Name: solution **Student ID:** ____________________

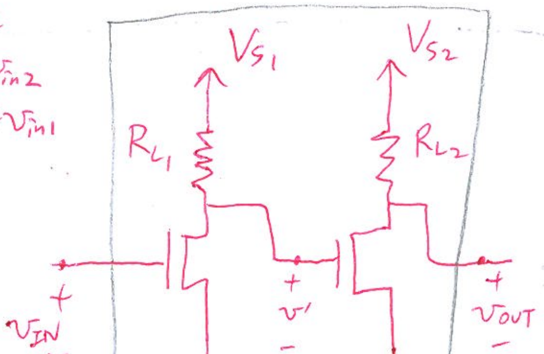
National Taiwan Normal University
Department of Computer Science and Information Engineering
CSU0007 - Basic Electronics
Final Exam (June. 15, 2020)

Clearly state each step of your answer.
In the following questions, consider the circuit in Figure 1 (drawn on the blackboard).

$K = 1\ mA/V^2$

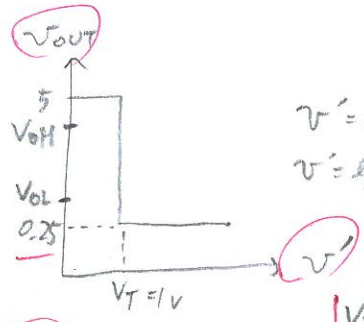
1. (10 points) Consider the S model of the MOSFET. $V_{S1}=V_{S2}=5V$. $R_{L1}=R_{L2}=10\ k\Omega$. $V_T=1V$. Suppose that $v_{IN}=0V$. $v_{OUT}=?$
2. (10 points) Consider the SR model. We want to design a circuit such that if v_{IN}=logic 0, v_{OUT} will be logic 0, and that if v_{IN}=logic 1, v_{OUT} will be logic 1. Suppose $V_T=1V$, $V_{S1}=V_{S2}=5V$, $R_{ON}=1\ k\Omega$, $R_{L1}=9\ k\Omega$, $R_{L2}=19\ k\Omega$. And we want to have a noise margin of 0.5V for logic 0 and a noise margin of 1V for logic 1. Give a valid set of thresholds V_{OL}, V_{OH}, V_{IL}, and V_{IH}.
3. (10 points) Following Question 2, suppose that now V_{OL}= 0.5V, V_{OH} =4V, V_{IL}=0.9V, and V_{IH}=3V, and $R_{ON}=2\ k\Omega$, $R_L=18\ k\Omega$, $V_{S1}=5$ V, $V_T=1V$. What are the valid value ranges for R_{L1} and V_{S2}?
4. (10 points) Again, consider the SR model. Suppose that we $V_{S1}=V_{S2}=5V$. $R_{L1}=10\ k\Omega$. $R_{ON}=2\ k\Omega$. $V_T=1V$. If we want $|v_{OUT}/v_{IN}|=0.5$, given $v_{IN}=0.5V$. What should be the value of resistance R_{L2}?
5. (10 points) Following Question 4, but now consider the SCS model. If we still want $|v_{OUT}/v_{IN}|=0.5$, given $v_{IN}=0.5V$. Explain why in this case the right MOSFET will not operate in the saturation region.
6. (10 points) Following Question 4, but now consider the SCS model. If $v_{IN}=1.8V$, find $v_{OUT}=?$
7. (10 points) Following Question 4, but now consider the SCS model. If $R_{L1}=8\ k\Omega$ and $R_{L2}=1.5\ k\Omega$. Find the maximum valid v_{IN} range for *both* MOSFETs to operate in the saturation region.
8. (10 points) Using graphical analysis to show that for a SCS model, if we increase R_{L2} and keep the same v_{IN} as before, then for the same v_{OUT} we will need to produce a smaller value of v'.
9. (10 points) Draw the small-signal model of the circuit in Figure 1.
10. (10 points) Following Question 9, suppose that we want to have the magnitude of the small-signal gain $|v_{out}/v_{in2}|=0.5$, what should be the DC bias V_{IN1}?

in this case
$v' = V_{IN2} + v_{in2}$
$v_{IN} = V_{IN1} + v_{in1}$



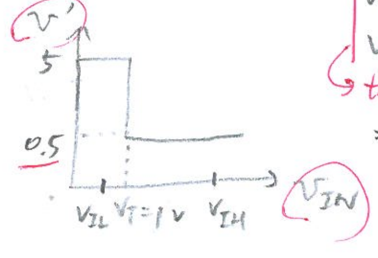
(2) v_{OUT} = logic 1 $\Rightarrow v_{OUT} = V_{S2} = 5V$

v_{OUT} = logic 0 $\Rightarrow v_{out} = 5 \times \frac{1}{19+1} = 0.25\ V$



v' = logic 1 $\Rightarrow v' = V_{S1} = 5$

v' = logic 0 $\Rightarrow v' = 5 \times \frac{1}{9+1} = 0.5\ V$



$V_{IL} - V_{OL} = 0.5$
$V_{OH} - V_{IH} = 1$
the definition of noise margin

$\Rightarrow V_{IL} = 0.8$
$V_{OL} = 0.3$
$V_{IH} = 3$
$V_{OH} = 4$

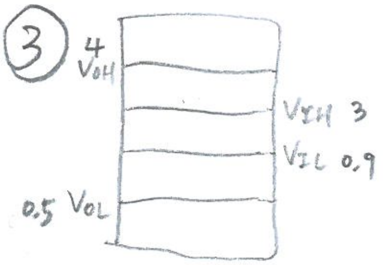
(1) $V_{IN} = 0 < V_T$ the left MOSFET is OFF

$\Rightarrow v' = V_{S1} \Rightarrow v' \geq V_T$

$\Rightarrow$ the right MOSFET is ON

$\Rightarrow v_{OUT} = 0\ V$ #

③



left MOSFET ON → right MOSFET OFF

$\Rightarrow v' = V_{S1} \times \dfrac{2}{R_{L1}+2} < V_T \Rightarrow R_{L1} > 8\ k\Omega$

right MOSFET ON $\Rightarrow v_{OUT} \leq 0.5\,V$

$\Rightarrow V_{S2} \times \dfrac{2}{R_{L2}+2} < 0.5 \Rightarrow V_{S2} \leq 5\,V$

right MOSFET OFF $\Rightarrow V_{S2} \geq 4 \Rightarrow 4 \leq V_{S2} \leq 5$

(Note that if $R_{L2} = 8\,k\Omega$, we'll have $V_{S2} \times \frac{2}{8+2} < 0.5 \Rightarrow V_{S2} < 2.5$, which conflicts to $V_{S2} \geq 4$)

If you think of the left MOSFET inverter and the right MOSFET inverter as two components, you may write

$v' = V_{S1} \times \dfrac{2}{R_{L1}+2} < V_{OL}$, which gives $R_{L1} > 18\ k\Omega$

④ $5 \times \dfrac{2}{R_{L2}+2} = \underset{}{\overset{v_{OUT}}{0.25}} \Rightarrow R_{L2} = 38\ k\Omega$ #

⑤ $\left| \dfrac{v_{OUT}}{v_{IN}} \right| = 0.5$ and $v_{IN} = 0.5\,V$ means we need $v_{OUT} = 0.25\,V$

This suggests that the V_{DS} of the right MOSFET is 0.25 V.

But $V_{IN} = 0.5\,V$ implies that V_{GS} of the right MOSFET is 5 V.

Thus we have $V_{GS} - V_T > V_{DS}$ and $V_{GS} > V_T$, which means that the right MOSFET is operating in the triode region.

⑥ $V_{IN} > V_T$ suppose in saturation, then $v' = V_{S1} - \dfrac{k(V_{IN}-V_T)^2}{2} \cdot R_{L1} = 5 - \dfrac{10^{-3} \times 0.64}{2} \times 10 \times 10^3$

$\Rightarrow v' = 1.8\,V$

verify $V_{IN} - V_T < 1.8\,V$, so indeed it operates in the saturation region.

To compute v_{OUT}, apply the same procedure for the right MOSFET.

Since I did not give the value of R_{L2} in this question, it's fine to just write $v_{OUT} = V_{S2} - \dfrac{k(v'-V_T)^2}{2} R_{L2} = 5 - 0.32 \times 10^{-3} R_{L2}$ #

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① Ⓐ First, for the right MOSFET to operate in the saturation region, the maximum input voltage range is

$$V_T \rightarrow \frac{-1+\sqrt{1+2V_S R_{L_2} K}}{R_{L_2}\cdot K} + V_T$$

(see Pages 358~359 in the textbook)

$$\Rightarrow 1 \rightarrow \underbrace{\frac{-1+\sqrt{1+2\times 5\times 1.5\times 10^3\times 10^{-3}}}{1.5\times 10^3\times 10^{-3}}}_{=\,2} + 1$$

$\Rightarrow$ 1 ~ 3 V for v' this range dominates.

Ⓑ Then, for the left MOSFET, the maximum output range for the saturation region is

$$V_{S_1} \rightarrow \frac{-1+\sqrt{1+2V_{S_1}\cdot R_{L_1}\cdot K}}{R_{L_1}\cdot K}$$

(again, see pages 358~359)

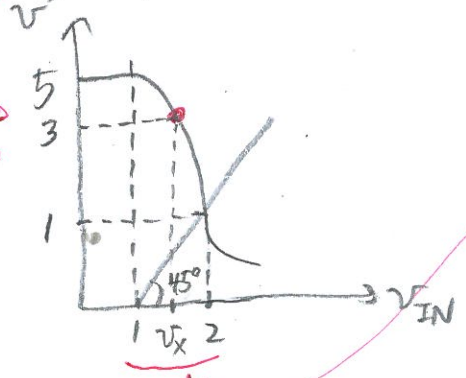
$$\Rightarrow 5 \rightarrow \frac{-1+\sqrt{1+2\times 5\times 8\times 10^3\times 10^{-3}}}{8\times 10^3\times 10^{-3}}$$

$\Rightarrow$ 5 ~ 1 V for v'

Ⓒ Similarly, the maximum input range for the left MOSFET to operate in the saturation region is $V_T \rightarrow \frac{-1+\sqrt{1+2V_{S_1}\cdot R_{L_1}\cdot K}}{R_{L_1}\cdot K} + V_T$

$\Rightarrow$ 1 ~ 2 V for v_{IN}

Combining Ⓐ, Ⓑ, Ⓒ:



The maximum valid v_{IN} range is

$v_X \sim 2V$

where $3 = 5 - \frac{K(v_X - V_T)^2}{2}\cdot R_{L_1}$

$3 = 5 - 4(v_X - 1)^2$

$v_X = 1 + \sqrt{0.5}$

$\Rightarrow$ $1+\sqrt{0.5}\,V \le v_{IN} \le 2\,V$ #

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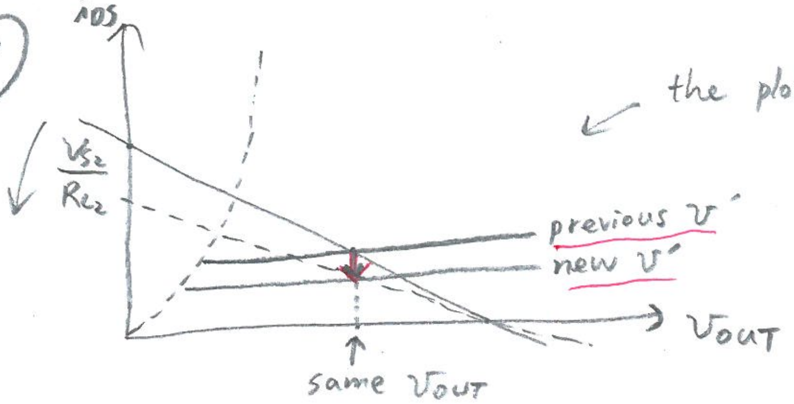
⑧

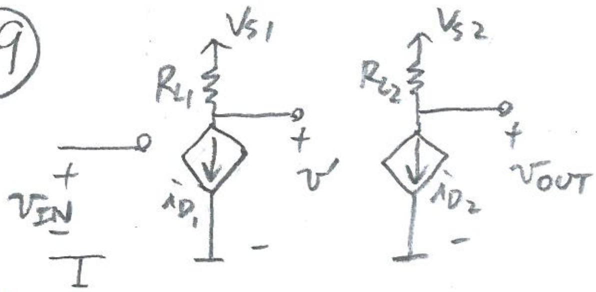


the plot for "the right MOSFET"

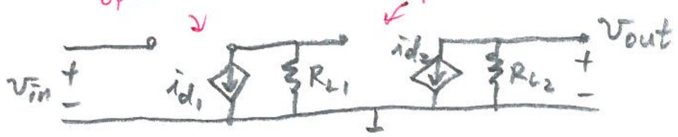
(the phrase "keep the same V_{IN}" is unnecessary.)

for further study, that means we will need a larger value of R_{L1}, and beware that R_{L1} must not be too large to cause the left MOSFET to enter the triode region.

⑨



small-signal model



⑩
$$\begin{cases} 0.5 = \left| \dfrac{v_{out}}{v_{in2}} \right| = K(V_{IN2} - V_T)R_{L2} \\[2ex] V_{IN2} = V_{S1} - \dfrac{K(V_{IN1} - V_T)^2}{2} \cdot R_{L1} \end{cases}$$

(note that
$v' = V_{IN2} + v_{in2}$
$v_{IN} = V_{IN1} + v_{in1}$)

our target

I mistakenly circled this one on the blackboard...

$$\Rightarrow \begin{cases} V_{IN2} = \dfrac{0.5}{KR_{L2}} + V_T \\[2ex] V_{S1} - V_{IN2} = \dfrac{KR_{L1}(V_{IN1} - V_T)^2}{2} \end{cases}$$

$$\Rightarrow V_{IN1} = V_T + \sqrt{(V_{S1} - V_{IN2}) \cdot \frac{2}{KR_{L1}}}$$

$$= V_T + \sqrt{\frac{2(V_{S1} - V_{IN2})}{KR_{L1}}}$$

$$= V_T + \sqrt{\frac{2\left(V_{S1} - \frac{0.5}{KR_{L2}} - V_T\right)}{KR_{L1}}}$$

3

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