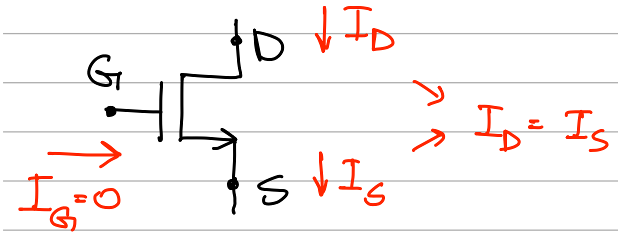
MOSFET:



$V_{OV} = V_{GS} - V_T$

① $V_{GS} < V_T$: MOSFET OFF

$I_D = I_S = 0$

Triode:

② $V_{GS} > V_T$,

$V_{DS} < V_{OV}$.

$\boxed{I_D = k\left(V_{OV}V_{DS} - \frac{V_{DS}^2}{2}\right)}$

"channel ^almost^ linear"

③ Saturation:

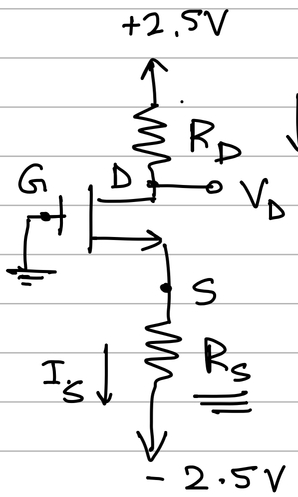
$V_{GS} > V_T$,

$V_{DS} > V_{OV}$.

$\boxed{I_D = \frac{k V_{OV}^2}{2}}$

channel in "pinch off" state. Flows same current.

Ex 2:



$V_T = 0.7V$

$k = 3.2 \ mA/V^2$

MOSFET operates at $I_D = 0.4mA$ and $V_D = +0.5V$. $\therefore R_D = \frac{2.5 - 0.5}{0.4} = 5k\Omega$

"ohm's law"

Soln:

$V_G = 0$, $V_S = $ idk , $V_D = 0.5V$

Assume saturation:

$$\boxed{I_D} = \frac{k V_{OV}^2}{2} = \frac{k}{2}(V_{GS} - V_T)^2$$

$$\Rightarrow 0.4 = \frac{\cancel{3.2}^{1.6}}{\cancel{2}}(0 - V_S - 0.7)^2 \Rightarrow \frac{\cancel{0.4}^{1}}{\cancel{1.6}_{4}} = (V_S + 0.7)^2$$

$$\Rightarrow V_S^2 + 1.4V_S + 0.7^2 = 0.25 \Rightarrow V_S^2 + 1.4V_S + 0.24 = 0$$

$$\Rightarrow V_S = \underline{-0.2V} \text{ or } \underline{-1.2V}$$

$V_G = 0V,\ V_D = 0.5V,\ V_S = \quad ,\ I_D = 0.4\,mA.,\ V_T = 0.7V$

$V_S = -0.2V$

$$V_{GS} = 0 - (-0.2) = 0.2V$$

$$V_{OV} = V_{GS} - V_T = -0.5V$$

$$\boxed{R_S = \frac{(-0.2)-(-2.5)}{0.4} = 5.75\,k\Omega}$$

$$V_{DS} = 0.5 - (-0.2) = 0.7V \quad \therefore V_{DS} > V_{OV}$$

$$V_{GS} = 0 - (-0.2) = 0.2V \Rightarrow \boxed{\begin{matrix} V_{GS} < V_T \\ 0.2 < 0.7 \end{matrix}} \rightarrow$$ assumption not verified via this value of V_s.

$V_s = -1.2V$

$$V_{GS} = 0 - (-1.2) = 1.2V$$

$$\boxed{R_s = \frac{(-1.2)-(-2.5)}{0.4} = 3.25\,k\Omega}$$

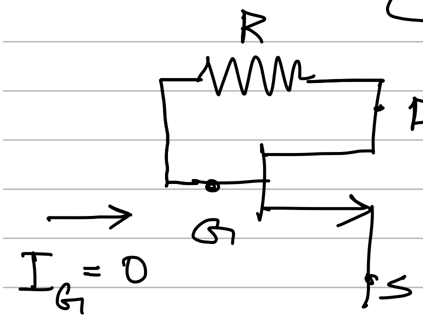
$V_{GS} = (0 - (-1.2)) = 1.2V > V_T$

$$V_{OV} = 1.2 - 0.7 = 0.5V$$

$$V_{DS} = 0.5 - (-1.2) = 1.7V \quad V_{DS} > V_{OV}$$

* Two values of V_s were not consistent. They corresponded to two values of R_s.

$$\boxed{V_{GS} = 1.2V > 0.7V}$$



$$V_{GS} = V_G - V_S$$

Here, $V_G = V_D \Rightarrow V_G - V_S = V_D - V_S$

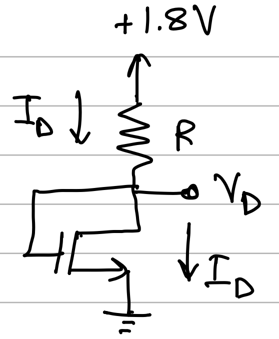
$$\Rightarrow V_{GS} = V_{DS}$$

$V_{DS} = V_{GS}$ implies $V_{DS} > V_{GS} - V_T$

$$\uparrow = \uparrow \qquad \uparrow > \uparrow$$

$\therefore V_{DS} > V_{OV} \rightarrow$ Condition for saturation in MOSFET

$\therefore$ This type of MOSFET is always in saturation



$V_T = 0.5V$

$k' = \mu_n C_{ox} = 0.4 mA/V^2$

$\frac{W}{L} = \frac{0.72 \mu m}{1.8 \mu m}$

$= 0.4$

$\boxed{k = k' \frac{W}{L}}$

$\boxed{k' = \mu_n C_{ox}}$

$k = k'\left(\frac{W}{L}\right) = 0.4 \times 0.4$

$= 1.6 \, mA/V^2$

We know, MOSFET in saturation:

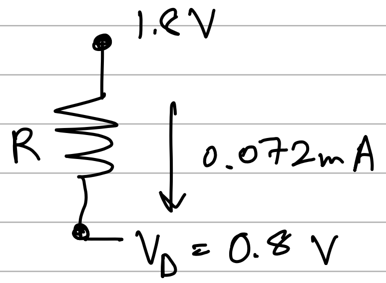
$I_D = \frac{k}{2} V_{ov}^2 \qquad V_G = V_D, \; V_S = 0,$

For what R, we get $V_D = 0.8V$?

$V_G = 0.8V, \; V_{GS} = 0.8V, \; V_{ov} = 0.8 - 0.5 = 0.3V$

$I_D = \frac{1.6}{2}(0.3)^2 = 0.072 \, mA$

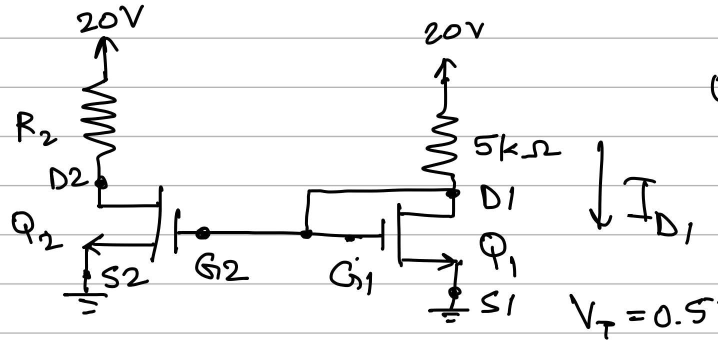
Ohm's Law:



$\Rightarrow R = \frac{1.8 - 0.8}{0.072} = 13.89 k\Omega$

[Practice sheet Q1]

P1:



$V_T = 0.5V$

$Q_1 \rightarrow$ saturation

$k' = 2 mA/V^2$

$\frac{W}{L} = 2.5$

$k = k'\left(\frac{W}{L}\right) = 5$

(a) Exactly the argument for D, G shorted above.

(b) Saturation region edge: $V_{DS2} = V_{ov2}$

Q1 : $V_{S1} = 0V$, $\boxed{V_{D1} = V_{G1}}$, $V_T = 0.5V$, $V_{GS1} = V_{G1} - V_{S1}$
$= V_{G1}$

saturation : $I_D = \frac{k}{2} V_{ov}^2 = \frac{5}{2} \times (V_{GS1} - V_T)^2$

$\Rightarrow I_{D1} = 2.5 (V_{G1} - 0.5)^2$ — (I)

Ohm's Law : $I_{D1} = \frac{20 - V_{D1}}{5} = \frac{20 - V_{G1}}{5}$ — (II)

$\therefore$ (I), (II) $\rightarrow \frac{20 - V_{G1}}{5} = \frac{5}{2} (V_{G1} - 0.5)^2$

$\Rightarrow 40 - 2V_{G1} = 25 \left[V_{G1}^2 - V_{G1} + \frac{1}{4} \right]$

$\Rightarrow 160 - 8V_{G1} = 100V_{G1}^2 - 100V_{G1} + 25$

$\Rightarrow 100V_{G1}^2 - 92V_{G1} - 135 = 0$

$\Rightarrow V_{G1} = 1.71V$ or, $-0.79V$

✓ $\rightarrow$ ✗

$V_{GS} < V_T$
$-0.79 < 0.5$
Not possible

$\therefore V_{G2} = V_{G1} = 1.71V$

Q2 :

Assume saturation :

$V_{G2} = 1.71$, $V_{S2} = 0$, $V_{D2} = ?$, $I_{D2} = ?$

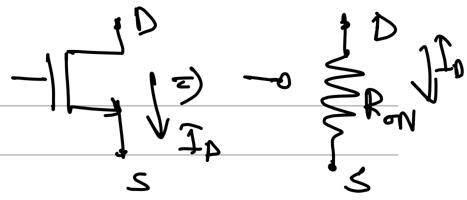
$V_{DS2} = V_{ov} = V_{GS2} - V_T = (V_{G2} - V_{S2}) - V_T = 1.71 - 0.5$
$= 1.21V$

$V_{DS2} = 1.21V$, $V_{D2} = 1.21V$ $[V_{S2} = 0]$

$I_{D2} = \frac{k}{2} V_{ov}^2 = \frac{5}{2} \times (1.21)^2 = 3.66$ mA

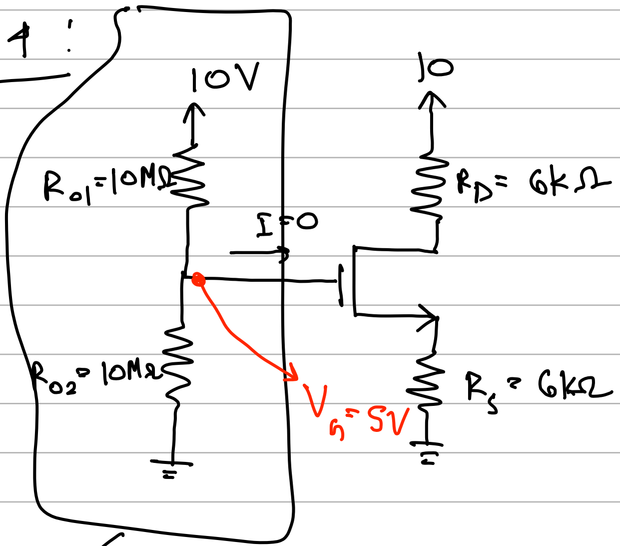
$R = \frac{20 - V_{D2}}{I_{D2}} = \frac{20 - 1.21}{3.66} = 5.134$ kΩ

(c) R_{ON} for Q2 $\Rightarrow$



$$R_{ON} = \frac{V_D - V_S}{I_D} = \frac{1.21 - 0}{3.66} = 0.33\ k\Omega$$
$$= 330\ \Omega$$

Ex 4 :

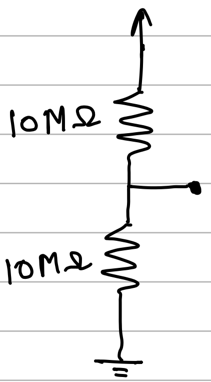


$V_T = 1V$

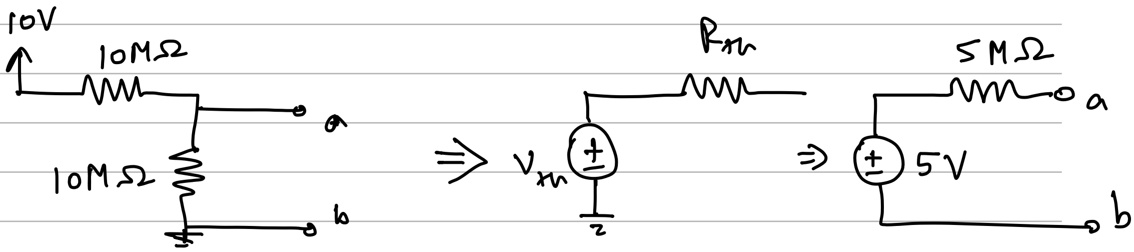
$k = k'\left(\frac{W}{L}\right) = 1\ mA/V^2$

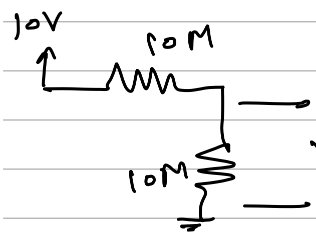
input side ckt can be independently solved

[$I_G = 0$, very similar to op amp]

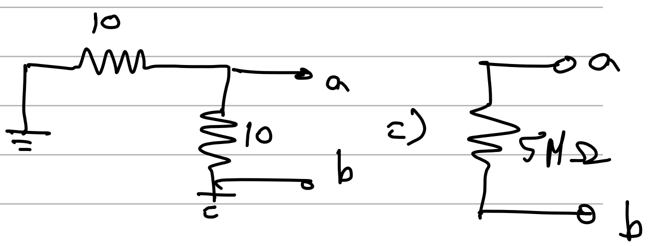


$$V_G = \frac{10\ M\Omega}{10\ M\Omega + 10\ M\Omega} \times (10V) = 5V$$

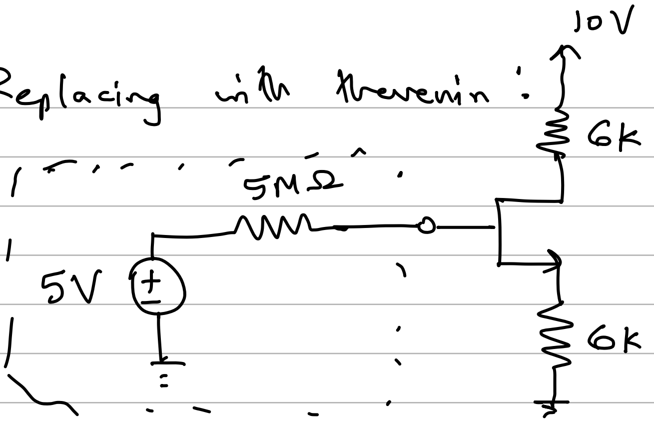




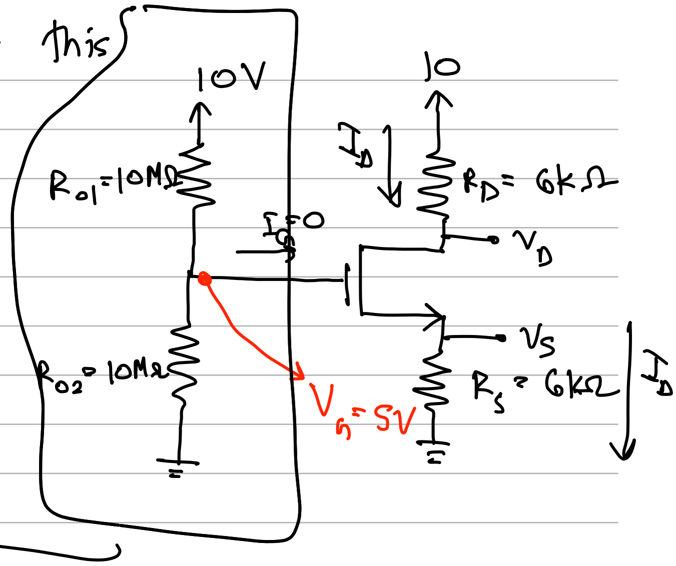
$$V_{th} = \frac{10}{10+10} \times (10)$$
$$= 5V$$



Replacing with thevenin:



or this



$V_G = 5V, \quad V_S = ?, \quad V_D = ?, \quad V_T = 1V$

Assume saturation: $I_D = \frac{k}{2} V_{ov}^2 = \frac{1}{2}(V_{GS} - V_T)^2$

$= \frac{1}{2}(5 - V_S - 1)^2$

$R_S \rightarrow \frac{V_S - 0}{6} = I_D$

$= \frac{1}{2}(4 - V_S)^2 \quad \text{— (I)}$

$\Rightarrow I_D = \frac{V_S}{6} \quad \text{— (II)}$

(I), (II) replacing I_D: $\frac{V_S}{6} = \frac{1}{2}(16 - 8V_S + V_S^2)$

$\Rightarrow V_S = 3(16 - 8V_S + V_S^2) = 48 - 24V_S + 3V_S^2$

$\Rightarrow 3V_S^2 - 25V_S + 48 = 0 \qquad V_S = 5.33V, \ 3V$

$R_D \Rightarrow \frac{10 - V_D}{6} = I_D = \frac{V_S - 0}{6} \Rightarrow V_D = 10 - V_S$

$V_S = 5.33$:

$V_D = \frac{14}{3} = 4.67V. \quad V_{DS} = 4.67 - 5.33 = -\frac{2}{3} < V_{ov}$

$V_S = 3V$:

$V_D = 7V, \quad V_{DS} = 7 - 3 = 4V > V_{ov}$ ✓

* When you assume a state, just show that the assumption is consistent for one specific root, You only have to have one root that verifies your assumption. Discard any other roots that does otherwise.

Assumption verification:

Triode	Saturation	OFF
$V_{GS} > V_T$	$V_{GS} > V_T$	$V_{GS} < V_T$
$V_{DS} < V_{OV}$	$V_{DS} > V_{OV}$	