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MOSFET TUTORIAL - 1

6. $$g_m = \frac{\partial I_D}{\partial V_{GS}}$$

$$I_D = \mu_n C_{ox} \left(\frac{W}{L}\right) \left[(V_{gs} - V_{th}) V_{ds} - \frac{1}{2} V_{ds}^2\right]$$

$$\Rightarrow \boxed{\frac{\partial I_D}{\partial V_{GS}} = \mu_n C_{ox} \left(\frac{W}{L}\right) V_{ds} = g_m}$$

$g_m = 0$ when $V_{ds} = 0$ because when $V_{ds} = 0$, even though channel is present, current will not flow. Hence, resistance $= \infty \Rightarrow g_m = \frac{1}{\text{Resistance}} = 0$.

8. $$R_{ON} = \frac{1}{\mu_n C_{ox} \left(\frac{W}{L}\right)(V_{gs} - V_{th})}$$

<u>Case-1</u>: $$500 = \frac{1}{\mu_n C_{ox} \left(\frac{W}{L}\right)(1 - V_{th})} \quad - (1)$$

<u>Case-2</u>: $$400 = \frac{1}{\mu_n C_{ox} \left(\frac{W}{L}\right)(1.5 - V_{th})} \quad - (2)$$

Dividing (1) by (2), $$\frac{5}{4} = \frac{1.5 - V_{th}}{1 - V_{th}}$$

$$\Rightarrow 5 - 5V_{th} = 6 - 4V_{th}$$

$$\Rightarrow V_{th} = -1\,V$$, which is not possible as V_{th} cannot be negative.

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7. $\mu_n C_{ox} = 200 \ \mu A/V^2$

$$R_{ON} = \frac{1}{\mu_n C_{ox}\left(\frac{W}{L}\right)(V_{gs} - V_{th})}$$

$$= \frac{1}{200\times10^{-6}\times 20\,(1.8 - V_{th})}$$

$$= \frac{250}{1.8 - V_{th}}$$

For minimum R_{ON}, $V_{th} \approx 0$

$$\Rightarrow \text{Minimum } R_{ON} = \frac{250}{1.8} = 138.88\ \Omega$$

TUTORIAL – 2

1. $V_{DS} = V_{DD} - R_D I_D = V_{DD} - R_D \mu_n C_{ox}\left(\frac{W}{L}\right)\left[(V_{gs} - V_{th})V_{ds} - \frac{1}{2}V_{ds}^2\right]$

$$\Rightarrow 1 = V_{DD} - R_D(\mu_n C_{ox})\left(\frac{W}{L}\right)\left[(V_{gs} - V_{th}) - \frac{1}{2}V_{ds}\right]$$

$$\cancel{\Rightarrow V_{ds} = \quad V_{DD} - 1}$$

$$V_{ds} = (V_{gs} - V_{th}) - \frac{V_{DD} - 1}{\mu_n C_{ox}\left(\frac{W}{L}\right)R_D}$$

$$\Rightarrow V_{ds} = (1 - 0.4) - \frac{0.8}{(10^{-4})\left(\frac{2}{0.18}\right)(10^3\times5)}$$

$$= 0.6 - \frac{0.072}{5\times10^{-1}} = 0.6 - \frac{0.72}{5}$$

$$= \frac{2.28}{5} = 0.456\,V$$

$$I_D R_D + V_{DS} = V_{DD}$$

$$\Rightarrow \quad I_D \times 5 \times 10^3 = 1.8 - 0.456$$

$$\Rightarrow \quad \boxed{I_D = 268.8 \ \mu A}$$

③ At saturation,

$$V_{gs} - V_{th} = V_{DS} = V_{DD} - I_D R_D$$

$$\Rightarrow V_{gs} - V_{th} = V_{DD} - R_D \left[\mu_n C_{ox} \frac{W}{L} \frac{(V_{gs} - V_{th})^2}{2} \right]$$

Let $V_{gs} - V_{th} = x$

$$\Rightarrow \quad x = V_{DD} - R_D \mu_n C_{ox} \frac{W}{2L} x^2$$

$$\Rightarrow \left(R_D \mu_n C_{ox} \frac{W}{2L} \right) x^2 + x - V_{DD} = 0$$

$$\Rightarrow \quad x = \frac{-1 + \sqrt{1 + 4V_{DD} \times R_D \mu_n C_{ox} \frac{W}{2L}}}{R_D \mu_n C_{ox} \frac{W}{L}}$$

$$\Rightarrow V_{GS} - V_{th} = \frac{-1 + \sqrt{1 + 2 R_D V_{DD} \mu_n C_{ox} \frac{W}{L}}}{R_D \mu_n C_{ox} \frac{W}{L}}$$

$$\Rightarrow \boxed{V_{GS} = \frac{-1 + \sqrt{1 + 2 R_D V_{DD} \mu_n C_{ox} \frac{W}{L}}}{R_D \mu_n C_{ox} \frac{W}{L}} + V_{th}}$$

* To check if it is in saturation region, $I_D = I_{sat}$ classmate

Then calculate V_{ds} from $V_{DD} - I_D R_D$, it should be $\geq V_{gs} - V_{th}$ Page

2. (i) For saturation, $V_{DS} = V_{gs} - V_{th}$.

$$V_{gs} - V_{th} = V_{DD} - I_{sat} R_D$$

$$\Rightarrow V_{gs} - V_{th} = V_{DD} - R_D \times \mu_n C_{ox} \left(\frac{W}{L}\right) \frac{(V_{gs} - V_{th})^2}{2}$$

$$\Rightarrow 0.6 = 1.8 - (5\times10^3) \times (10^{-4}) \left(\frac{W}{L}\right) \left(\frac{0.36}{2}\right)$$

$$\Rightarrow 0.6 = 1.8 - (0.09) \frac{W}{L}$$

$$\Rightarrow \frac{9}{100} \frac{W}{L} = 1.2$$

$$\Rightarrow \boxed{\frac{W}{L} = \frac{40}{3} = \frac{2.4}{0.18}}$$

For saturation, $V_{ds} \geq V_{gs} - V_{th}$

For linear, $V_{ds} < V_{gs} - V_{th}$

(ii) $\cancel{V_{ds} = \frac{V_{DD} - V_{ds1}}{R_D} =}$

$$V_{DD} - V_{ds_1} = I_D R_D$$

$$1.8 - V_{ds1} = \frac{1}{\cancel{2}} \times \cancel{2}\times10^{-4} \times \frac{40}{\cancel{3}} (\cancel{0.36}\ 0.12) \times 5\times10^3$$

$$1.8 - V_{ds_1} = 4.8\times10^{-4} \times 5\times10^3 = 2.4$$

$$\cancel{V_{ds_1}} \quad V_{ds_1} = \cancel{1.4 V}\ 0.6V$$

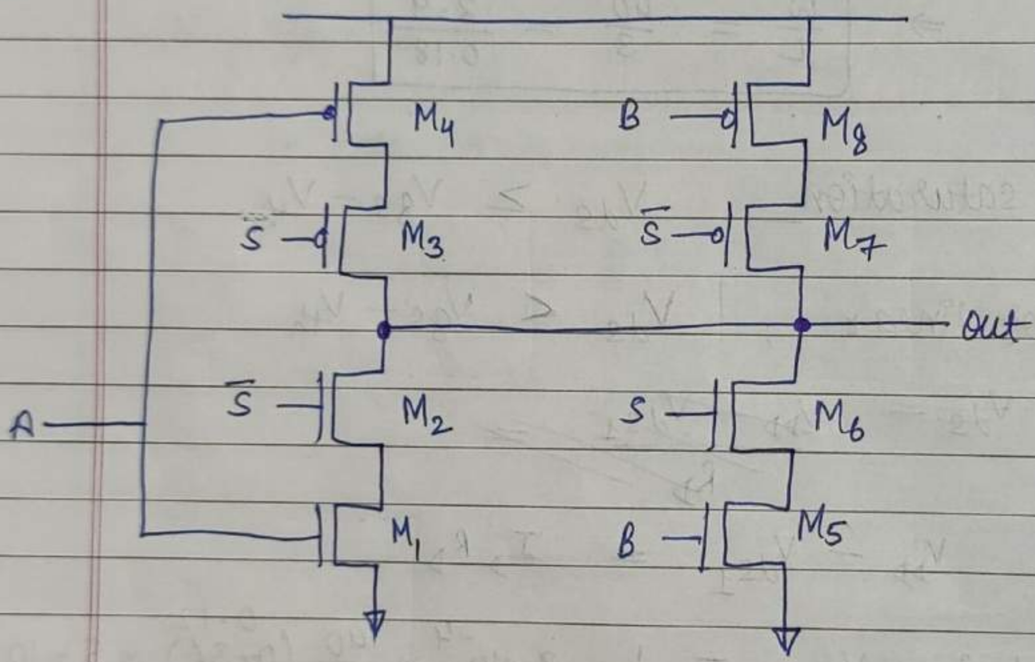
$$1.8 - V_{ds_2} = \frac{1}{2} \times 2\times10^{-4} \times \frac{40}{3} \times \frac{\cancel{0.36}}{\cancel{4}} \times 5\times10^3$$

Multiplexer

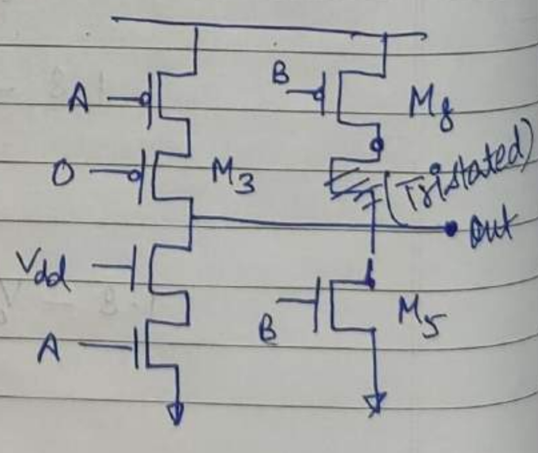
Inverting multiplexer :-

A	B	S	out	
		0	$\overline{A}$	$\Rightarrow \overline{S} \cdot \overline{A}$
		1	$\overline{B}$	$\Rightarrow S \cdot \overline{B}$

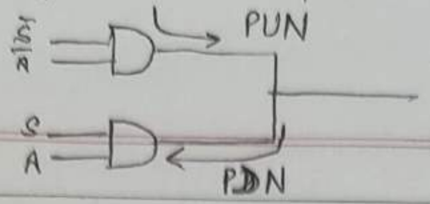
we can invert the result obtained to get multiplexer



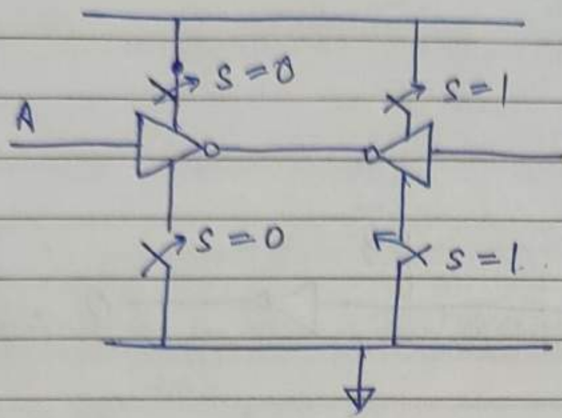
When $S = 0 \Rightarrow \overline{S} = 1$



We cannot do / implement multiplexer using previous created gates as :-

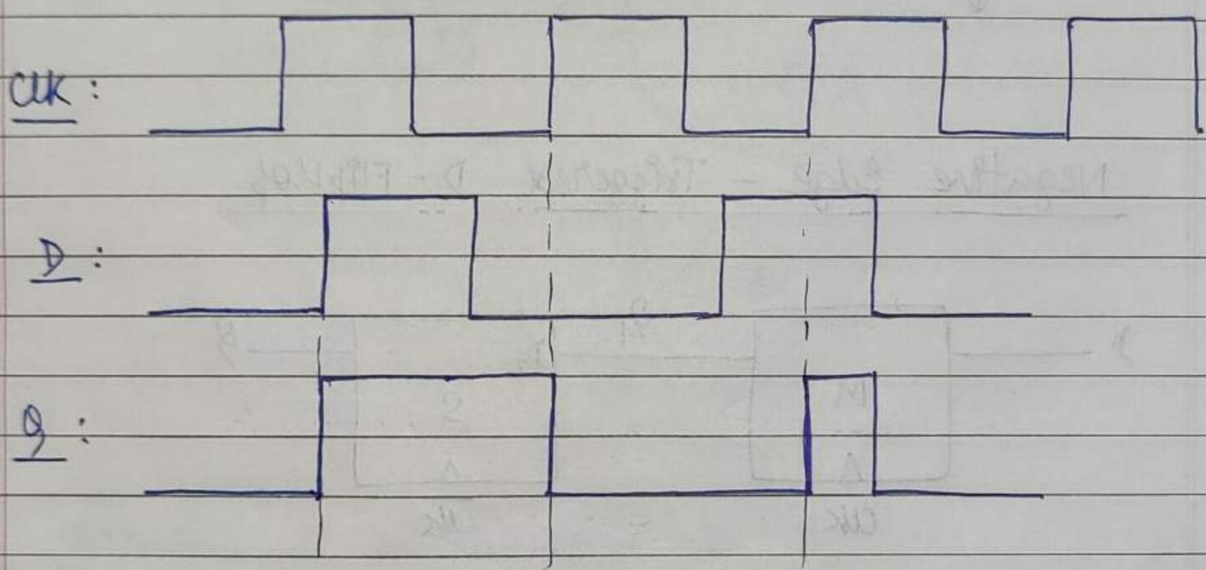


} Because PUN will charge V_{out} & simultaneously PDN will discharge V_{out}



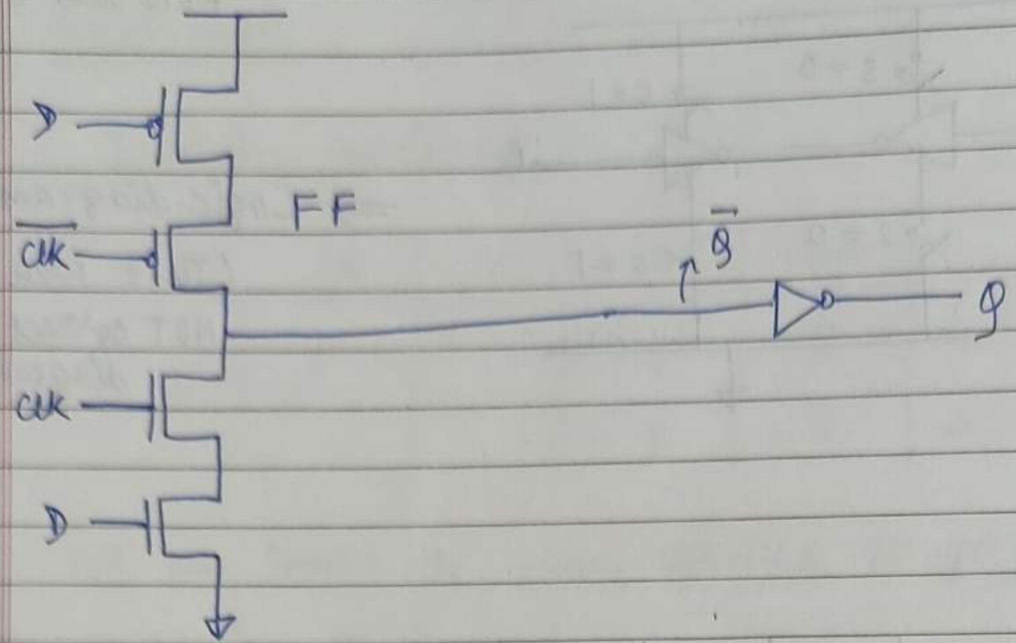
⟹ Logic diagram (Just idea NOT correct diagram)

Latch

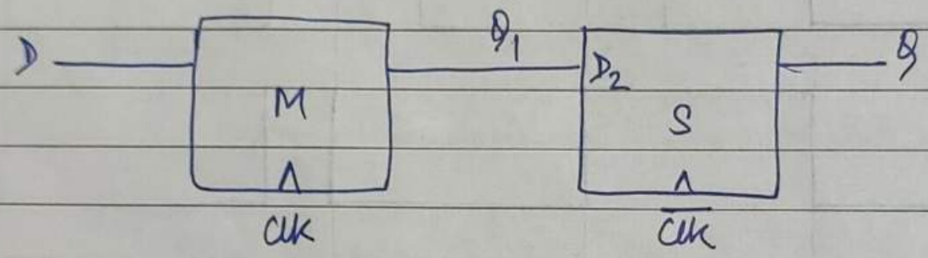


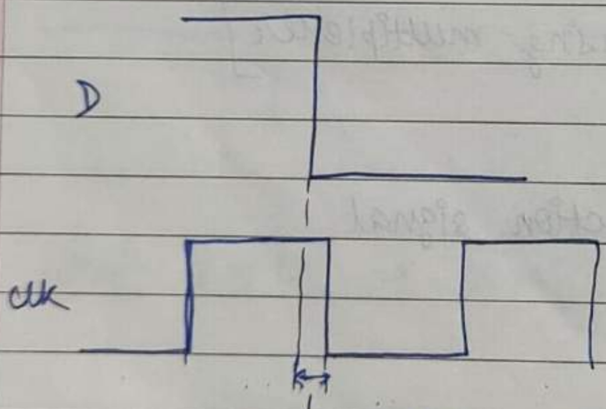
[Can realise latch using multiplexer]

Connect clk as selection signal



Negative Edge - Triggered D-Flipflop





$\to \Delta t > \text{Delay}$

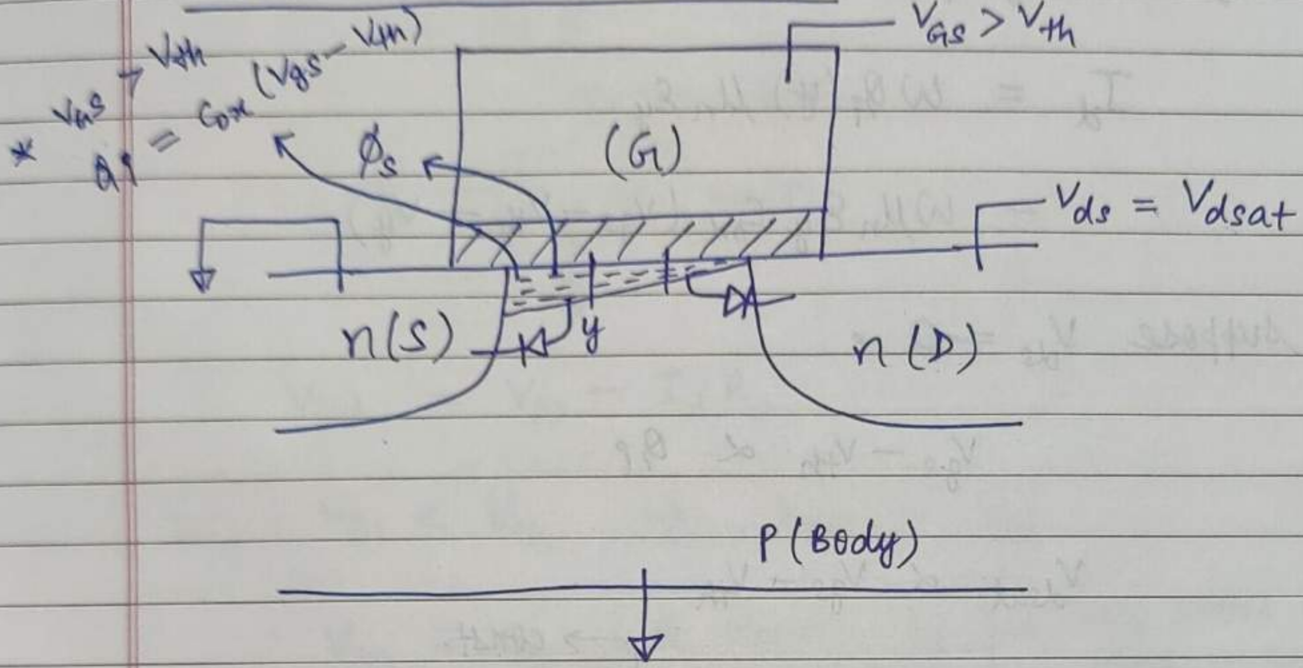
$\parallel$

setup time

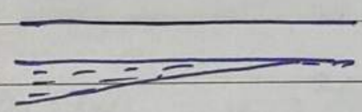
For safe functioning of logic,

$$(V_{DD} - V_{OH}) < (V_{DD} - V_{OL})$$

MOSFET in Saturation



Potential at source edge is ϕ_s

Magnified picture : 

At the drain edge of channel,

$V_{ds} = 0 \longrightarrow \phi_s$

$V_{ds} = V_d \longrightarrow \phi_s + V_d$ $\quad Q_i(\text{drain edge}) = C_{ox}[V_{GS} - V_{th} - V_d]$

$V_{ds} = V_{dsat} \longrightarrow \phi_s + V_{dsat}$

$$Q_i = 0 = C_{ox}\left[V_{gs} - V_{th} - V_{dsat}\right]$$

$$\boxed{V_{dsat} = V_{gs} - V_{th}}$$

I_d at any point in channel should be same.

$$I_d = W\,Q_i(y)\,\mu_n\,\mathcal{E}_y$$

$$= W\mu_n\,\mathcal{E}_y\,C_{ox}\,(V_{gs} - V_{th} - V_y)$$

suppose $V_{ds} = 0$.

$$V_{gs} - V_{th} \propto Q_i$$

$$V_{dsat} \propto V_{gs} - V_{th}$$

$$\mathcal{E}_y = f(V_{dsat}, \underbrace{L}_{\rightarrow\ \text{const.}})$$

$$\Rightarrow \mathcal{E}_y \propto (V_{gs} - V_{th})$$

$$\left[\begin{aligned} V_{dsat} &= V_{ds} \\ &= -\int_{y=0\,(S)}^{y=L\,(D)} \mathcal{E}_y\,dy \\ &= V_{gs} - V_{th} \end{aligned}\right]$$

$$I_d = W\mu_n C_{ox}\,(V_{gs} - V_{th})\,\underbrace{\mathcal{E}_y}_{\propto V_{dsat} = V_{gs} - V_{th}}\,(\text{source edge})$$

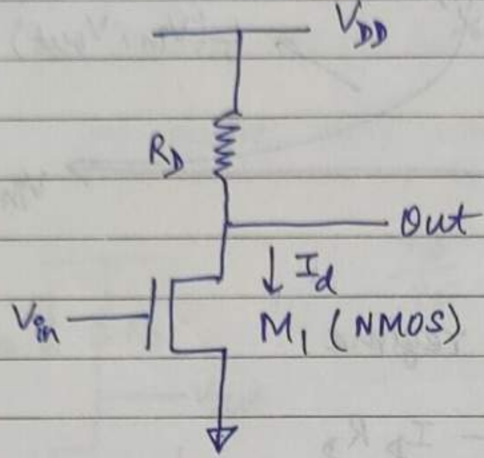
$$I_d \propto \cancel{V_{ds}}\,(V_{gs} - V_{th})^2$$

$$I_d \propto \frac{W}{L}\mu_n C_{ox}\,(V_{gs} - V_{th})^2$$

$$\left(\mathcal{E}_y \approx \frac{V_{dsat}}{L} = \frac{V_{gs} - V_{th}}{L}\right)$$

MOS Amplifiers

→ Linearly scaled output



$$V_{out} = V_{DD} - I_d R_D$$

$V_{in} < V_{th} \Rightarrow V_{out} = V_{DD}$

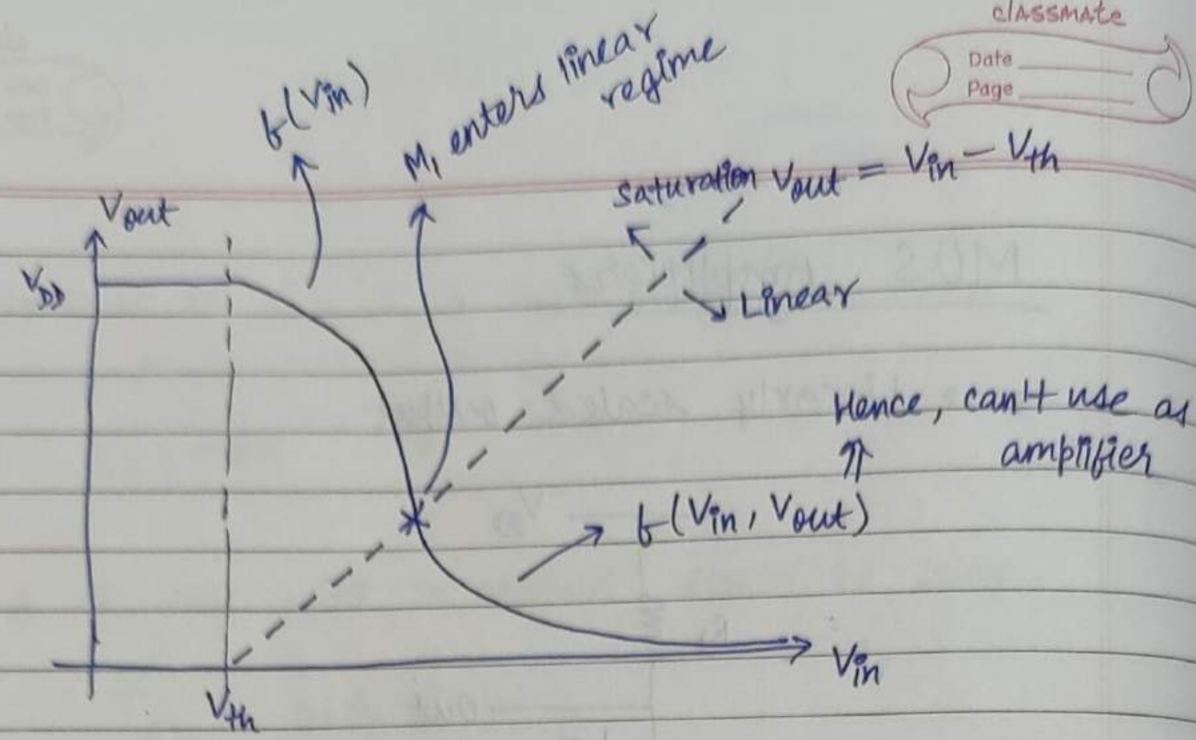
$V_{in} \geq V_{th}$ but nearly V_{th} [⇒ very small current flows ⇒ V_{out} slightly less than V_{DD}]

$V_{GS} = V_{in} \Rightarrow V_{GS} - V_{th} = V_{dsat} \approx 0$

$V_{out} \approx V_{DD} \Rightarrow M_1$ is in saturation

$$I_d = k\mu_n C_{ox}\left(\frac{W}{L}\right)(V_{gs} - V_{th})^2$$

$$V_{out} = V_{DD} - \left[k\mu_n C_{ox}\left(\frac{W}{L}\right)(\underset{\downarrow\, V_{in}}{V_{gs}} - V_{th})^2\right] R_D$$



→ M_1 enters linear regime

$$V_{out} = V_{DD} - I_D R_D$$

$$= V_{DD} - \mu_n C_{ox}\left(\frac{W}{L}\right)(V_{gs} - V_{th}) R_D$$

$$V_{out} = \frac{V_{DD}}{1 + \mu_n C_{ox}\left(\frac{W}{L}\right)(V_{gs} - V_{th}) R_D}$$

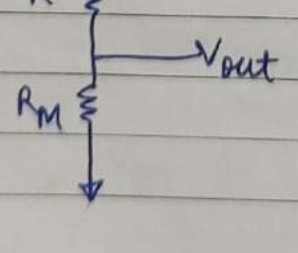
Deep in linear regime

$$I_D = \mu_n C_{ox}\left(\frac{W}{L}\right)(V_{gs} - V_{th}) \overset{V_{ds}}{\cancel{V_{out}\ R_D}}$$

$$V_{ds} = I_D \times R_M \Rightarrow R_M = \frac{V_{ds}}{I_d} = \frac{1}{\mu_n C_{ox} \frac{W}{L} (V_{gs} - V_{th})}$$

↓

Resistance dependent on V_{gs}

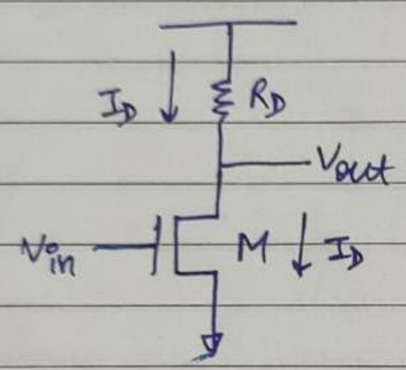


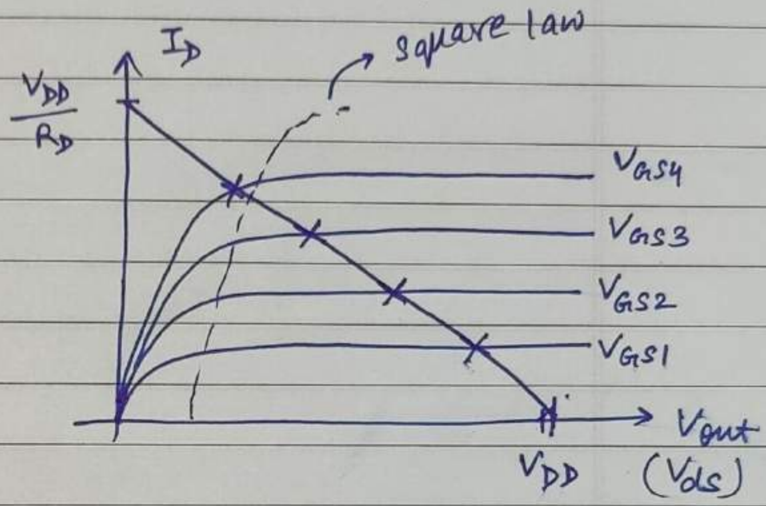
$$V_{out} = \left(\frac{R_M}{R_D + R_M}\right) V_{DD} = V_{DD} \frac{(R_M/R_D)}{(1 + R_M/R_D)}$$

Once it enters linear regime I_D depends on V_{in} and V_{out} both

$\Rightarrow$ we want $I_D = f(V_{in})$

$\Rightarrow$ Hence, here can't use as amplifier





$V_{out} = V_{ds}$

$$= V_{DD} - I_D R_D = V_{DD} - K_1 (V_{gs} - V_{th})^2 R_D \geq V_{gs} - V_{th}$$

(validity)

$$\Rightarrow \quad V_{DD} - K_1 (V_{gs} - V_{th})^2 R_D - V_{out} = 0$$

Also, $V_{out} = V_{DD} - I_D R_D$