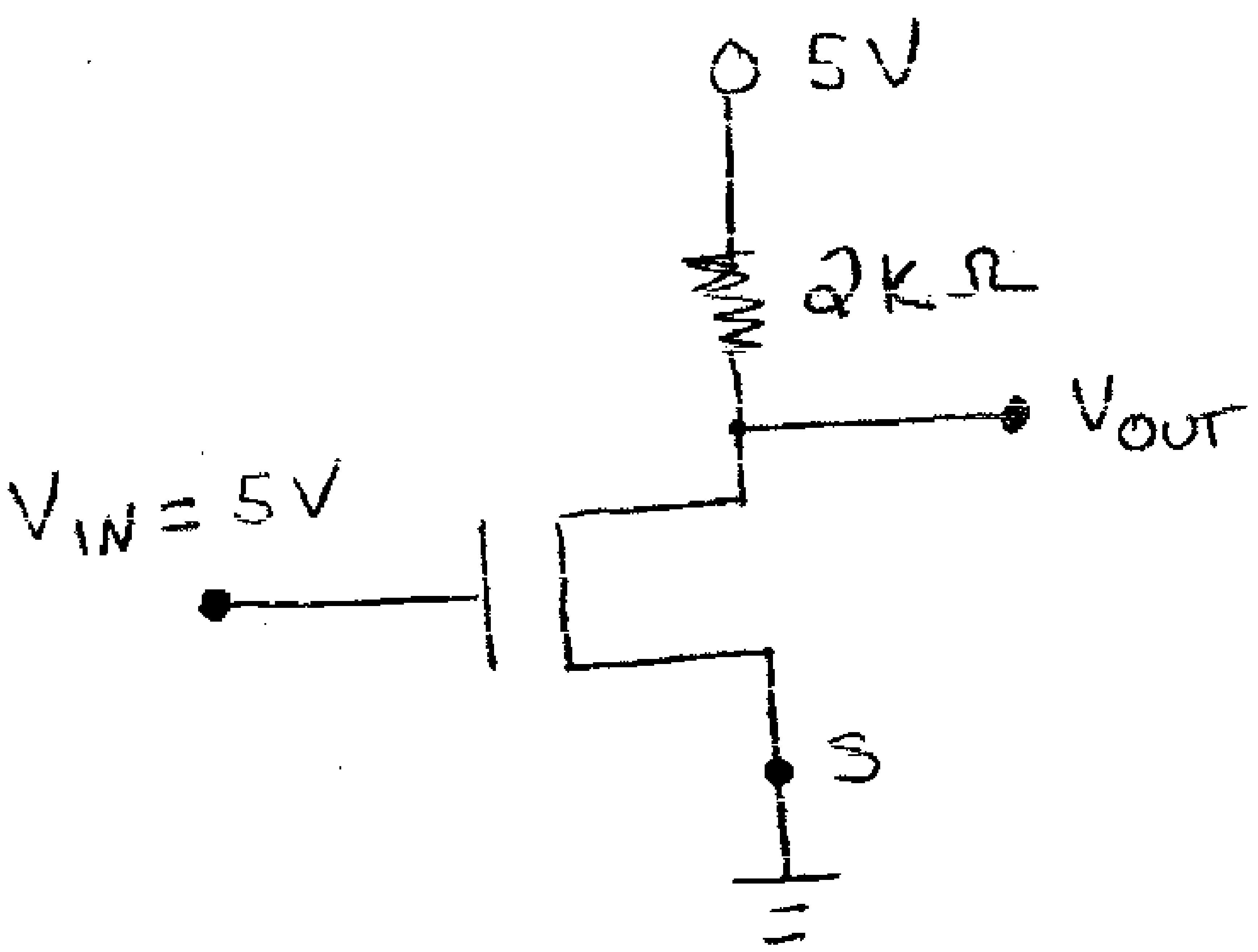


$V_{TH(n)} = 1V$

$\lambda_n = 0$

$\frac{W}{L}\mu_n C_{ox} = 1mA/V^2$

Find V_{GS}, V_{DS}, I_D, and Vout.

- $V_{GS} = V_G = V_{in} = \boxed{5V.}$

  $V_{GS} > V_{TH} \Rightarrow$ not cutoff mode.

- Assume saturation mode. (i.e. $V_{DS} > V_{GS} - V_{TH}$).

  Then, $i_D = \frac{1}{2} \cdot (1mA/V^2) \cdot (\underbrace{V_{GS} - V_{TH}}_{=4V})^2 = 8mA.$

  $\Rightarrow V_{out} = 5 - (2k\Omega)(8mA) = 5 - 16 = -11\ V.$

  $\Rightarrow$ not saturation mode.

- Assume ~~cutoff~~ $\boxed{\text{triode mode}}$. Then, $V_{DS} < V_{GS} - V_{TH} = 4V.$

  $i_D = (1mA/V^2)(V_{GS} - V_{TH} - V_{DS}/2)\ V_{DS}$, and

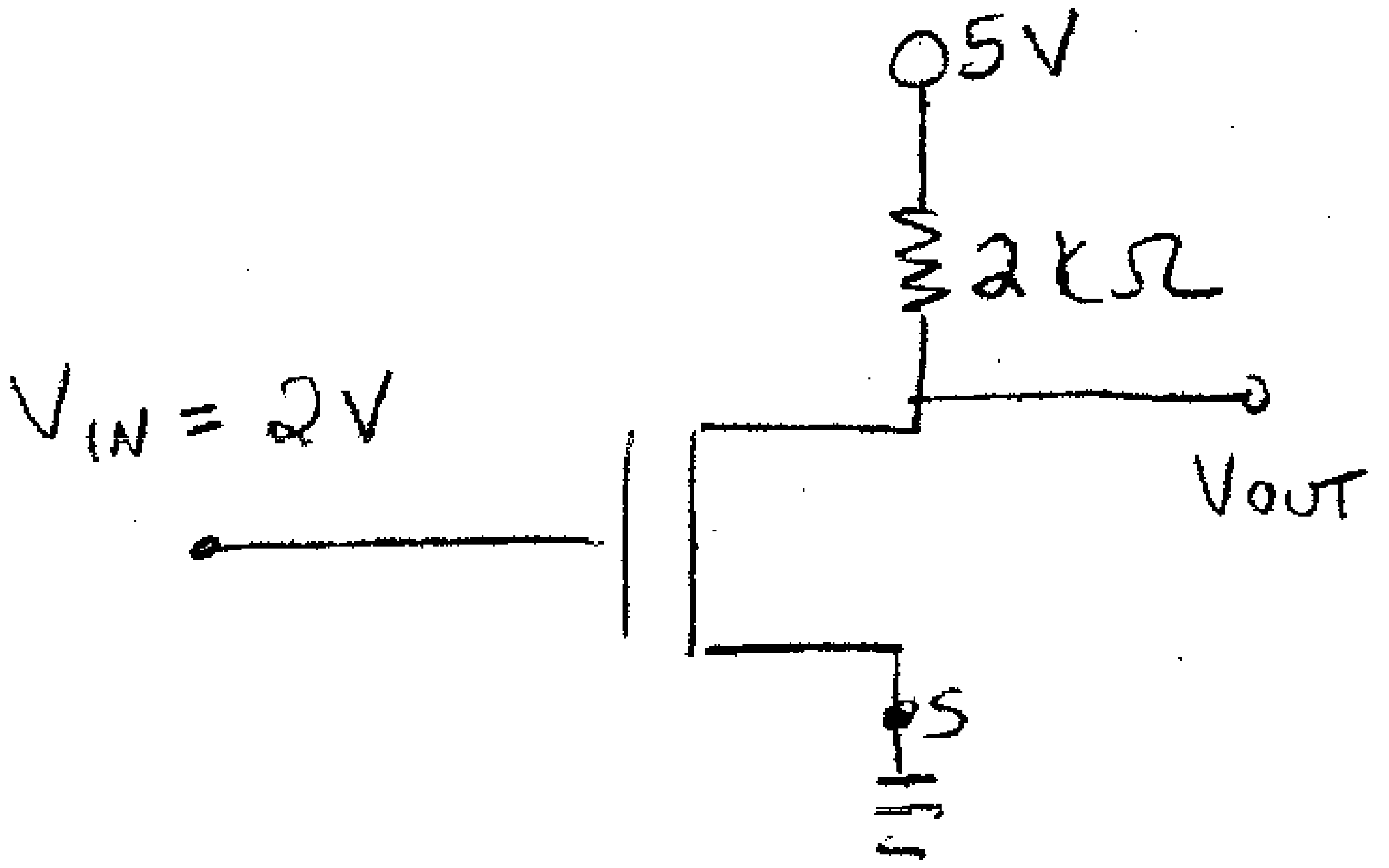
  $i_D = \frac{5 - V_{DS}}{2k}.$

  ~~Subs~~ $\frac{5 - V_{DS}}{2k} = (1mA/V^2)(4 - V_{DS}/2)\ V_{DS}$

  $5 - V_{DS} = (8 - V_{DS}) \cdot V_{DS} \Rightarrow V_{DS}^2 - 9V_{DS} + 5 = 0$

  $V_{DS} = \frac{9 \pm \sqrt{81 - 20}}{2} \approx \frac{9 \pm 7.8}{2}$. $V_{DS} < 4V \Rightarrow V_{DS} = \frac{9 - 7.8}{2} = \boxed{0.6V}$

  $\Rightarrow \boxed{V_{out} = 0.6V}$, $i_D = \frac{5 - 0.6}{2k} = \boxed{2.2mA}$.



$V_{TH(n)} = 1V$

$\lambda_n = 0$

$\frac{W}{L} \mu_n C_{ox} = 1mA/V^2$

Find V_{GS}, V_{DS}, I_D & V_{OUT}.

- $V_{GS} = V_{in} = \boxed{2V}$.

$V_{GS} > V_{TH} = 1V \Rightarrow$ not cutoff mode.

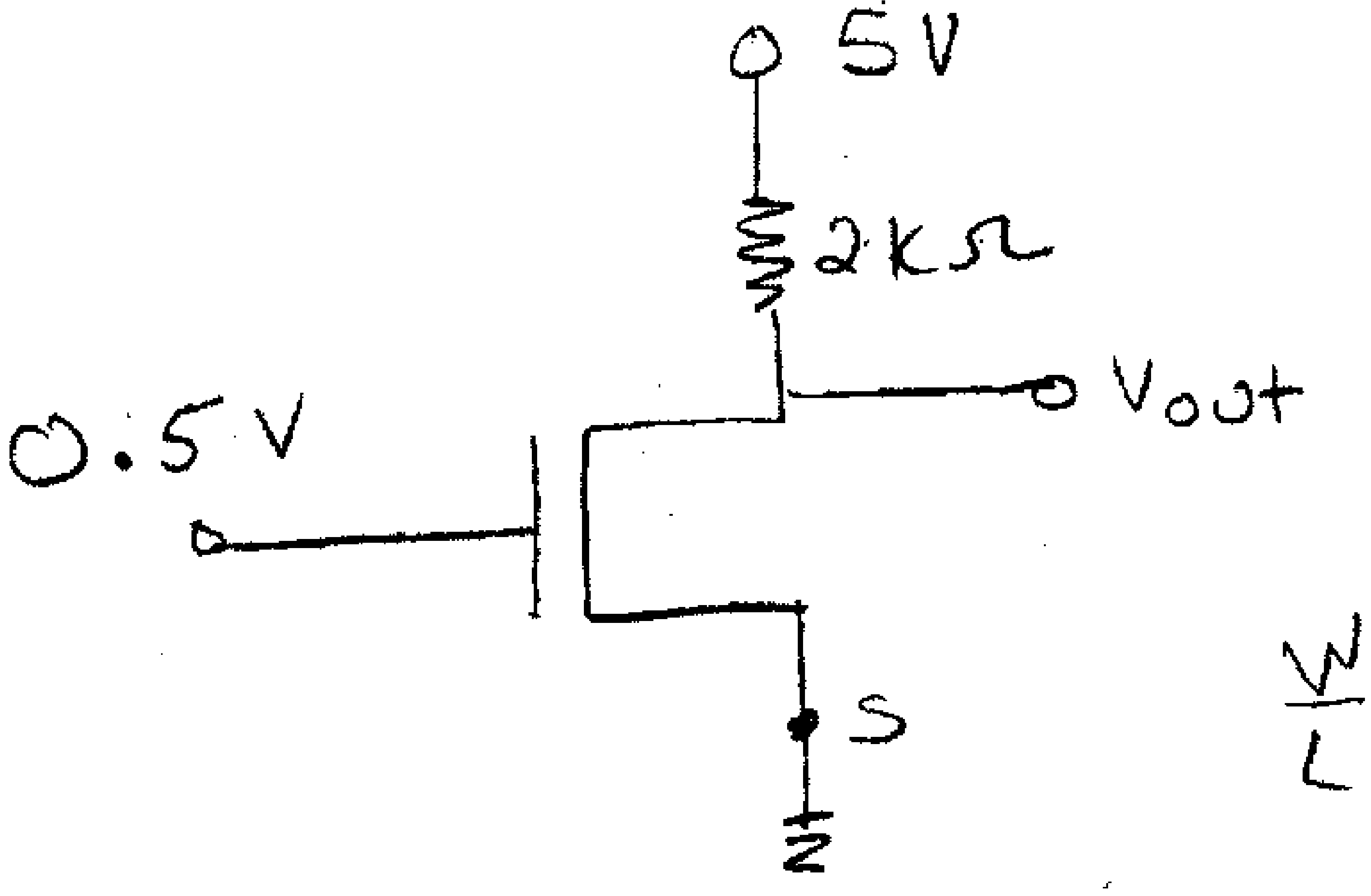
- Assume $\boxed{\text{saturation mode}}$. ($V_{DS} > V_{GS} - V_{TH} = 1V$).

Then, $i_D = \frac{1}{2} \cdot (1mA/V^2)(\underbrace{V_{GS} - V_{TH}}_{1V})^2 = \boxed{0.5mA}$

$V_{DS} = 5 - (2k)(0.5m) = \boxed{4V}$.

$V_{DS} > V_{GS} - V_{TH}$ ✓ (saturation mode ✓)

So, $V_{out} = \boxed{4V}$.



$V_{TH(n)} = 1V$

$\lambda_n = 0$

$\frac{W}{L}\mu_n C_{ox} = 1\ mA/V^2$

Find V_{GS}, V_{DS}, I_D & V_{OUT}.

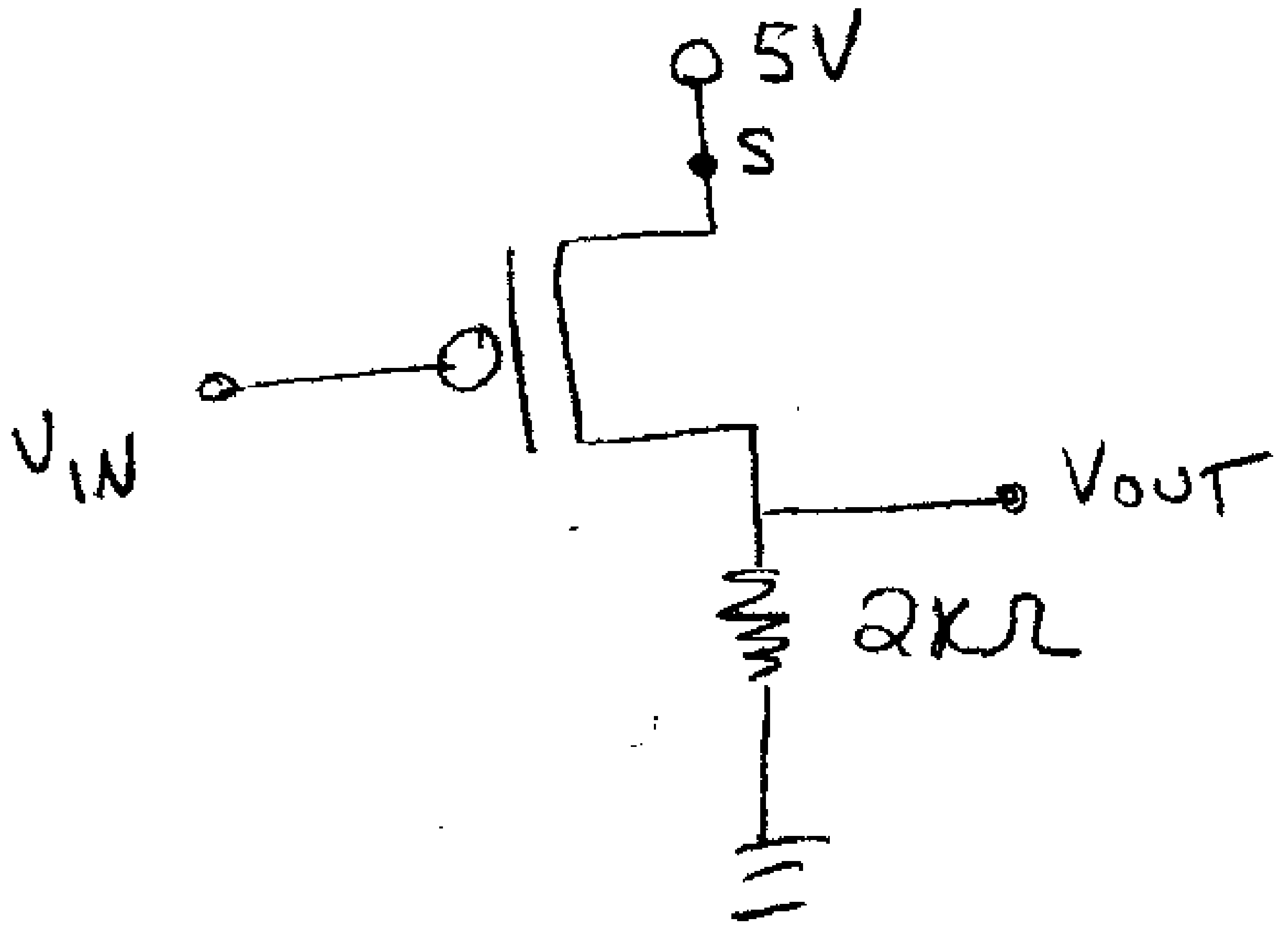
$V_{GS} = V_G - V_s = 0.5V - 0V = \boxed{0.5 V}$

$V_{GS} = 0.5V < V_{TH} = 1V \Rightarrow$ $\boxed{\text{cut-off mode}}$

cutoff mode $\Rightarrow i_D = \boxed{0 A}$

$V_{out} = 5 - (2k)(0) = \boxed{5 V}$

$V_{DS} = V_{out} = \boxed{5 V}$.



$V_{TH(p)} = -1V$

$\lambda_p = 0$

$\frac{W}{L} \mu_p C_{ox} = 1 \frac{mA}{V^2}$

This circuit is the complement of the NMOS inverter.

Find V_{OUT} for $V_{IN} = 4.5V$, $3V$, and $0V$.

1) $V_{in} = 4.5 V. \Rightarrow V_{GS} = V_G - V_S = 4.5 - 5 = -0.5 V.$

$V_{GS} = -0.5 V > V_{TH} = -1V \Rightarrow$ cutoff mode $\Rightarrow i_D = 0 A$

$\Rightarrow V_{out} = (2k\Omega)(0A) = \boxed{0V}.$

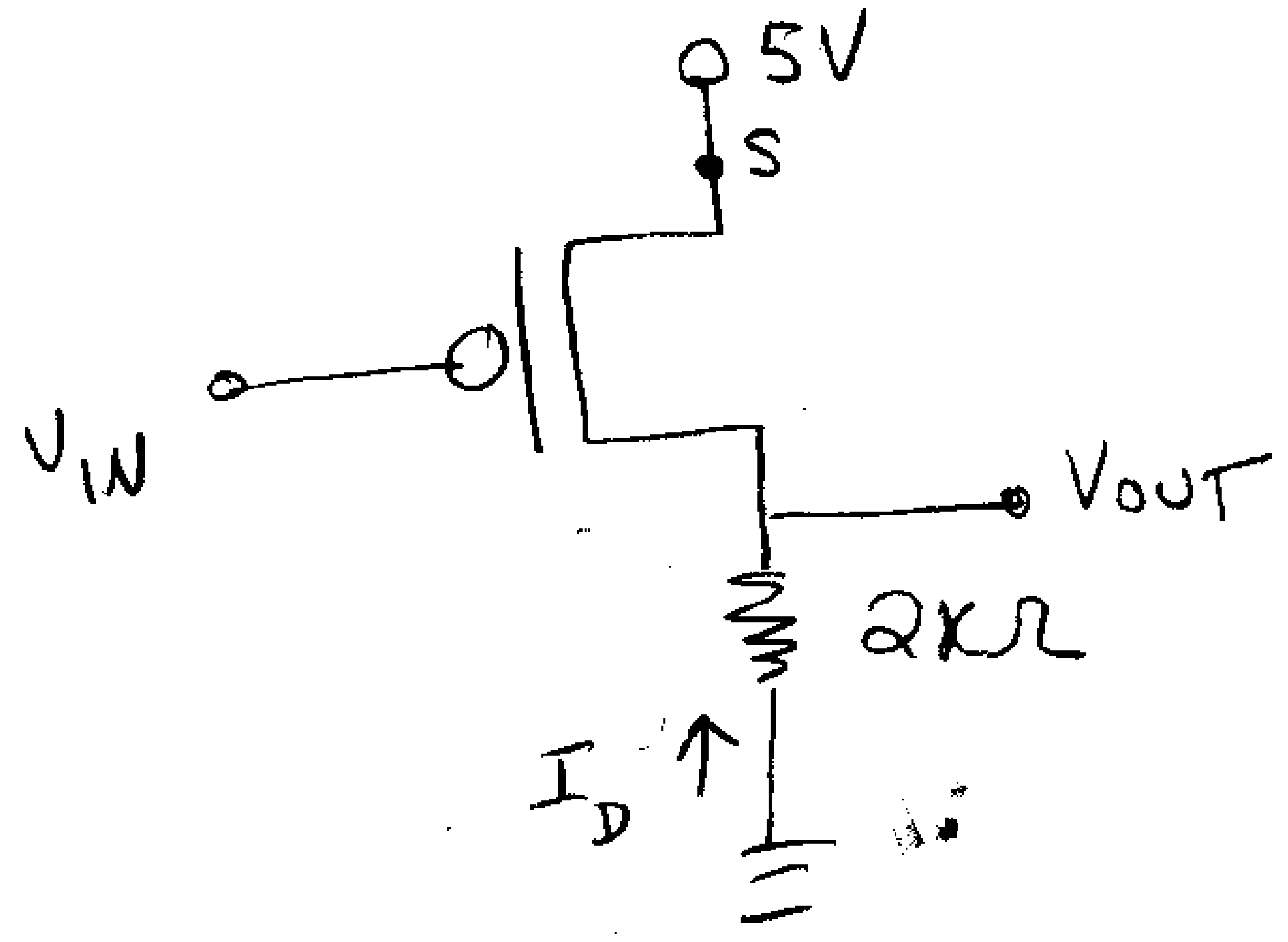
2) $V_{in} = 3V. \Rightarrow V_{GS} = 3 - 5 = -2V.$

$V_{GS} < V_{TH} \Rightarrow$ not cutoff. Assume saturation. Then,

$$i_D = -(1mA/V^2) \cdot \frac{1}{2} (\underbrace{V_{GS} - V_{TH}}_{-2-(-1)})^2 = -0.5mA.$$

$\Rightarrow V_{out} = V_D = (2k)(-0.5m) = \boxed{-1 V.}$

$V_{DS} = V_D - V_S = -1 - 5 = -6 V. <' V_{GS} - V_{TH} \Rightarrow$ indeed in saturation mode.



$V_{TH(p)} = -1V$

$\lambda p = 0$

$\frac{W}{L}\mu_p C_{ox} = 1\frac{mA}{V^2}$

This circuit is the complement of the NMOS inverter.

Find V_{OUT} for $V_{IN} = 4.5V$ 3V, and 0V.

$V_{IN} = 0$: $V_{GS} = 0V - 5V = -5V$ not cutoff

assume Saturation $I_D = -1\frac{mA}{V^2}\frac{1}{2}(-5V - -1V)^2 = -8mA$

$V_{DS} = -2kI_D - 5V = 11V$ not possible for PMOS

so triode mode;

$I_D = -1\frac{mA}{V^2}(-5V - -1V - \frac{V_{DS}}{2})V_{DS}$

KVL: $V_{DS} = -2kI_D - 5V \Rightarrow I_D = -\left(\frac{5V + V_{DS}}{2K}\right)$

Solve simultaneously to get

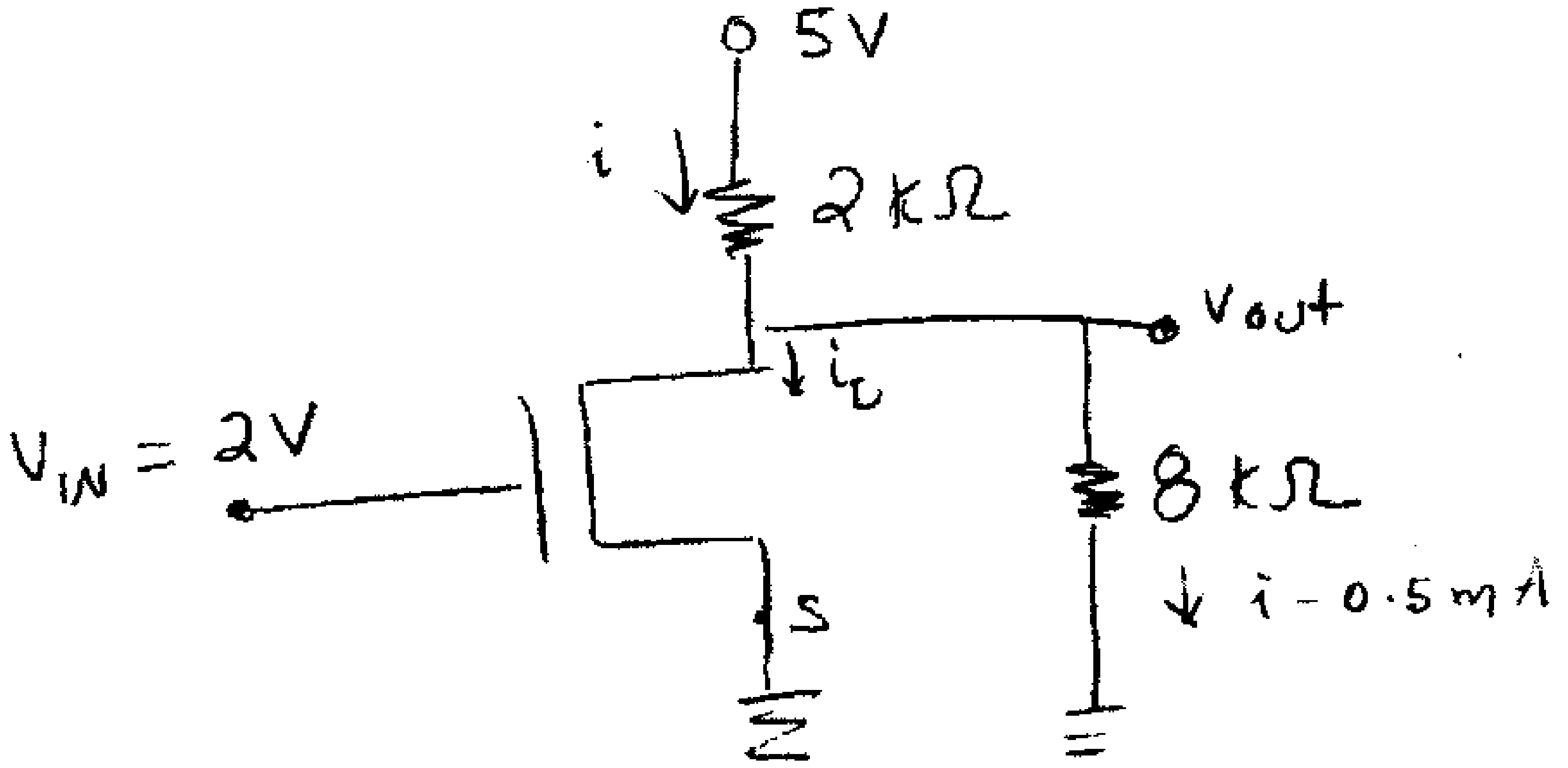
$V_{DS} = \{-0.6, -8.\overset{3}{\cancel{4}}$ not possible for triode mode

$I_D = -\left(\frac{5V - 0.6}{2K}\right) = -2.2mA$

$V_{OUT} = -2kI_D = 4.4V$

Our inverters had open outputs.

If there is something (a "load") attached, the voltages & currents are different.



Find V_{GS}, V_{DS}, I_D & V_{OUT}.

- $V_{GS} = V_G - V_S = 2 - 0 = \boxed{2V} > V_{TH} = 1V \Rightarrow$ not cutoff.
- Assume saturation mode. Then,

$$i_D = (1mA/V^2) \cdot \frac{1}{2} (\underbrace{V_{GS} - V_{TH}}_{2-1})^2 = \boxed{0.5 mA}$$

KVL: $5V = 2k \cdot i + 8k(i - 0.5mA)$

$5 = i \cdot 10k - 4$

$i = \frac{9}{10k} = 0.9mA \Rightarrow V_{out} = 8k(0.9m - 0.5m)$

$= 8k(0.4m)$

$= \boxed{3.2V}$

$V_{DS} = V_{out} = \boxed{3.2V} > V_{GS} - V_{TH}$

$\Rightarrow$ saturation mode ✓