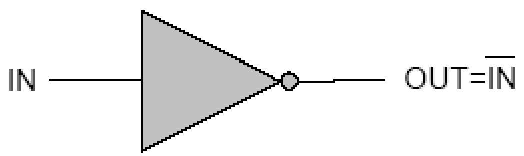
Lect. 23: Inverters (Razavi 15.1, 2, 3)

Digital Electronics

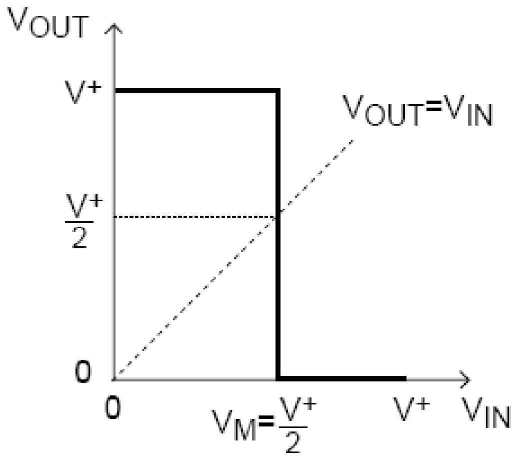
How to implement logic circuits?

➔ Inverters are the basic building block!

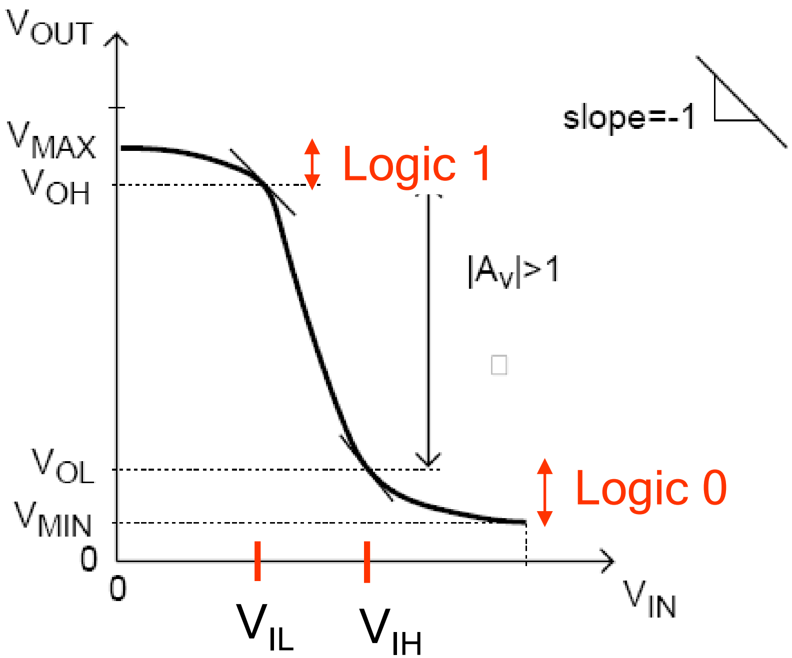


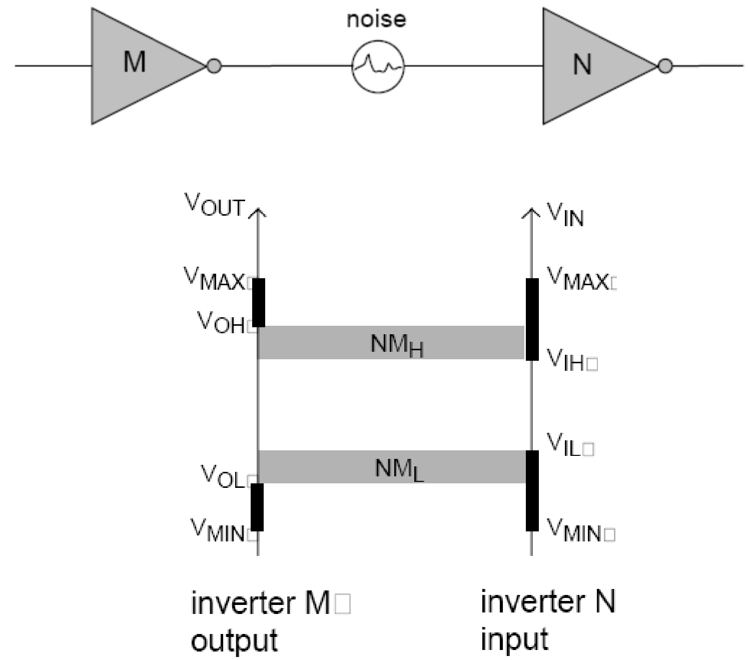
IN	OUT
0	1
1	0

Ideally,



Real inverters



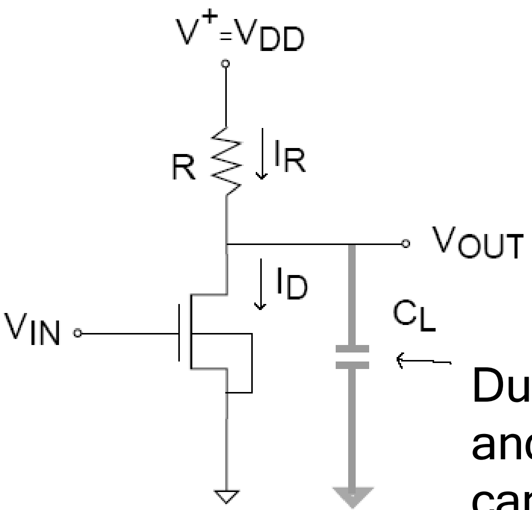


$$NM_H = V_{OH} - V_{IH}$$
$$NM_L = V_{IL} - V_{OL}$$

Larger noise margin ➔ smaller V_{IH}, larger V_{IL} ➔ Larger $|A_v|$

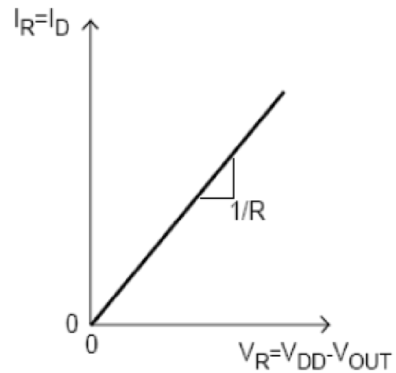
Lect. 23: Inverters

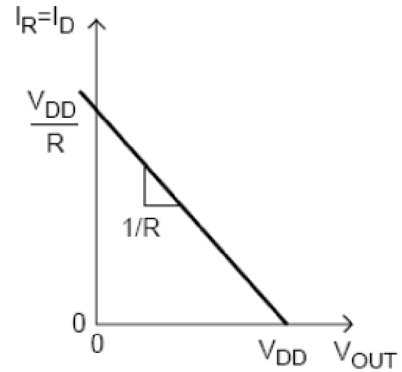
How to implement an inverter? CS amplifier configuration



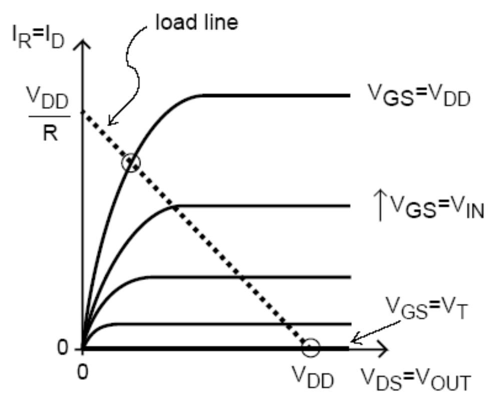
Due to load and internal capacitance

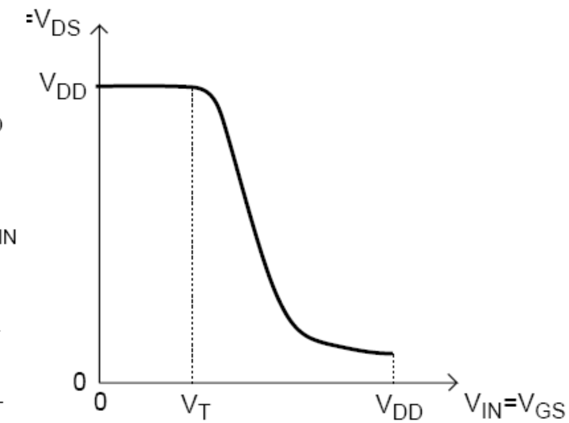
Load line analysis



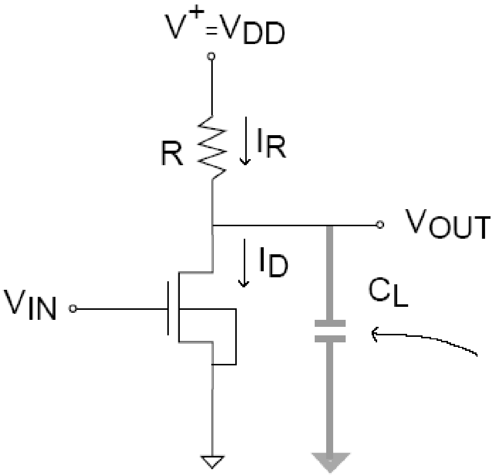


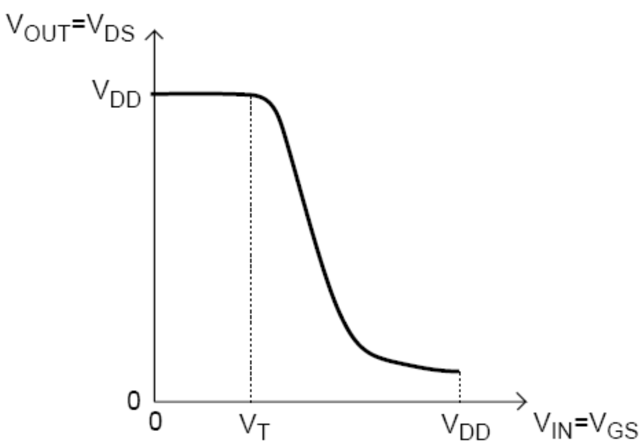
V_{OUT} vs V_{IN} ?





Lect. 23: Inverters





For V_{MIN}, MOSFET in triode

$$I_D = \frac{W}{L}\mu_n C_{ox}\left(V_{GS} - \frac{1}{2}V_{DS} - V_T\right)V_{DS}$$

$$I_D = \frac{W}{L}\mu_n C_{ox}(V_{DD} - \frac{V_{MIN}}{2} - V_T)V_{MIN}$$

$$= I_R = \frac{V_{DD} - V_{MIN}}{R}$$

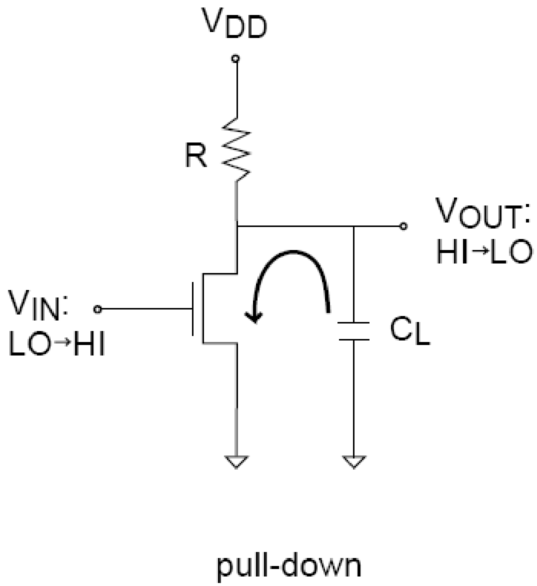
$$V_{MIN} \approx -\frac{V_{DD}}{1 + \mu_n C_{ox}\frac{W}{L}R(V_{DD} - V_T)}$$

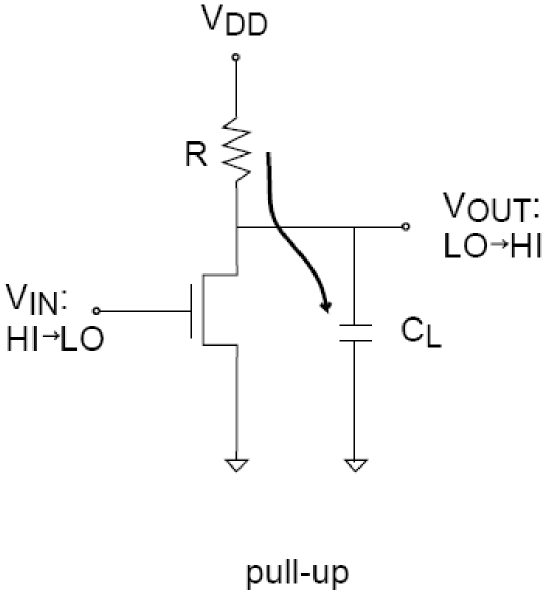
A_v = ?

Large R preferred

Lect. 23: Inverters

Dynamics





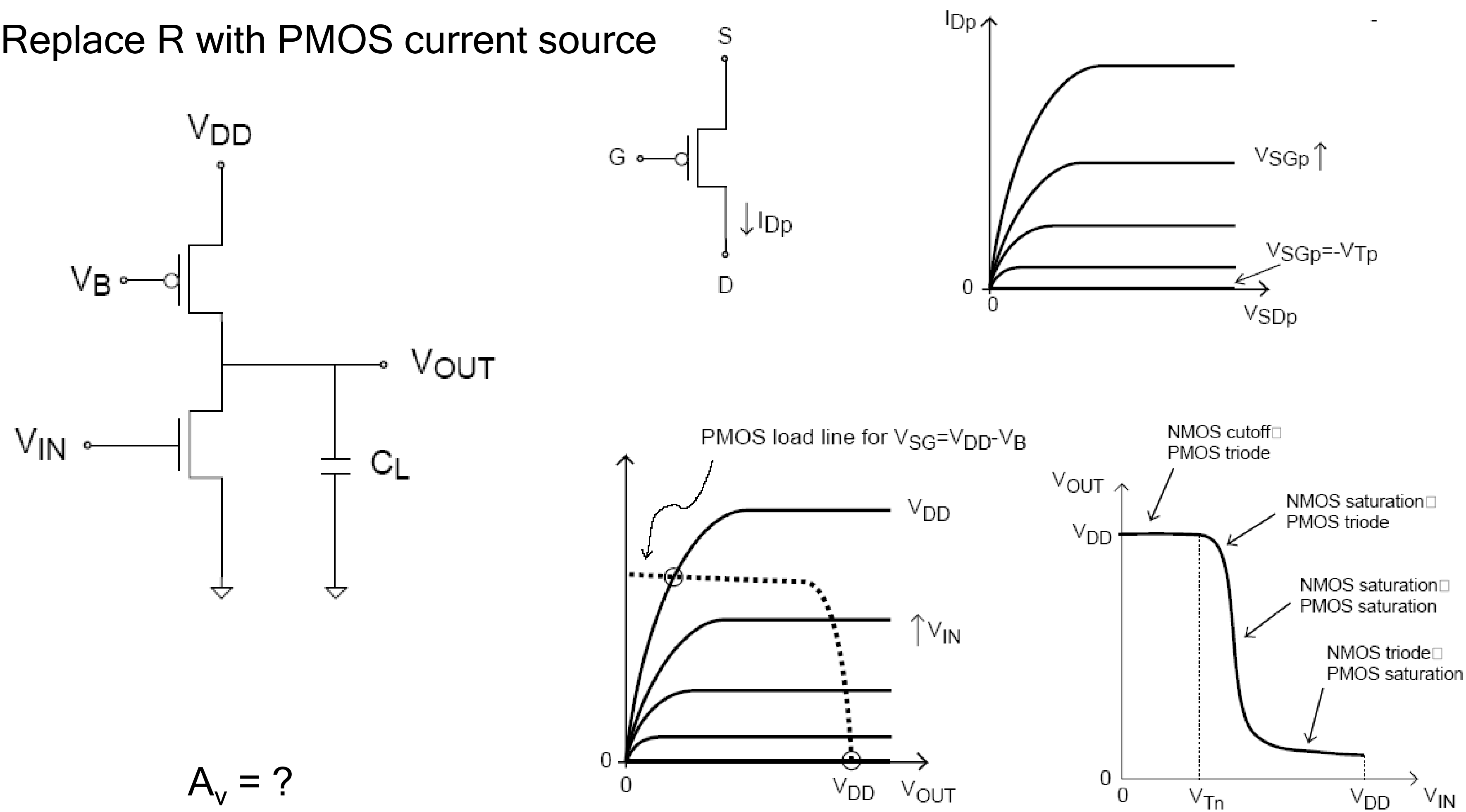
RC time constant for pull-down and pull-up operation

Small R preferred for fast operation

➔ Better way of implementing inverters?

Lect. 23: Inverters

Replace R with PMOS current source



$A_v = ?$

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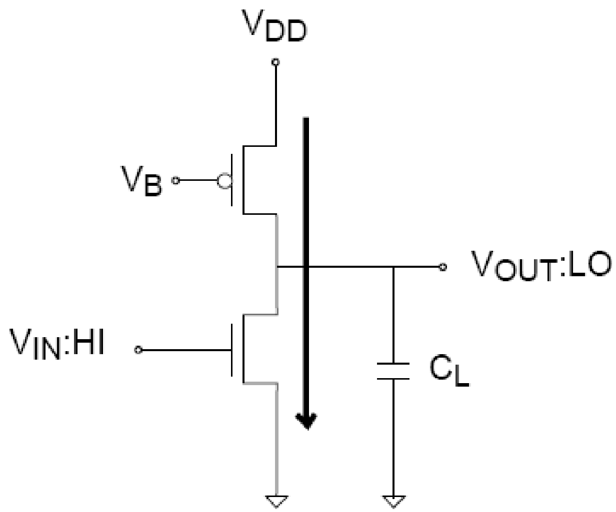
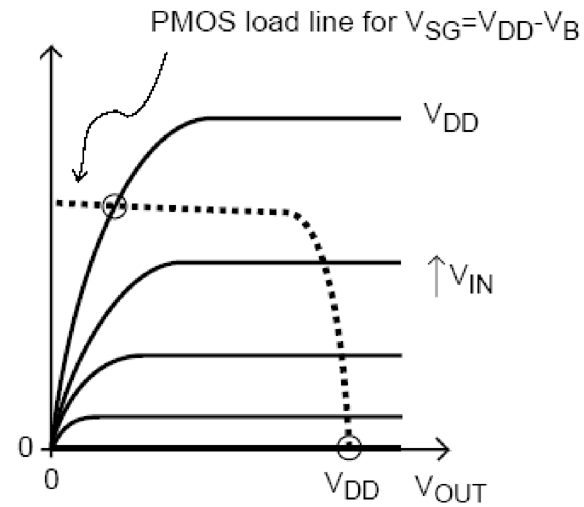
Lect. 23: Inverters





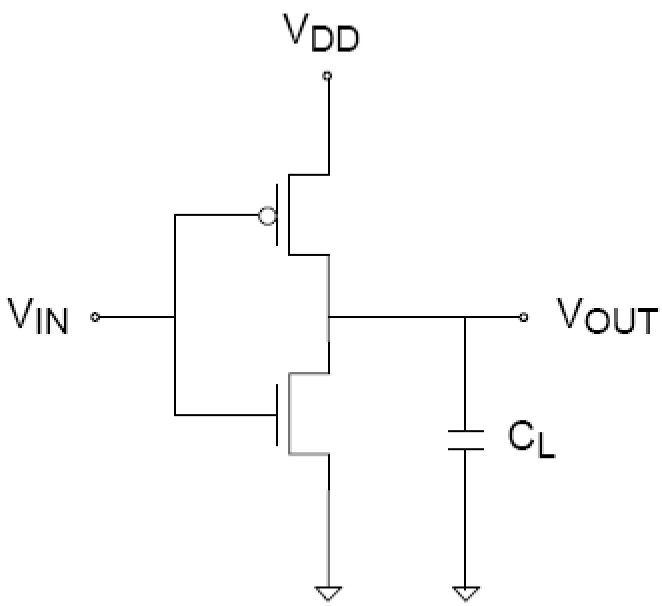
Direct current path when V_{IN} is high

Static power consumption!

➔ How can we shut it off when input is high?

Lect. 23: Inverters

Complementary MOS (CMOS) Inverter



$V_{IN} = V_{DD}$

NMOS ON, PMOS OFF

➔ $V_{OUT} = 0$

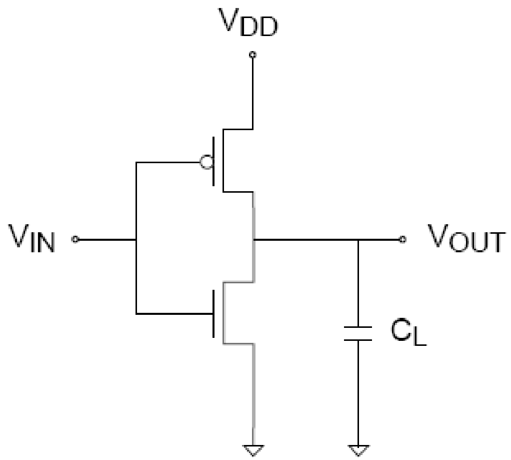
$V_{IN} = 0$

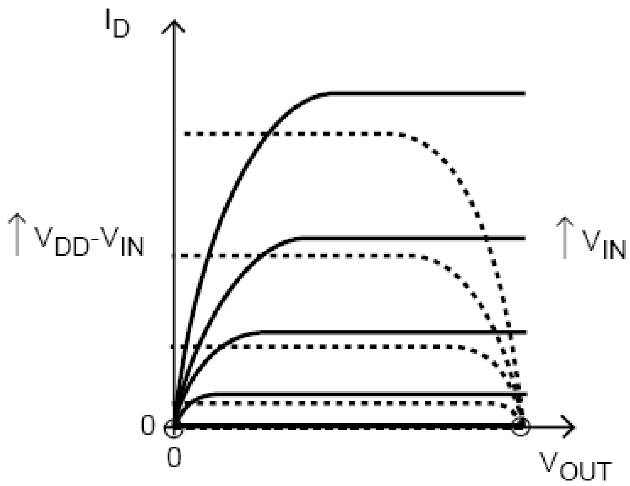
NMOS OFF, PMOS ON

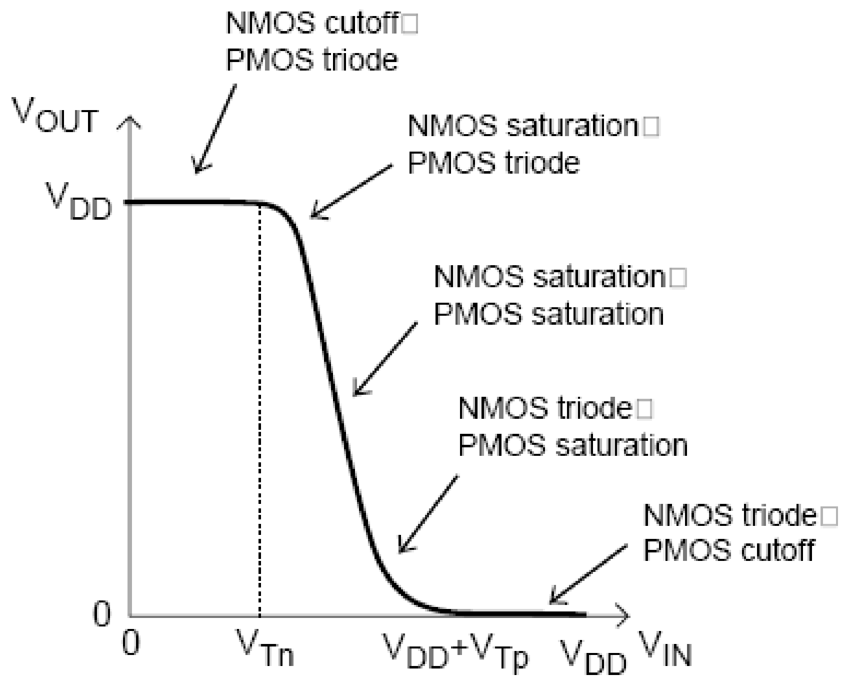
➔ $V_{OUT} = V_{DD}$

➔ The most popular building block for today's digital electronics!

Lect. 23: Inverters



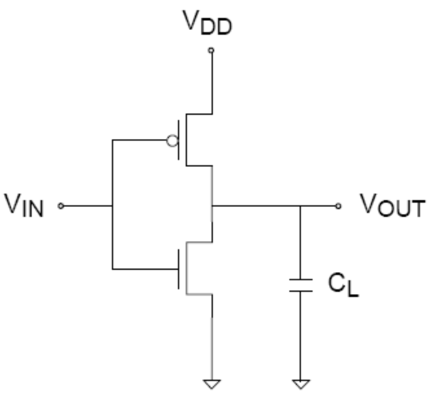


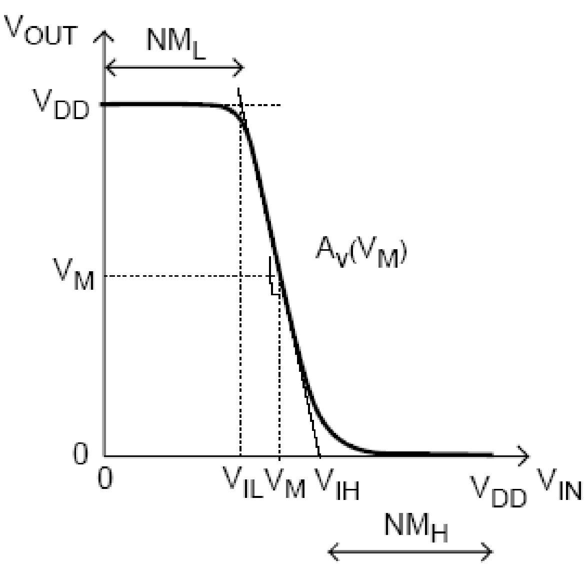


Rail-to-Rail logic

Lect. 23: Inverters

Estimation of important parameters for CMOS inverter: V_M, $A_v(V_M)$, NM_L, NM_H





For V_M ($V_{IN} = V_{OUT} = V_M$)

$$\frac{1}{2}\frac{W_n}{L_n}\mu_n C_{ox}(V_M - V_{Tn})^2 = \frac{1}{2}\frac{W_p}{L_p}\mu_p C_{ox}(V_{DD} - V_M + V_{Tp})^2$$

Using $k_n = \frac{W_n}{L_n}\mu_n C_{ox}, \quad k_p = \frac{W_p}{L_p}\mu_p C_{ox}$

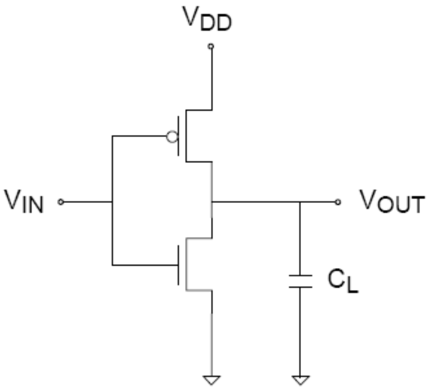
$$V_M = \frac{V_{Tn} + \sqrt{\frac{k_p}{k_n}}(V_{DD} + V_{Tp})}{1 + \sqrt{\frac{k_p}{k_n}}}$$

V_M can be engineered with controlling k_p/k_n

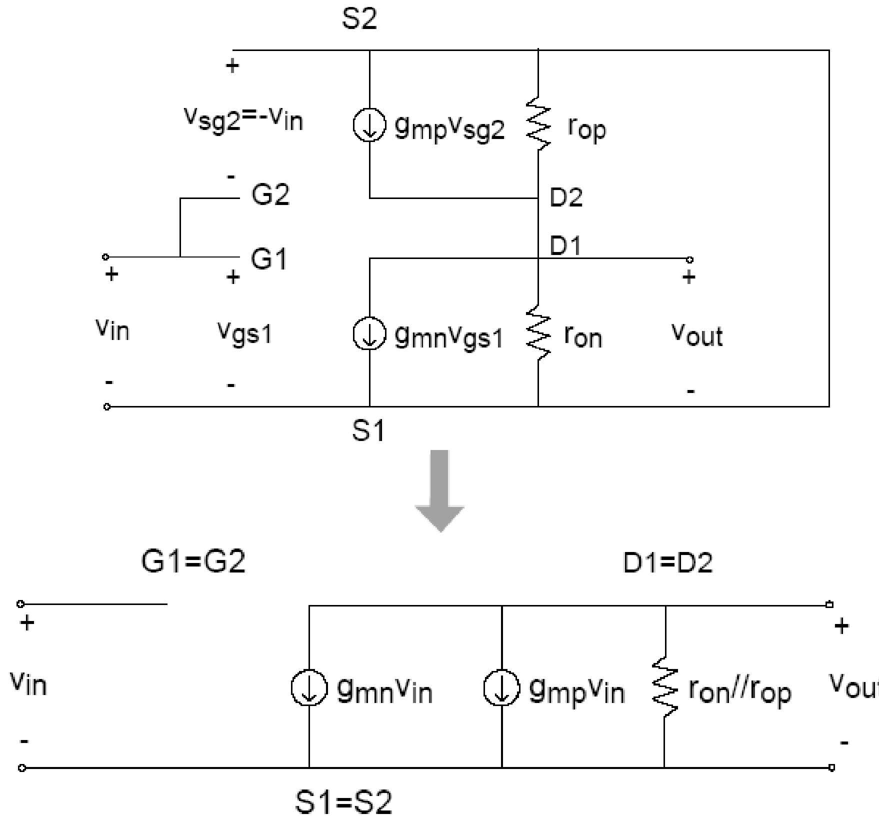
If V_{Tn}=-V_{Tp} and k_p=k_n, V_M= $V_{DD}/2$

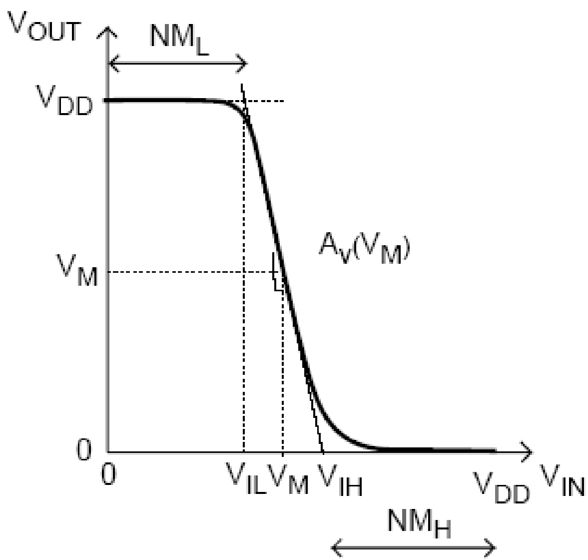
$(W_p \sim 3W_n)$

Estimation of important parameters for CMOS inverter: V_M, $A_v(V_M)$, NM_L, NM_H



$A_v(V_M)$

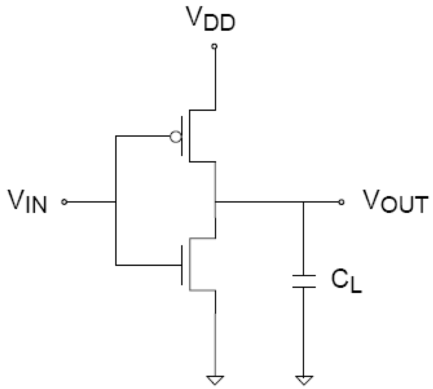


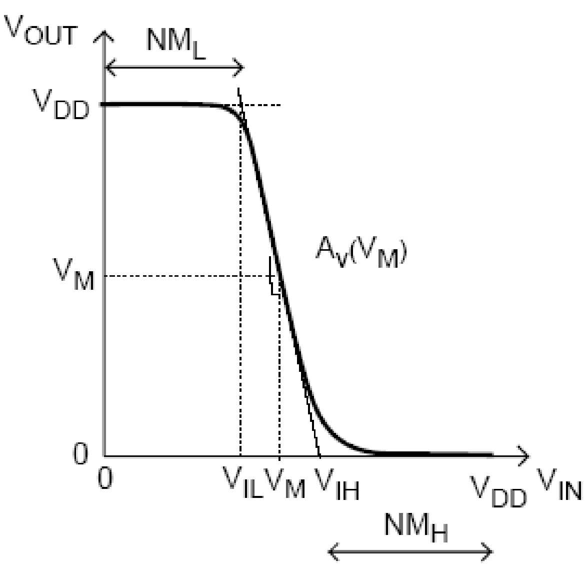


$$A_v = -(g_{mn} + g_{mp})(r_{on}//r_{op})$$

Lect. 23: Inverters

Estimation of important parameters for CMOS inverter: V_M, $A_v(V_M)$, NM_L, NM_H





Noise Margin Estimation:

$$NM_H = V_{OH} - V_{IH}$$
$$NM_L = V_{IL} - V_{OL}$$

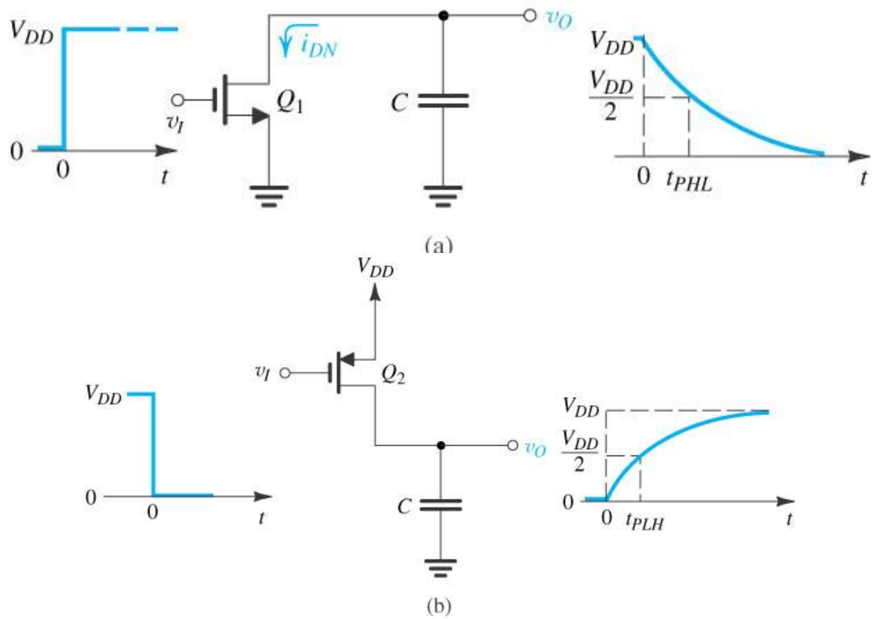
$$NM_H = V_{DD} - V_{IH} = V_{DD} - V_M\left(1 + \frac{1}{|A_v|}\right)$$

$$NM_L = V_{IL} = V_M - \frac{V_{DD} - V_M}{|A_v|}$$

When $V_M = V_{DD}/2$, $NM_H = NM_L$

Lect. 23: Inverters

Estimation of propagation delay,



$$t_{P,HL} \sim \frac{1.7C}{k_n V_{DD}}$$

$$t_{P,LH} \sim \frac{1.7C}{k_p V_{DD}}$$

$$t_P = \frac{1}{2}\left(t_{PHL} + t_{PLH}\right)$$

In each cycle, $Q = CV_{DD}$ is charged and discharged over V_{DD}

In each cycle, energy of CV_{DD}^2 is consumed

Power consumption: fCV_{DD}^2

➔ Make them smaller, smaller, smaller, smaller, smaller, smaller …