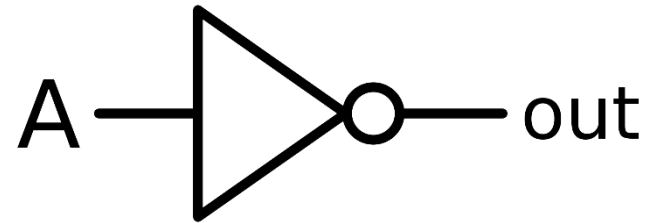


Lecture 3: Complementary Metal Oxide Semiconductor (CMOS)

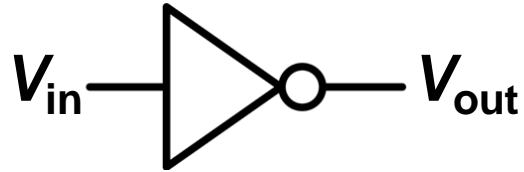


Outline

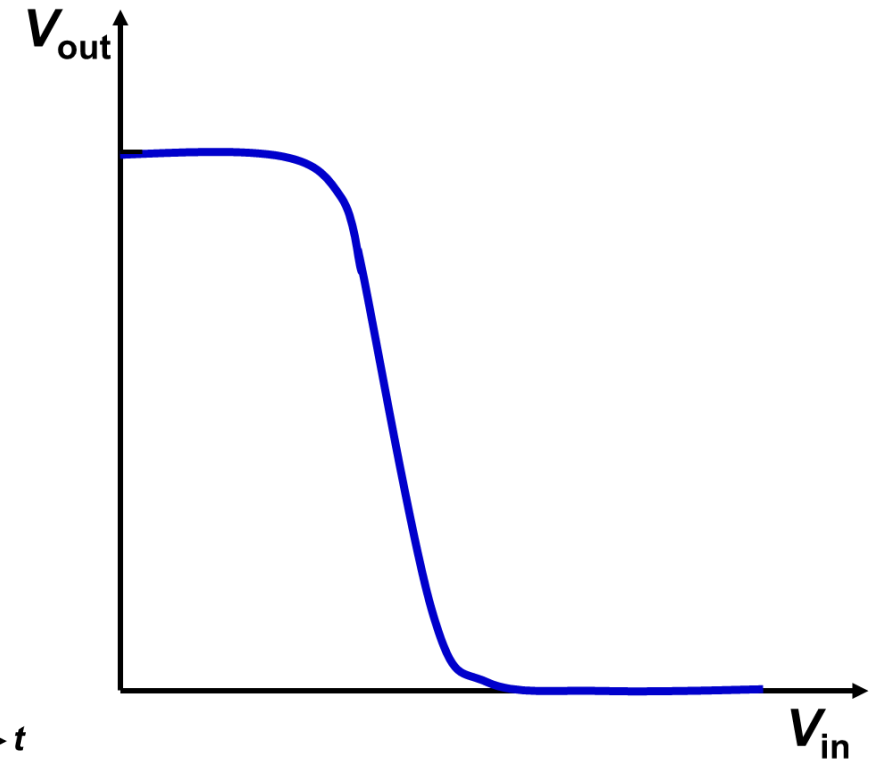
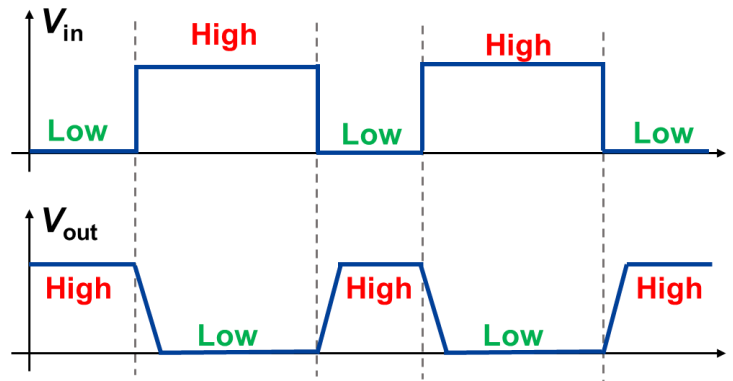
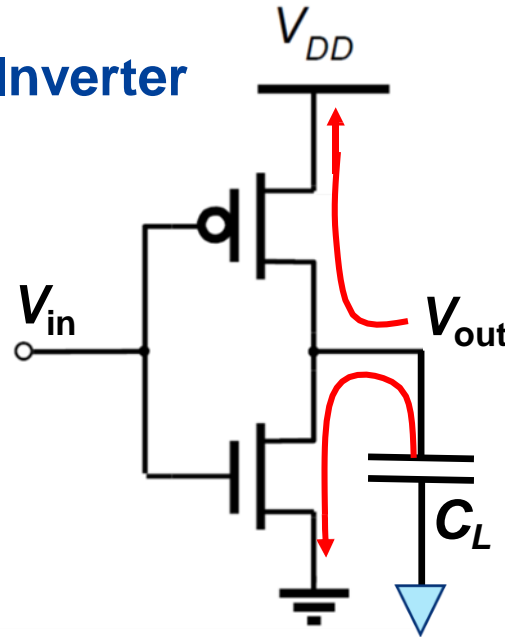
- **CMOS Inverter Operating Principle**
 - Operating in logical high, low and transitions
- **CMOS Inverter Voltage Transfer Characteristic (VTC)**
 - Five operating regions
 - VTC Construction
- **CMOS Inverter Reliability and Design Rules**
 - Switching Threshold
 - Noise Margin 噪声容忍门限

Static CMOS Inverter

Ideal Inverter



Real Inverter



GOAL: To quantify the voltage transfer characteristic (VTC)

MOSFET Modes of Operation

□ Cutoff: $V_{GS} - V_T < 0$

$$I_{DS} \sim 0$$

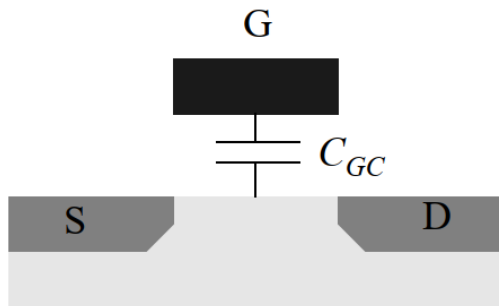
□ Linear (Resistive): $V_{GS} - V_T > V_{DS}$

$$I_{DS} = \frac{\mu_n C_{ox}}{2} \cdot \frac{W}{L} \cdot [2(V_{GS} - V_T)V_{DS} - V_{DS}^2]$$

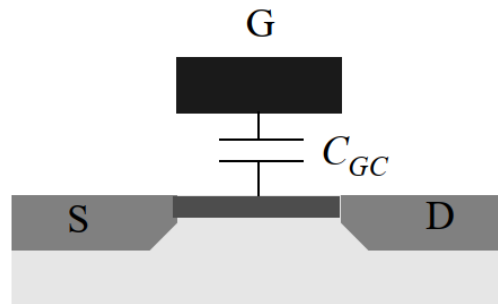
□ Current Saturation: $0 < V_{GS} - V_T < V_{DS}$

$$I_D(sat) = \frac{\mu_n C_{ox}}{2} \cdot \frac{W}{L} \cdot (V_{GS} - V_T)^2$$

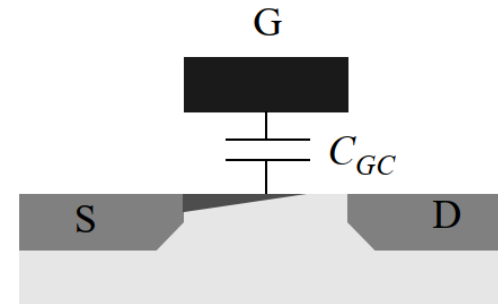
- MOSFET各端的电压定义了其工作状态。
- 因此在本章节后续的场景中可以先简单地这么理解，若MOSFET处在非关断的情况下，当 $|V_{DS}|$ 较小时，工作在Linear状态，当 $|V_{DS}|$ 较大时，工作在Saturation状态。



(a) cut-off



(b) resistive



(c) saturation

NMOS Operation Regions

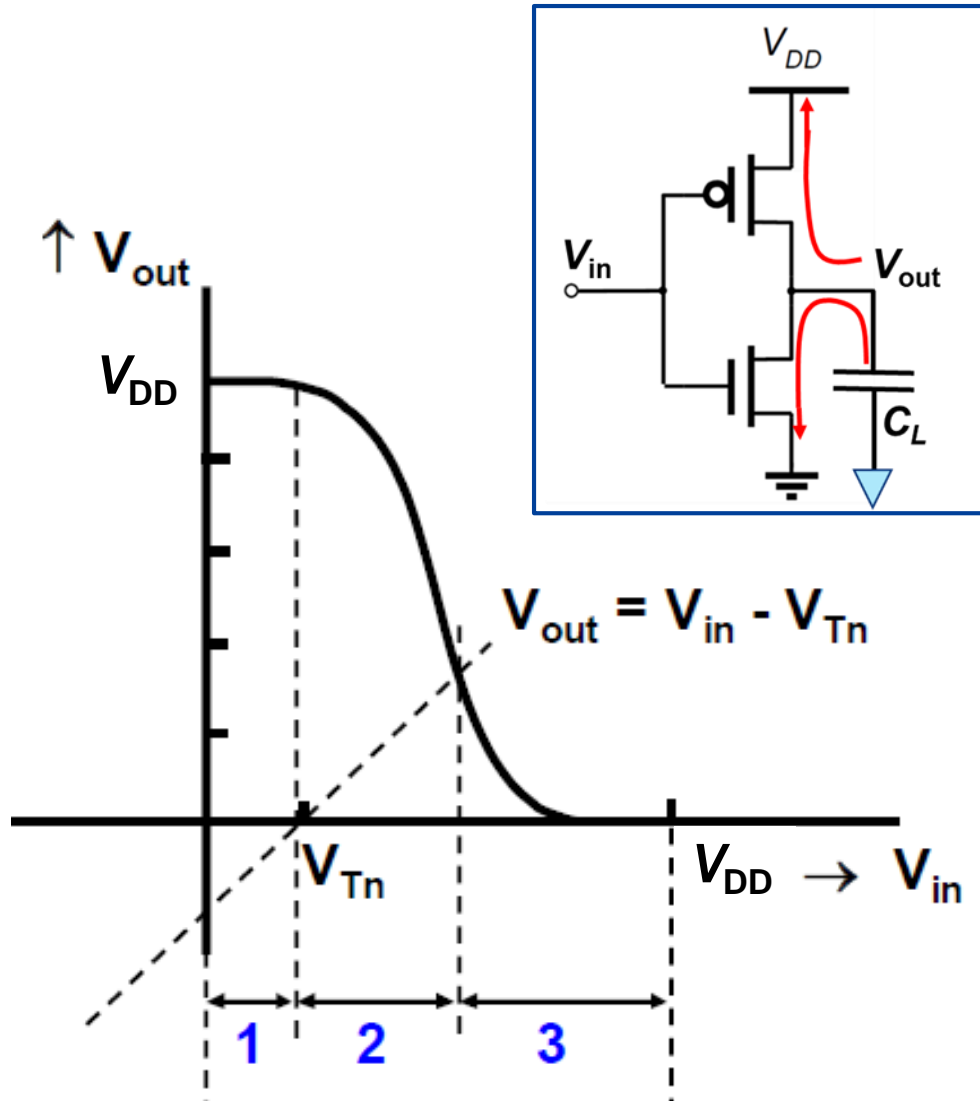
$$V_{GSn} = V_{in}, \quad V_{DSn} = V_{out}, \quad V_{Tn} > 0$$

NMOS

- 1 $V_{in} < V_{Tn} \Rightarrow$ **off**
- 2 $V_{Tn} \leq V_{in} \leq V_{out} + V_{Tn} \Rightarrow$ **saturation**
- 3 $V_{in} > V_{out} + V_{Tn} \Rightarrow$ **linear**



- V_{in} 从 低电平 $\rightarrow V_{DD}$, $|V_{DS}| = |V_{out}|$ 在初始时较大
- 此时NMOS首先由cut off状态, 变为saturation状态, 当 V_{out} 降低到一定程度后, 再变为linear状态。



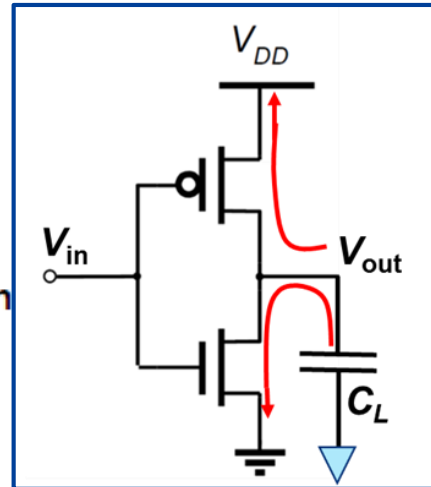
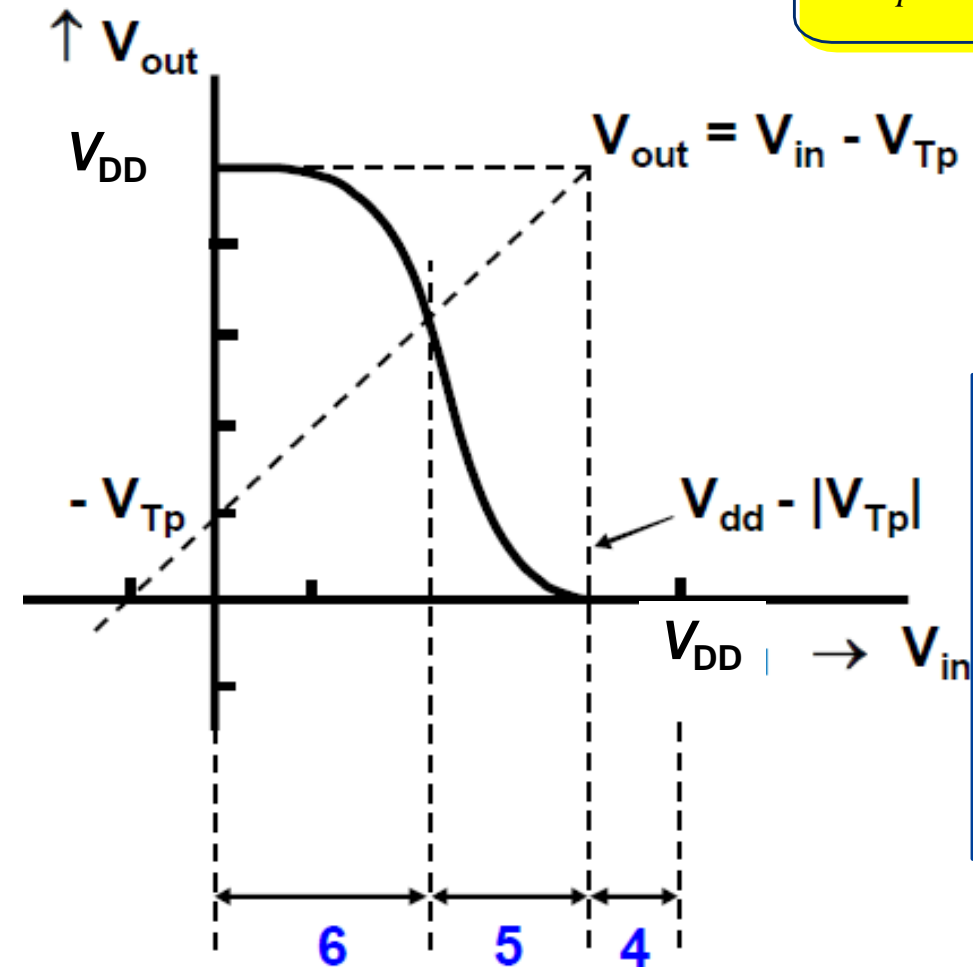
PMOS Operation Regions

$$V_{GSp} = V_{in} - V_{DD} < 0, \quad V_{DSp} = V_{out} - V_{DD} < 0, \quad V_{Tp} < 0$$

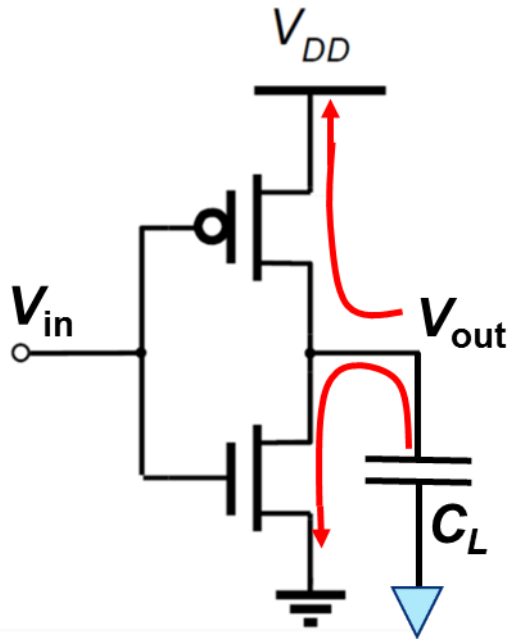
PMOS

- 4 $V_{in} > V_{DD} + V_{Tp} \Rightarrow \text{off}$
- 5 $V_{out} + V_{Tp} \leq V_{in} \leq V_{DD} + V_{Tp} \Rightarrow \text{saturation}$
- 6 $V_{in} < V_{out} + V_{Tp} \Rightarrow \text{linear}$

- V_{in} 从 V_{DD} → 低电平, $|V_{DS}| = |V_{DD} - V_{out}|$ 在初始时较大。
- 此时PMOS首先由cut off状态, 变为saturation状态, 当 V_{out} 的电压升高到一定程度后, 再变为linear状态。



CMOS Inverter Operation Region

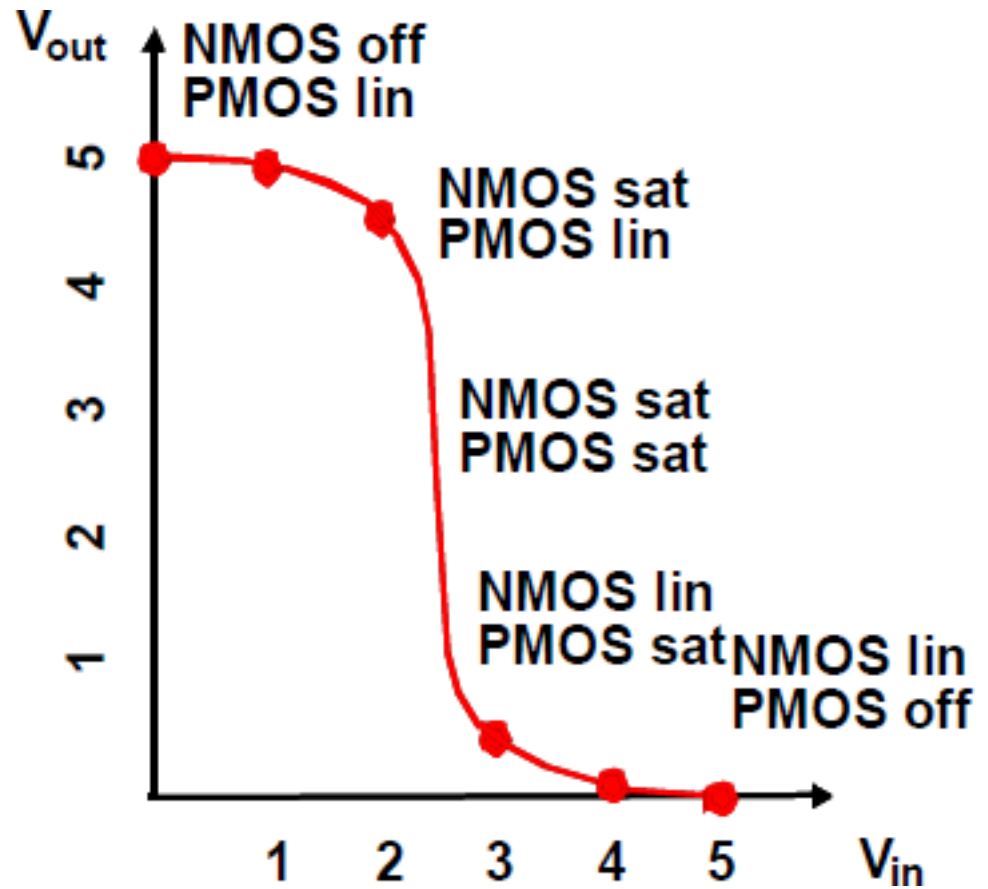
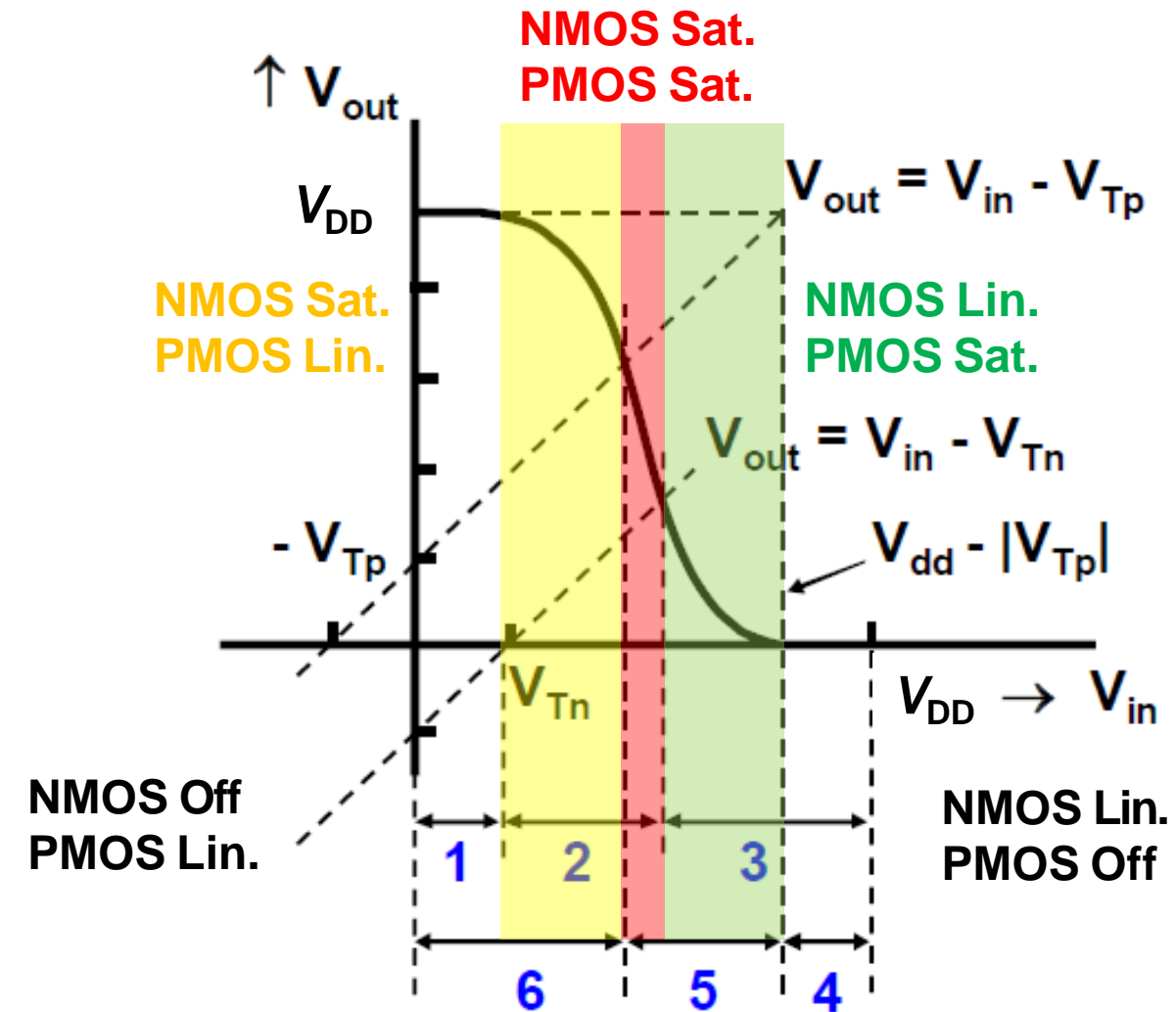


$$V_{GSn} = V_{in}, \quad V_{DSn} = V_{out}, \quad V_{Tn} > 0, \quad V_{Tp} < 0$$

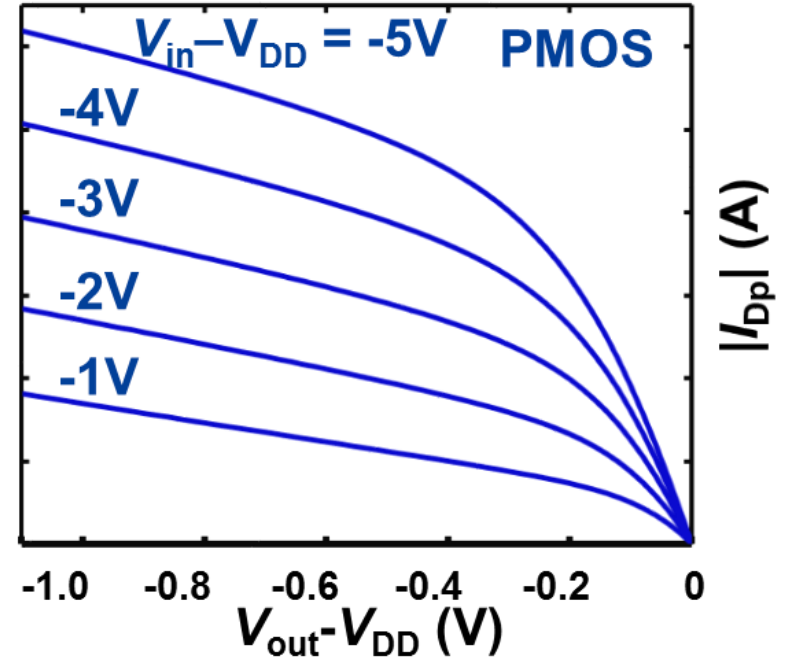
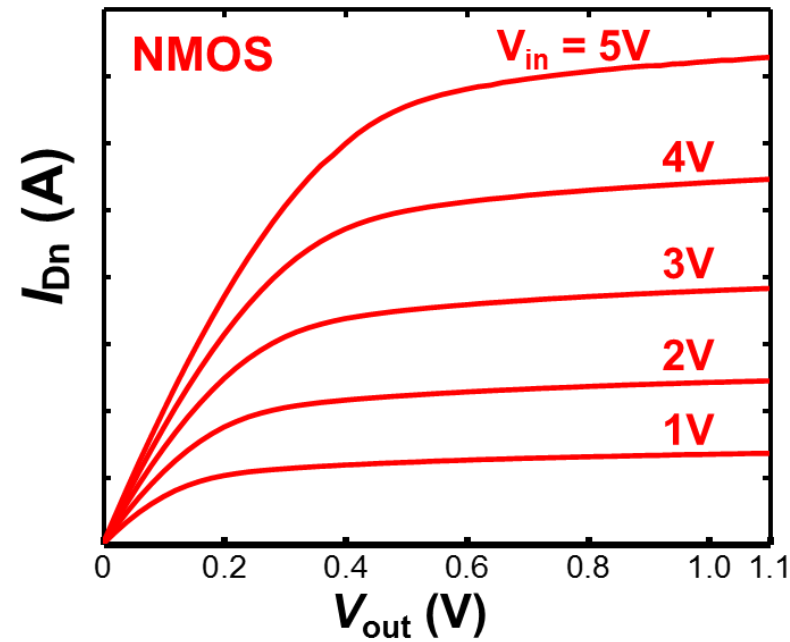
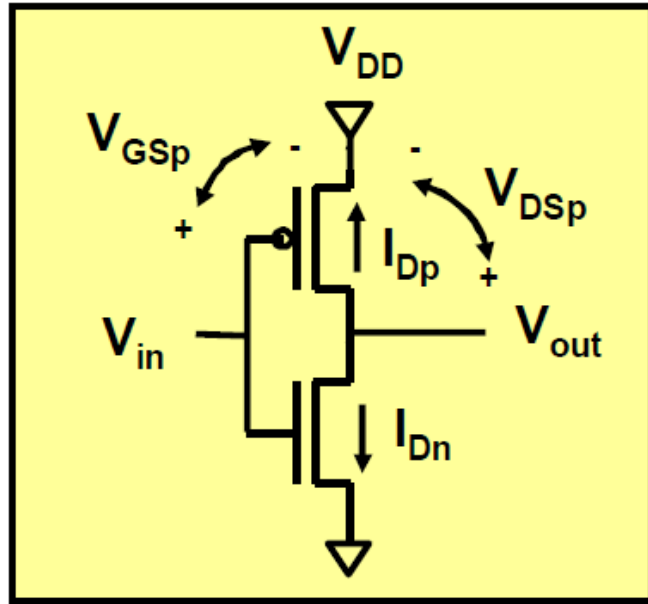
$$V_{GSp} = V_{in} - V_{DD} < 0, \quad V_{DSp} = V_{out} - V_{DD} < 0$$

	Cutoff	Linear	Saturation
	$ V_{GS} < V_T $	$ V_{GS} > V_T $ $ V_{DS} < V_{GS} - V_T $	$ V_{GS} > V_T $ $ V_{DS} > V_{GS} - V_T $
NMOS	$0 < V_{GS} < V_{Tn}$ $0 < V_{in} < V_{Tn}$	$V_{Tn} < V_{in} < V_{DD}$ $V_{out} < V_{in} - V_{Tn}$	$V_{Tn} < V_{in} < V_{DD}$ $V_{out} > V_{in} - V_{Tn}$
PMOS	$V_{DD} - V_{Tp} < V_{in} < V_{DD}$	$V_{in} < V_{DD} - V_{Tp} $ $V_{out} > V_{in} + V_{Tp} $	$V_{in} < V_{DD} - V_{Tp} $ $V_{out} < V_{in} + V_{Tp} $

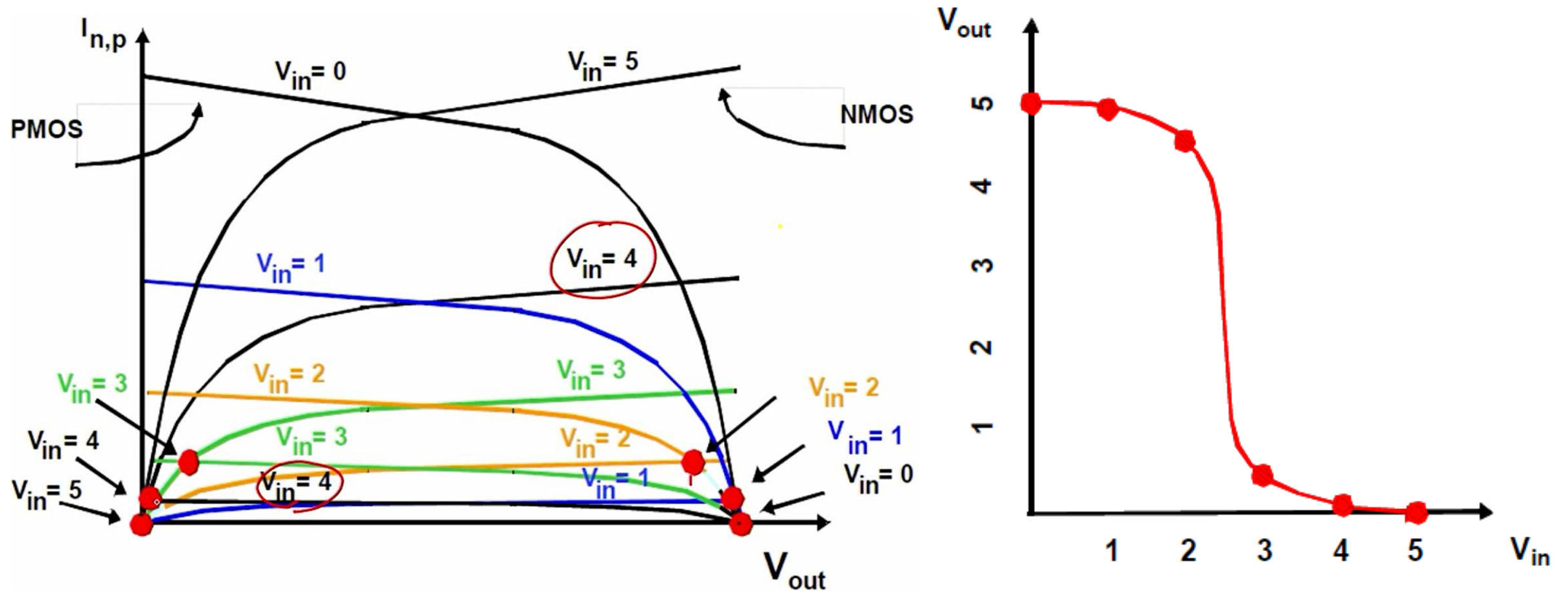
CMOS Inverter VTC



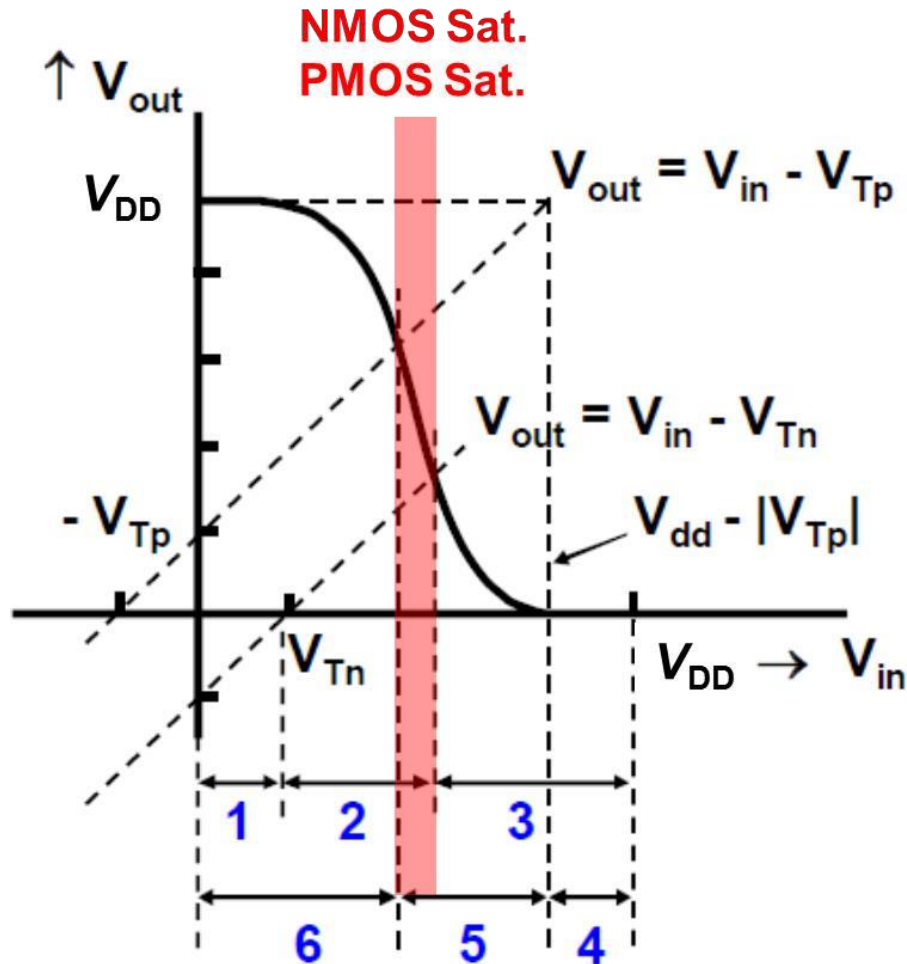
Construct the Inverter VTC



Construct the Inverter VTC

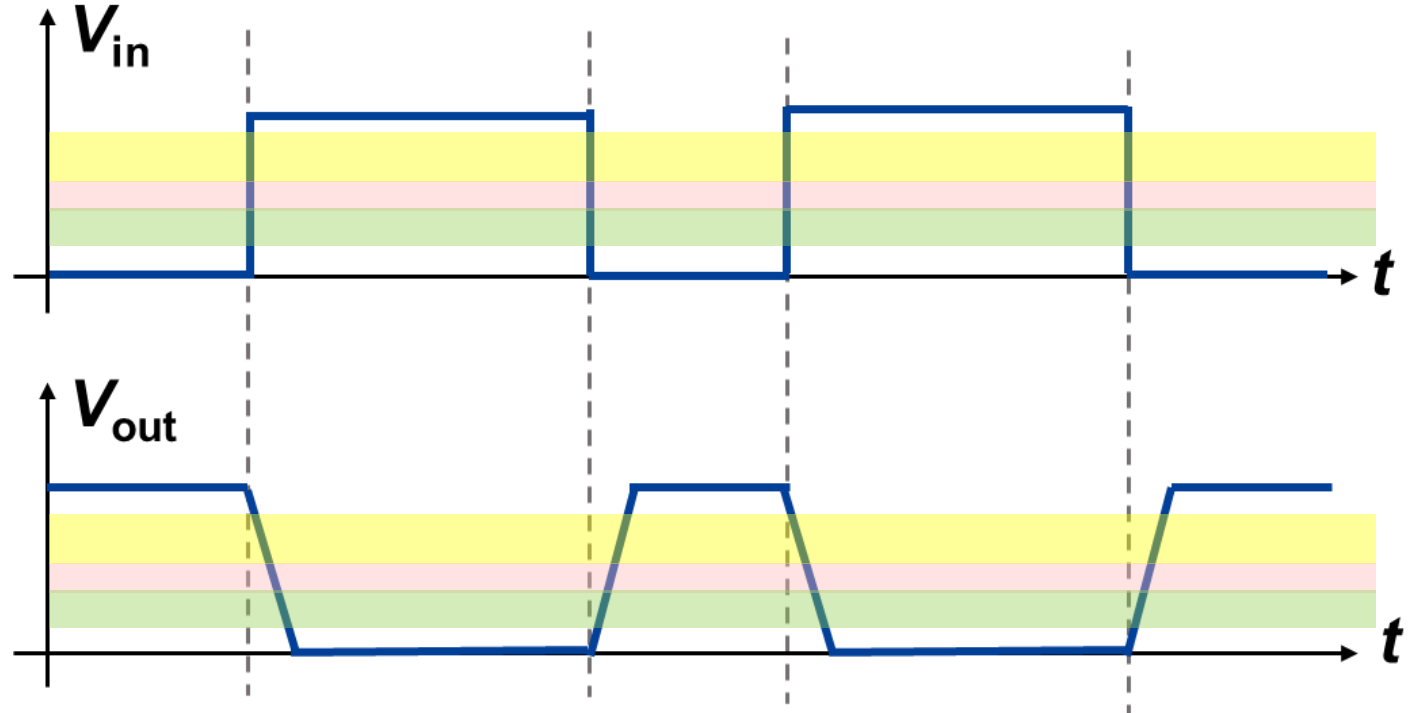
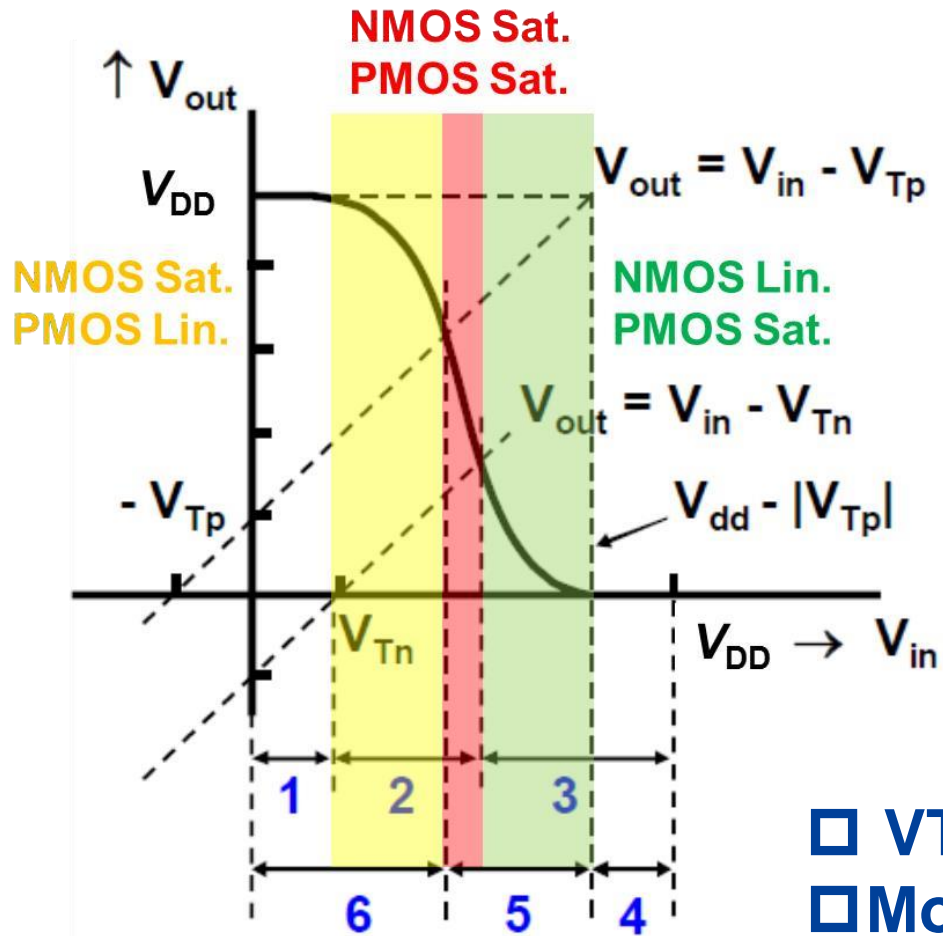


Comment on Inverter VTC



- VTC of the CMOS inverter exhibits a very narrow transition zone;
- In the transition region, both PMOS and NMOS are simultaneously on and in the saturation region → **large current from V_{DD} to GND.**
- In the transition region, a small change in input voltage results in a large output voltage variation → **Unstable.**
- In other regions, **static current can be neglected.**

Comment on Inverter VTC



- VTC is the **DC characteristic** of the CMOS inverter.
- Most cases of the time domain correspond to Regions 1 or 4 → **Static properties guaranteed.**