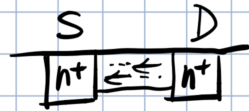
1) raising V_{GS} beyond V_{th} causes a channel (e^-) to form between S & D

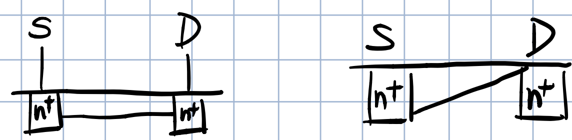
channel depend $\propto V_{ov}$

$$V_{ov} = V_{GS} - V_{th}.$$

2) Increasing V_{DS} a little causes current to flow from D to S.

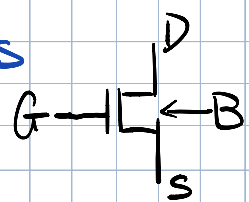


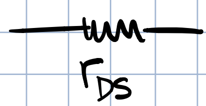
3) Increasing V_{DS} much more causes the channel to tapper at the drain when $V_{DS} = V_{ov} = V_{GS} - V_{th}$ the channel at the drain is pinched off.



current saturator.

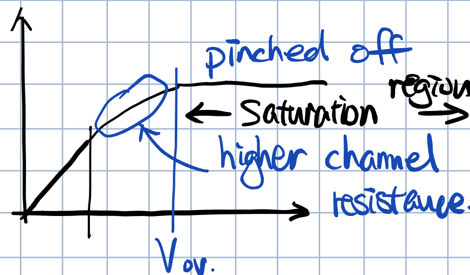
NMOS

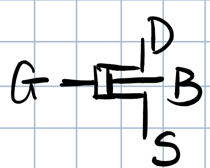




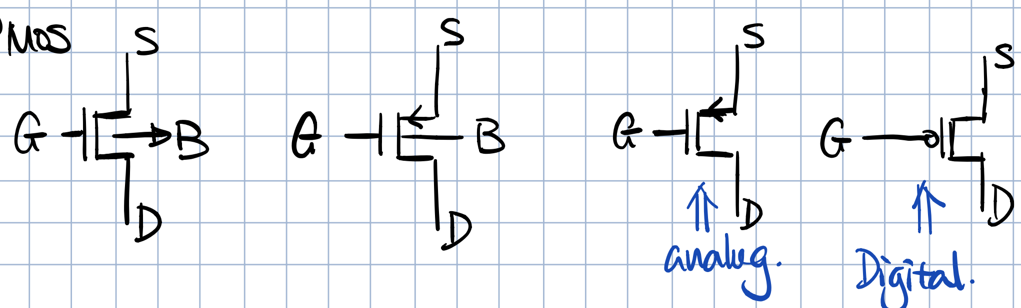
$$r_{DS} = \frac{1}{k_n'\left(\frac{W}{L}\right)V_{ov}}$$

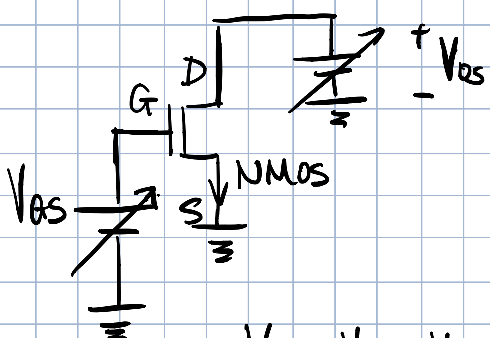
"channel persistance"

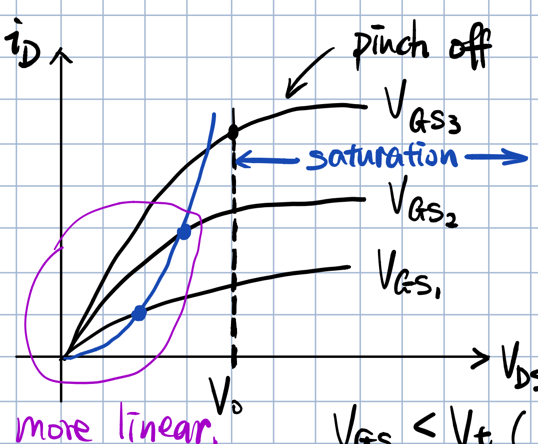




PMOS







$V_{GS} < V_t$ (cut off region)

$V_{ov} = V_{GS} - V_{th}$.

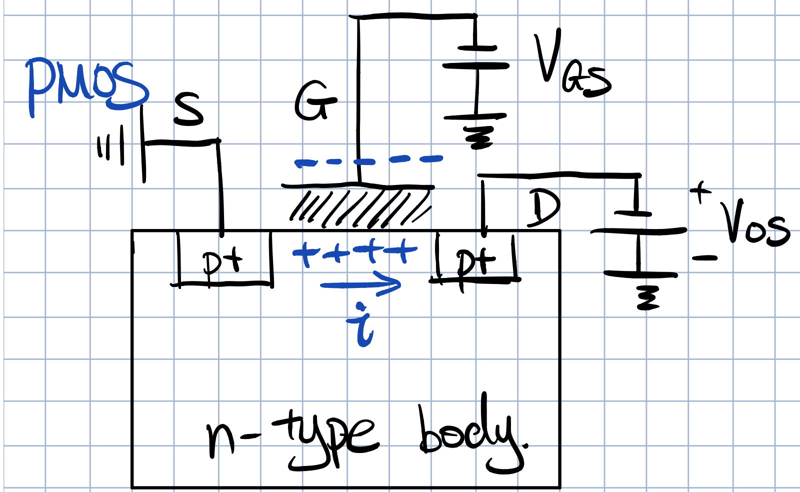
$V_{tn} > 0$ threshold.

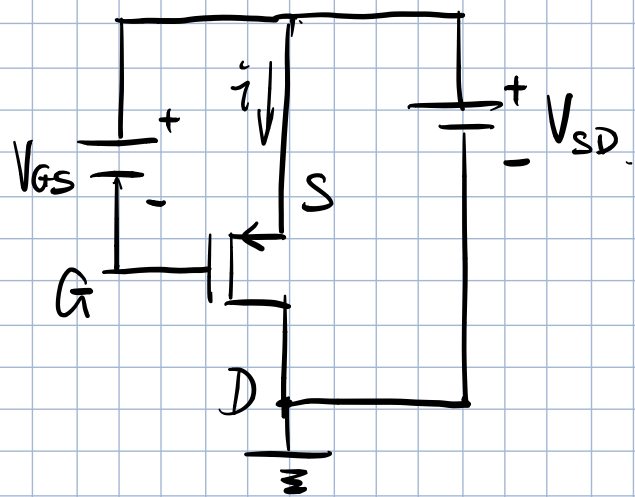
$V_{ov} = V_{GS} - V_{th}$.

$k_n' = \mu_n C_{oxide}$.

triode region: $i_D = k_n' \left(\frac{W}{L}\right)\left(V_{ov} V_{DS} - \frac{1}{2} V_{DS}^2\right)$

saturation: $i_D = k_n' \left(\frac{W}{L}\right) V_{ov}^2$





$V_{th} < 0$ (threshold)

$|V_{ov}| = |V_{GS}| - |V_{th}|$

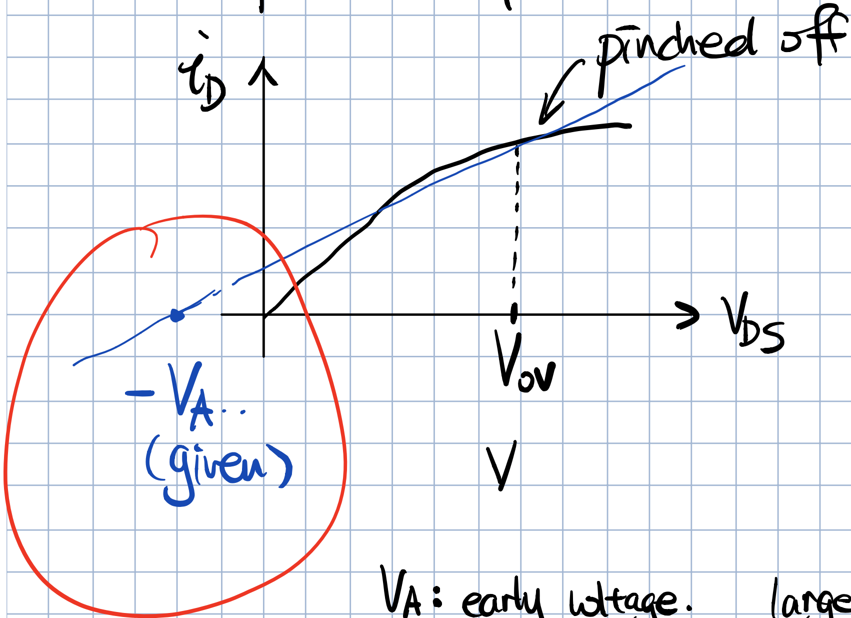
$k'_p = \mu_p C_{ox}$

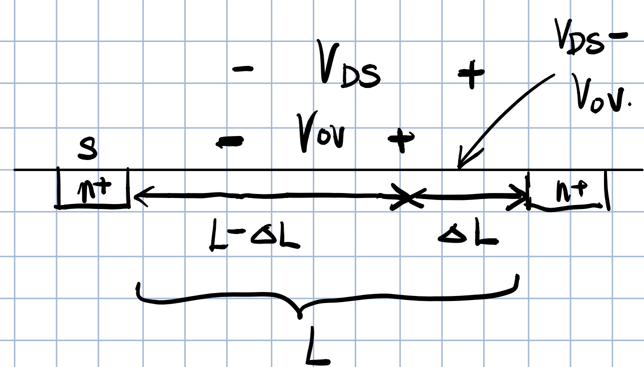
triode region:

$i_D = k'_p \left(\frac{W}{L}\right)\left(|V_{ov}||V_{DS}| - \frac{1}{2} V_{DS}^2\right)$

$i_D = \frac{1}{2} k_p' \left(\frac{W}{L}\right) V_{ov}^2$

$\rightarrow$ finite output resistance in saturation.





V_A: early voltage. large negative volume.

$i_D = k_n' \left(\frac{W}{L}\right) V_{ov}^2 \left(1 + \lambda V_{DS}\right)$

$$i_D = \underbrace{\tfrac{1}{2} k_n' \left(\tfrac{W}{L}\right) V_{ov}^2}_{\text{saturation current w/o channel length modulation.}} (1 + \lambda V_{DS}), \quad \lambda = 1/V_A$$

$$1/r_o = di_o/dV_{DS} = \underbrace{\tfrac{1}{2} k_n' \left(\tfrac{W}{L}\right) V_{ov}^2}_{I_D} \lambda = I_D \lambda, \quad \boxed{r_o = \frac{1}{I_D \lambda} = \frac{V_A}{I_D}}$$

model NMOS in saturation. $V_{ov} = V_{GS} - V_t$