} = 0$

$$I_{out} = I_{OUT}$$

Example 4



$I_S = 10^{-15}$, $\beta = \infty$, $V_A = 100$

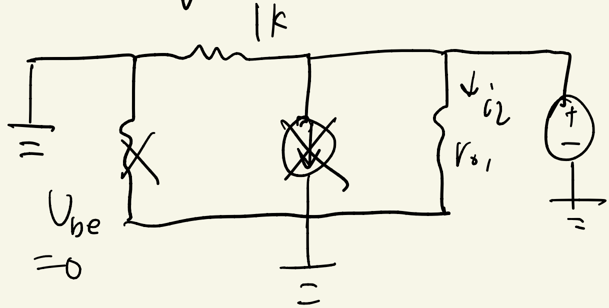
$V_{on} = 1V$

$$V_{in} = 2 + 0.01\sin(2\pi\, 100\, t)$$

$$I_{out} = I_{OUT} + i_{out}$$

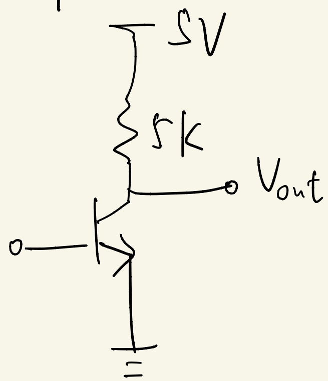
$$I_{OUT} = (10^{-15})\left(e^{\frac{1}{0.026}} - 1\right)\left(1 + \frac{2}{100}\right)$$

$\Downarrow$ small-signal analysis



$$\Rightarrow \quad i_{out} = i_2 = \frac{0.01}{r_{o1}}, \quad r_{o1} = \frac{V_A}{I_{OUT}}$$

Example 5



$V_{in} = 1 + 0.001 \sin(2\pi\, 100 t)$

$V_{out} = V_{OUT} + v_{out} = ?$

$A_v = v_{out} / v_{in} = ?$

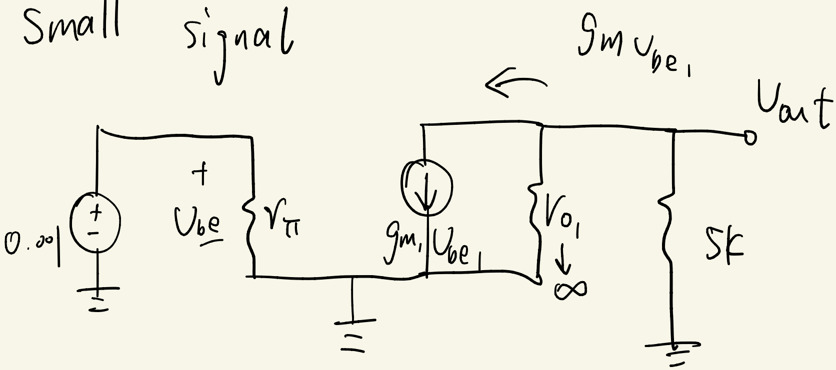
$\Downarrow$

$I_s = 5\times10^{-16},\ \beta = 200,\ V_A = \infty$

$V_{OUT} = 5 - (5K)(5\times10^{-16})\left(e^{\frac{1}{0.026}} - 1\right)$

☆check if ≥ 1 (in FAR)

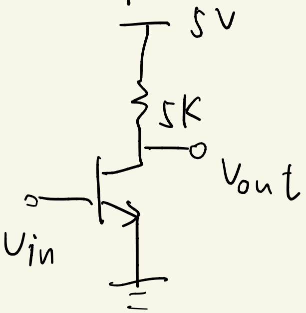
small signal



$v_{out} = -g_{m_1} v_{be_1} (5K)$

$A_v = \frac{v_{out}}{v_{in}} = -g_{m_1} (5K)$

Example 6



$I_S = 5\times10^{-16}$, $\beta = 200$

$V_A = 100$

$V_{in} = 0.7 + 0.001\sin(2\pi\, 100t)$

$v_{out} = -g_{m_1} v_{in} (r_{o_1} // 5k)$

$A_v = -g_{m_1}(r_{o_1} // 5k)$

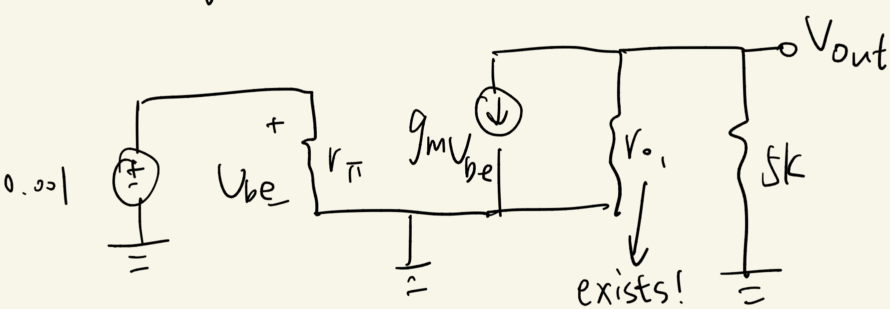
$V_{OUT} = ?$

$\Downarrow$

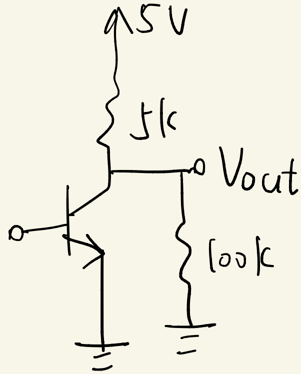
$$\frac{5 - V_{OUT}}{5k} = (5\times10^{-16})\left(e^{\frac{0.7}{0.026}} - 1\right)\left(1 + \frac{V_{OUT}}{100}\right)$$

check if $V_{OUT} \geq 0.7$

small-signal



Example 7



$I_S = 5\times10^{-16}$, $\beta = 200$,

$V_A = 100$

$V_{in} = 0.7 + 0.001\sin(2\pi\, 100 t)$

$V_{OUT} = ?$

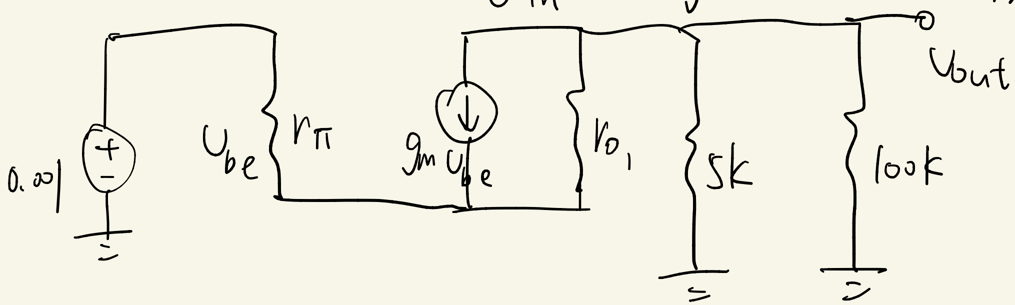
$$\frac{5 - V_{OUT}}{5k} = (5\times10^{-16})\left(e^{\frac{0.7}{0.026}} - 1\right)\left(1 + \frac{V_{OUT}}{100}\right) + \frac{V_{OUT}}{100k}$$

check V_{OUT}

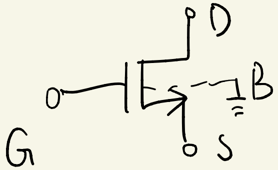
$\Downarrow$ small signal

$$v_{out} = -g_m v_{in} \left(r_{o1} \,//\, 5k \,//\, 100k\right)$$

$$A_v = \frac{v_{out}}{v_{in}} = -g_{m1}\left(r_{o1} \,//\, 5k \,//\, 100k\right)$$



NMOS



$$V_{TH} = V_{TH0} + \gamma\left(\sqrt{2\phi_F + V_{SB}} - \sqrt{2\phi_F}\right)$$

$$L_{eff} = L_{drawn} - 2L_D$$

Triode: $V_{DS} < V_{GS} - V_{TH}$

$$I_D = \mu_n C_{ox}\left(\frac{W}{L_{eff}}\right)\left[(V_{GS} - V_{TH})V_{DS} - \frac{1}{2}V_{DS}^2\right]$$

Saturation: $V_{DS} \geq V_{GS} - V_{TH}$

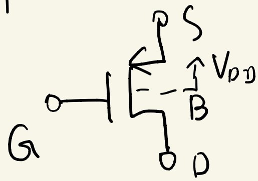
$$I_D = \frac{1}{2}\mu_n C_{ox}\left(\frac{W}{L_{eff}}\right)(V_{GS} - V_{TH})^2(1 + \lambda V_{DS})$$

channel-length: $\lambda \neq 0$

body-effect: $\gamma \neq 0$

☆ Since the structure of MOSFET is symmetric, D & S terminals exchange automatically with the change of V_D & V_S

PMOS:



$$|V_{TH}| = |V_{TH0}| + \gamma\left(\sqrt{|2\phi_F + V_{BS}|} - \sqrt{|2\phi_F|}\right)$$

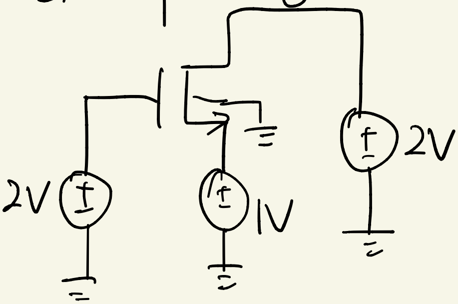
triode: $V_{SD} < V_{SG} - |V_{TH}|$

$$I_D = \mu_p C_{ox} \left(\frac{W}{L_{eff}}\right)\left[(V_{SG} - |V_{TH}|)V_{SD} - \frac{1}{2}V_{SD}^2\right]$$

saturation: $V_{SD} \geq V_{SG} - |V_{TH}|$

$$I_D = \frac{1}{2}\mu_p C_{ox} \left(\frac{W}{L_{eff}}\right)(V_{SG} - |V_{TH}|)^2 (1+\lambda V_{SD})$$

Example 8



$\lambda \neq 0 \quad \gamma \neq 0$

$\frac{W}{L} = \frac{10\mu m}{2\mu m} \qquad V_{TH0} = 0.7V$

$V_{GS} > V_{TH} \Rightarrow M_1$ turns on

$V_{DS} > V_{GS} - V_{TH} \Rightarrow M_1$ saturates

$\lambda = 0.1,\ \gamma = 0.45,\ L_D = 0.08$

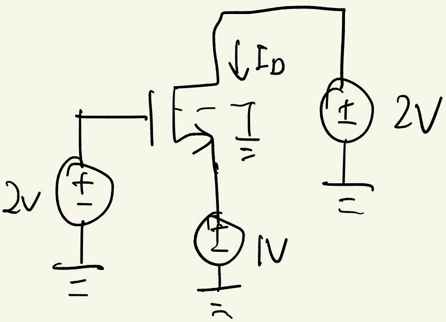
$I_D = ?$

$$V_{TH} = 0.7 + 0.45\left(\sqrt{0.9+1} - \sqrt{0.9}\right)$$

$$I_D = \frac{1}{2}\mu_n C_{ox}\left(\frac{W}{L_{eff}}\right)(V_{GS} - V_{TH})^2 (1 + \lambda V_{DS})$$

$$= \frac{1}{2}\mu_n C_{ox}\left(\frac{10}{2 - 0.08 \times 2}\right)(1 - V_{TH})^2 (1 + 0.1 \times 1)$$

Example 9 $\quad \lambda = 0 \quad \gamma = 0$



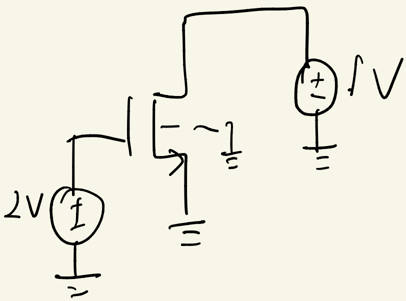
$V_{GS} > V_{TH}$

& $V_{DS} > V_{GS} - V_{TH}$ (sat)

$$V_{TH} = 0.7 + 0\left(\sqrt{0.9+1} - \sqrt{0.9}\right) = 0.7$$

$$I_D = \frac{1}{2}\mu_n C_{ox}\left(\frac{10}{2-0.08\times 2}\right)(1-0.7)^2$$

Example 10



$\lambda \neq 0 \quad \gamma \neq 0$

$V_{GS} > V_{TH} \Rightarrow$ on

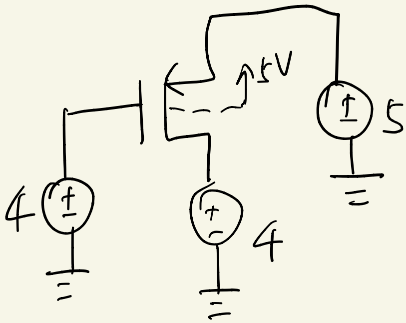
$V_{DS} < V_{GS} - V_{TH} \Rightarrow$ triode

$$V_{TH} = 0.7 + 0.45\left(\sqrt{0.9+0} - \sqrt{0.9}\right)$$
$$= 0.7$$

Although $\gamma \neq 0$, $V_{SB} = 0$, $V_{TH} = V_{TH0}$

$$I_D = \mu_n C_{ox}\left(\frac{W}{L_{eff}}\right)\left[(V_{GS} - V_{TH})V_{DS} - \frac{1}{2}V_{DS}^2\right]$$
$$= \mu_n C_{ox}\left(\frac{10}{2-0.08\times 2}\right)\left[(1-0.7)\times 1 - \frac{1}{2}\times 1^2\right]$$

Example 11 $\lambda \neq 0$ $\gamma \neq 0$



$V_{SG} > |V_{TH}| \Rightarrow$ turns on

$V_{SD} > V_{SG} - |V_{TH}| \Rightarrow$ saturates

$$|V_{TH}| = |-0.8| + 0.4\left(\sqrt{0.8+0} - \sqrt{0.8}\right)$$

$$I_D = \frac{1}{2}\mu_p C_{ox}\left(\frac{W}{L_{eff}}\right)\left(V_{SG} - |V_{TH}|\right)^2(1+\lambda V_{SD})$$

$$= \frac{1}{2}\mu_p C_{ox}\left(\frac{10}{2-0.09\times 2}\right)(1-0.8)^2(1+0.2\times 1)$$

$|V_{TH0}| = 0.8$, $\gamma = 0.4$

$\lambda = 0.2$

$L_D = 0.09$