EE 330
Lecture 38

Digital Circuit Design

- Basic Logic Gates
- Properties of Logic Families
- Characterization of CMOS Inverter

Exam Schedule

Final	Wed May 11	7:30 a.m.

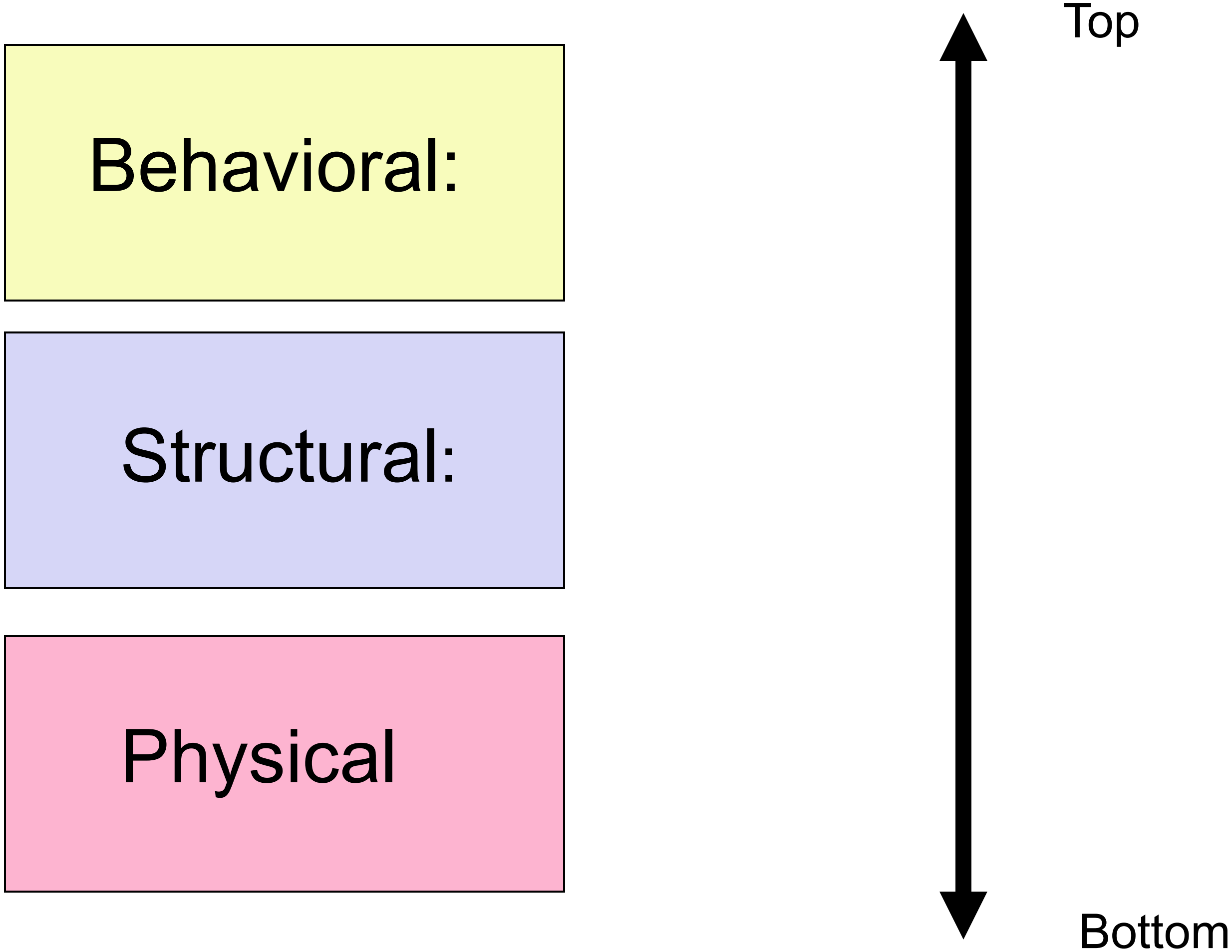
Photo courtesy of the director of the National Institute of Health (NIH)

As a courtesy to fellow classmates, TAs, and the instructor

Wearing of masks during lectures and in the laboratories for this course would be appreciated irrespective of vaccination status

Review from Last Lecture

Hierarchical Digital Design Domains:



Multiple Levels of Abstraction

Review from Last Lecture

Hierarchical Digital Design Domains:

Behavioral : Describes what a system does or what it should do

Structural : Identifies constituent blocks and describes how these blocks are interconnected and how they interact

Physical : Describes the constituent blocks to both the transistor and polygon level and their physical placement and interconnection

Multiple representations often exist at any level or sublevel

Review from Last Lecture

Logic Optimization

What is optimized (or minimized) ?

- Number of Gates
- Number or Levels of Logic
- Speed
- Delay
- Power Dissipation
- Area
- Cost
- Peak Current

• • •

Depends Upon What User Is Interested In

Review from Last Lecture

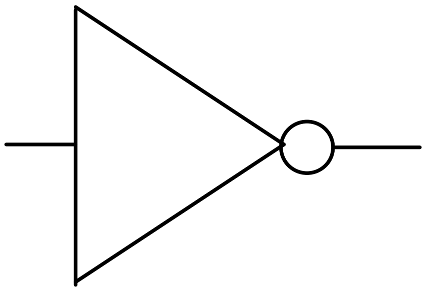
Standard Cell Library

- Set of primitive building blocks that have been pre-characterized for dc and high frequency performance
- Generally includes basic multiple-input gates and flip flops
- P-cells often included
- Can include higher-level blocks
  - Adders, multipliers, shift registers,counters,…
- Cell library often augmented by specific needs of a group or customer

Review from Last Lecture

The basic logic gates

It suffices to characterize the inverter of a logic family and then express the performance of other gates in that family in terms of the performance of the inverter.



What characteristics are required and desirable for an inverter to form the basis for a useful logic family?

What restrictions are there on the designer for building Boolean circuits?

- None !!!!
- It must “work” as expected
- Designer is Master of the silicon !

Desirable and/or Required Logic Family Characteristics

What are the desired characteristics of a logic family?

Desirable and/or Required Logic Family Characteristics

1. High and low logic levels must be uniquely distinguishable (even in a long cascade)
2. Capable of driving many loads (good fanout)
3. Fast transition times (but in some cases, not too fast)
4. Good noise margins (low error probabilities)
5. Small die area
6. Low power consumption
7. Economical process requirements

Desirable and/or Required Logic Family Characteristics

8. Minimal noise injection to substrate
9. Low leakage currents
10. No oscillations during transitions
11. Compatible with synthesis tools
12. Characteristics do not degrade too much with temperature
13. Characteristics do not vary too much with process variations

Are some of these more important than others?

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Are some of these more important than others?

Yes ! – must have well-defined logic levels for circuits to even function as logic

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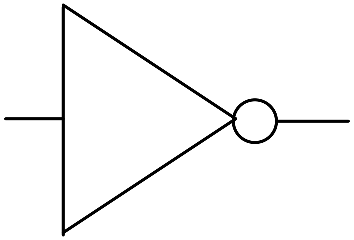
Yes ! – must have well-defined logic levels for circuits to even function as logic

What properties of an inverter are necessary for it to be useful for building a logic family

What are the logic levels for a given inverter of a given logic family?

What are the logic levels for a given inverter of for a given logic family?



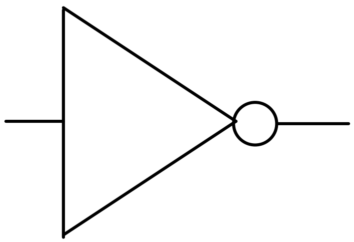
V_H=?

V_L=?

Can we legislate them ?

- Some authors choose to simply define a value for them
- Simple and straightforward approach
- **But what if the circuit does not interpret them the same way they are defined !!**

What are the logic levels for a given inverter of for a given logic family?



V_H=?

V_L=?

Can we legislate them ?

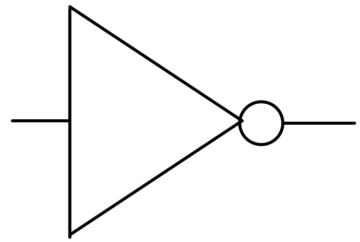
In 1897 the Indiana House of Representatives unanimously passed a measure redefining the area of a circle and the value of pi. (House Bill no. 246, introduced by Rep. Taylor I. Record.) The bill died in the state Senate.

Indiana Pi Bill

From Wikipedia, the free encyclopedia

The **Indiana Pi Bill** is the popular name for bill #246 of the 1897 sitting of the Indiana General Assembly, one of the most notorious attempts to establish mathematical truth by legislative fiat. Despite its name, the main result claimed by the bill is a method to square the circle, although it does imply various incorrect values of the mathematical constant π, the ratio of the circumference of a circle to its diameter.[1] The bill, written by a physician who was an amateur mathematician, never became law due to the

What are the logic levels for a given inverter of for a given logic family?



V_H=?

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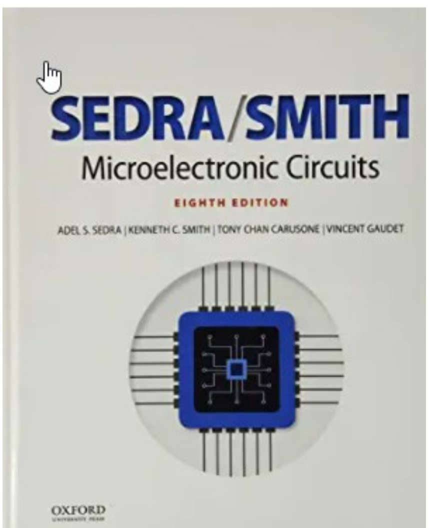
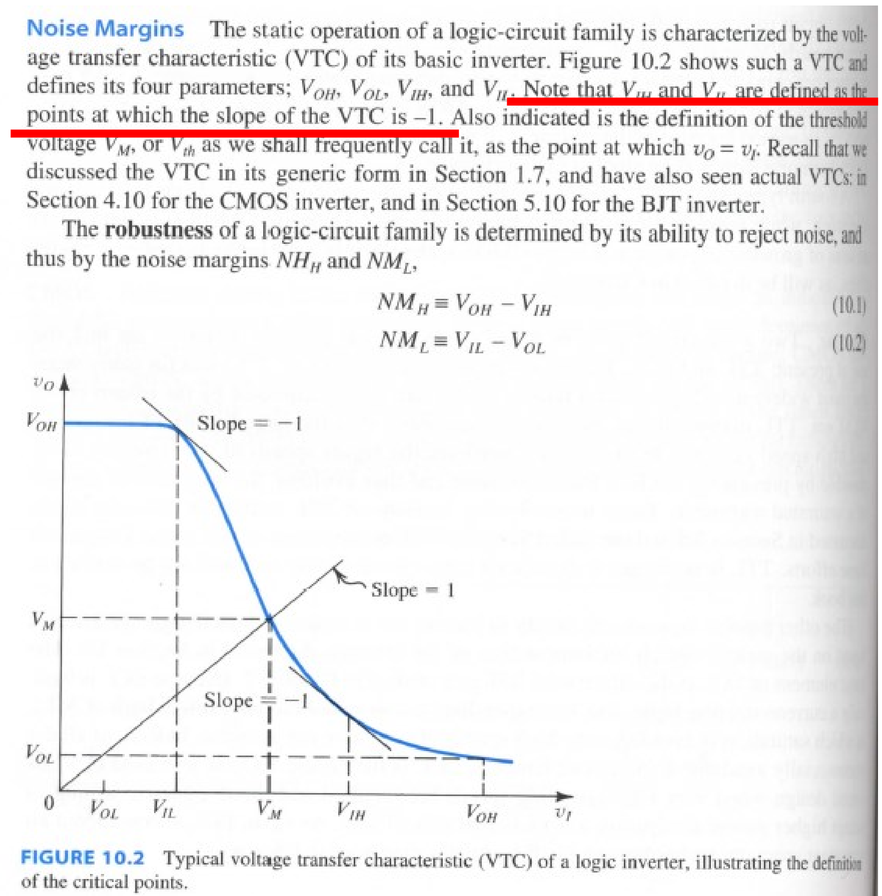
Can we legislate them ?



World's most widely used electronics text



Noise Margins The static operation of a logic-circuit family is characterized by the voltage transfer characteristic (VTC) of its basic inverter. Figure 10.2 shows such a VTC and defines its four parameters; V_{OH}, V_{OL}, V_{IH}, and V_{IL}. Note that V_{IH} and V_{IL} are defined as the points at which the slope of the VTC is –1. Also indicated is the definition of the threshold voltage V_M, or V_{th} as we shall frequently call it, as the point at which $v_O = v_I$. Recall that we discussed the VTC in its generic form in Section 1.7, and have also seen actual VTCs: in Section 4.10 for the CMOS inverter, and in Section 5.10 for the BJT inverter.

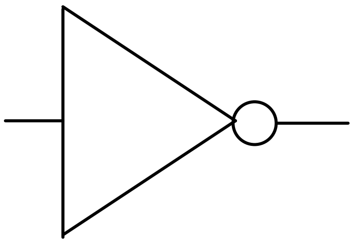
The **robustness** of a logic-circuit family is determined by its ability to reject noise, and thus by the noise margins NM_H and NM_L,

$$NM_H \equiv V_{OH} - V_{IH} \quad (10.1)$$

$$NM_L \equiv V_{IL} - V_{OL} \quad (10.2)$$

FIGURE 10.2 Typical voltage transfer characteristic (VTC) of a logic inverter, illustrating the definition of the critical points.

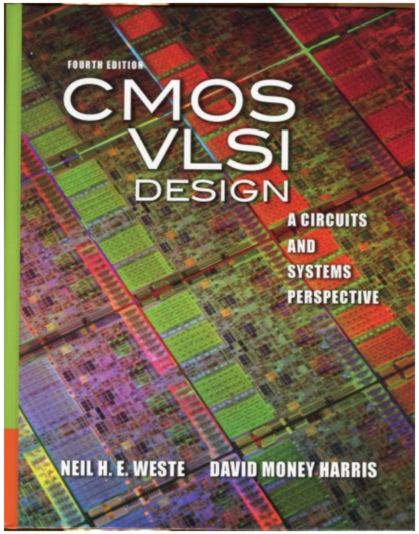
What are the logic levels for a given inverter of for a given logic family?



V_H=?

V_L=?

Can we legislate them ?



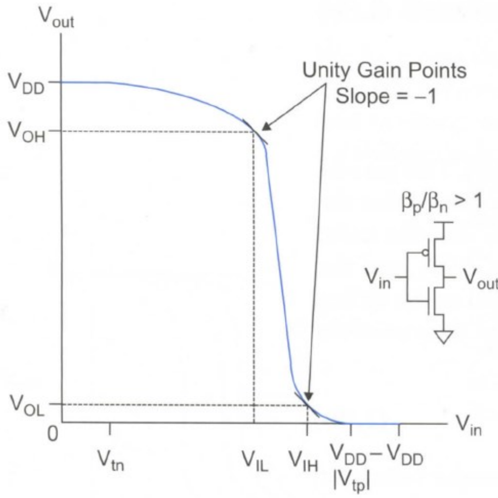
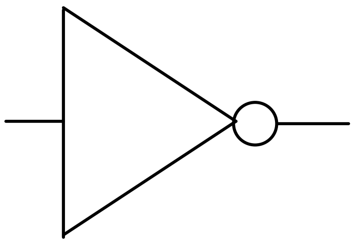


FIGURE 2.30 CMOS inverter noise margins

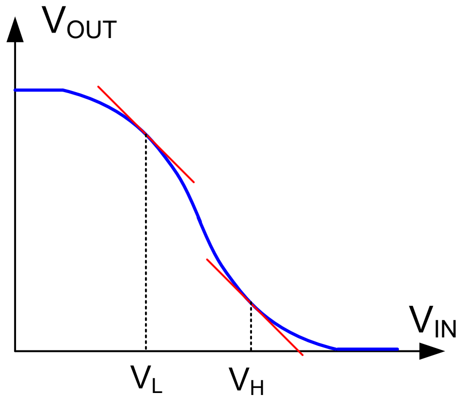
What are the logic levels for a given inverter of for a given logic family?



V_H=?　　　　V_L=?

Can we legislate them ?

- Some authors choose to define them based upon specific features of inverter
- Analytical expressions may be complicated
- But what if the circuit does not interpret them the same way they are defined !!



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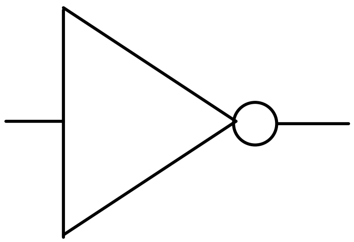
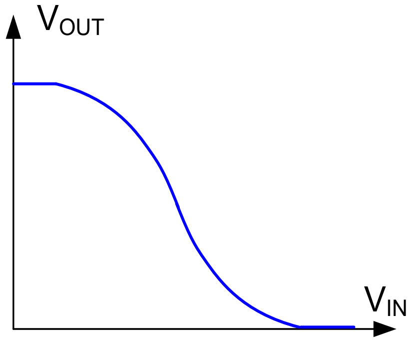


V_H=? V_L=?

Ask the inverter how it will interpret logic levels

- The inverter will interpret them the way the circuit really operate as a Boolean system !!
- Analytical expressions may be complicated
- How is this determination made?



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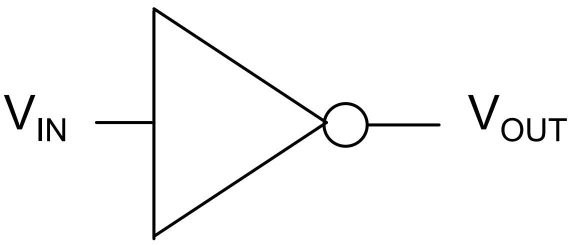

V_H=?

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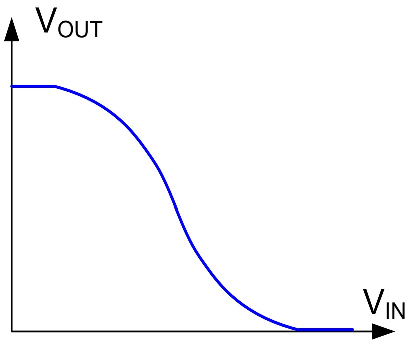
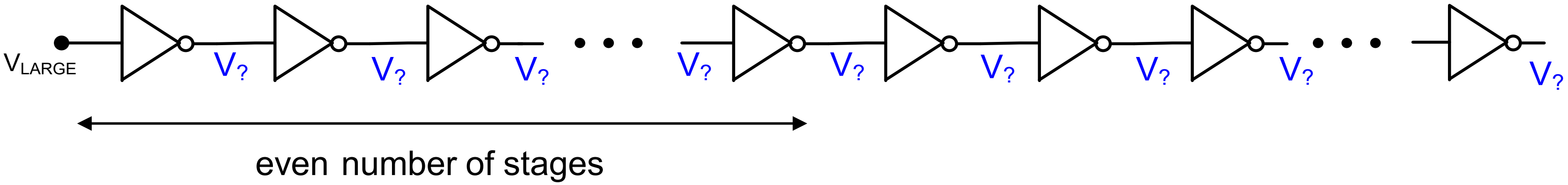


Consider a very long cascade of inverters

- Apply a large voltage at the input (alternatively a small input could be used)
- w.l.o.g. assume an even number of inverters in chain indicated



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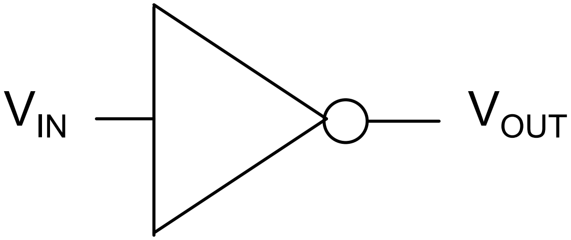

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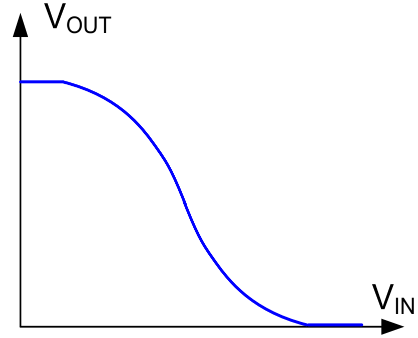

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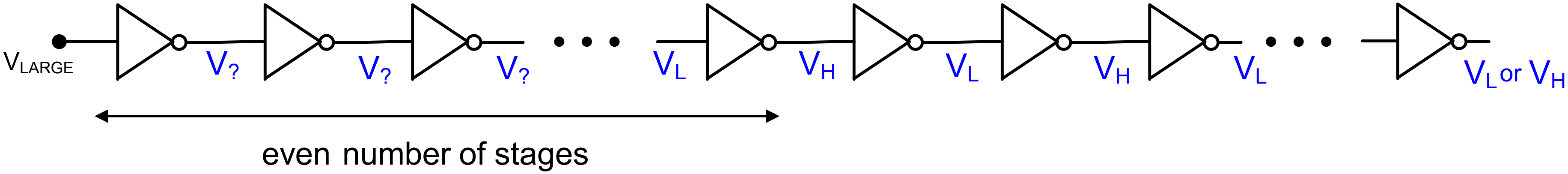
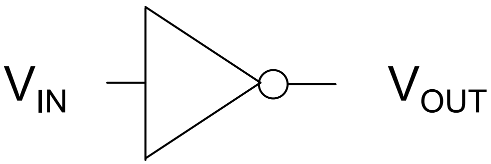


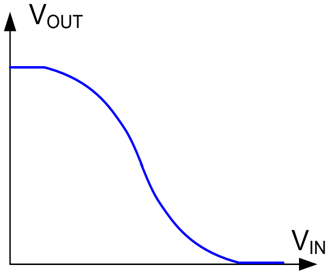
If logic levels are to be maintained, the voltage at the end of this even number of stages must be V_H, that of the next must be V_L, the next V_H, etc. until the start of the cascade is approached

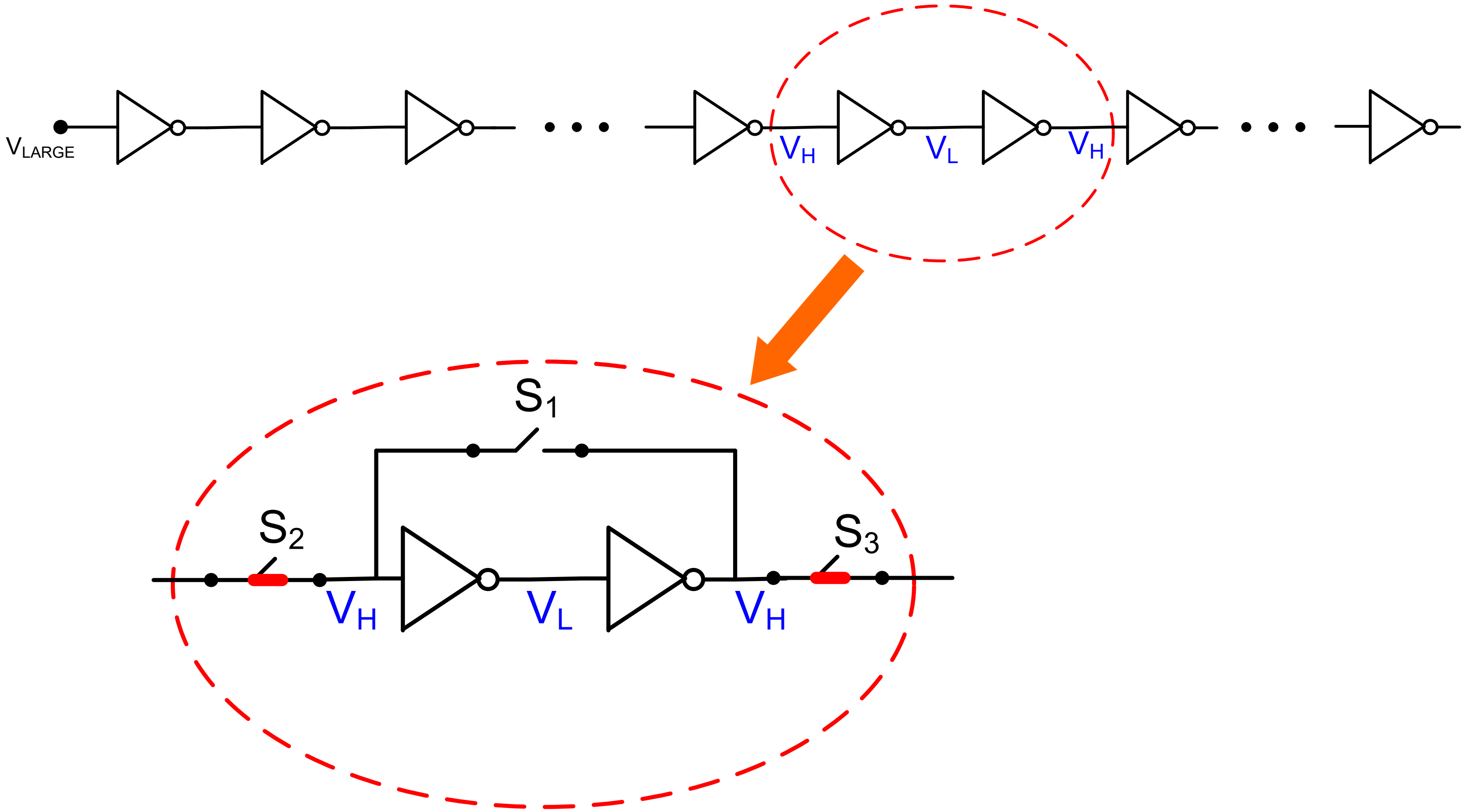
Ask the inverter how it will interpret logic levels



V_H=?

V_L=?





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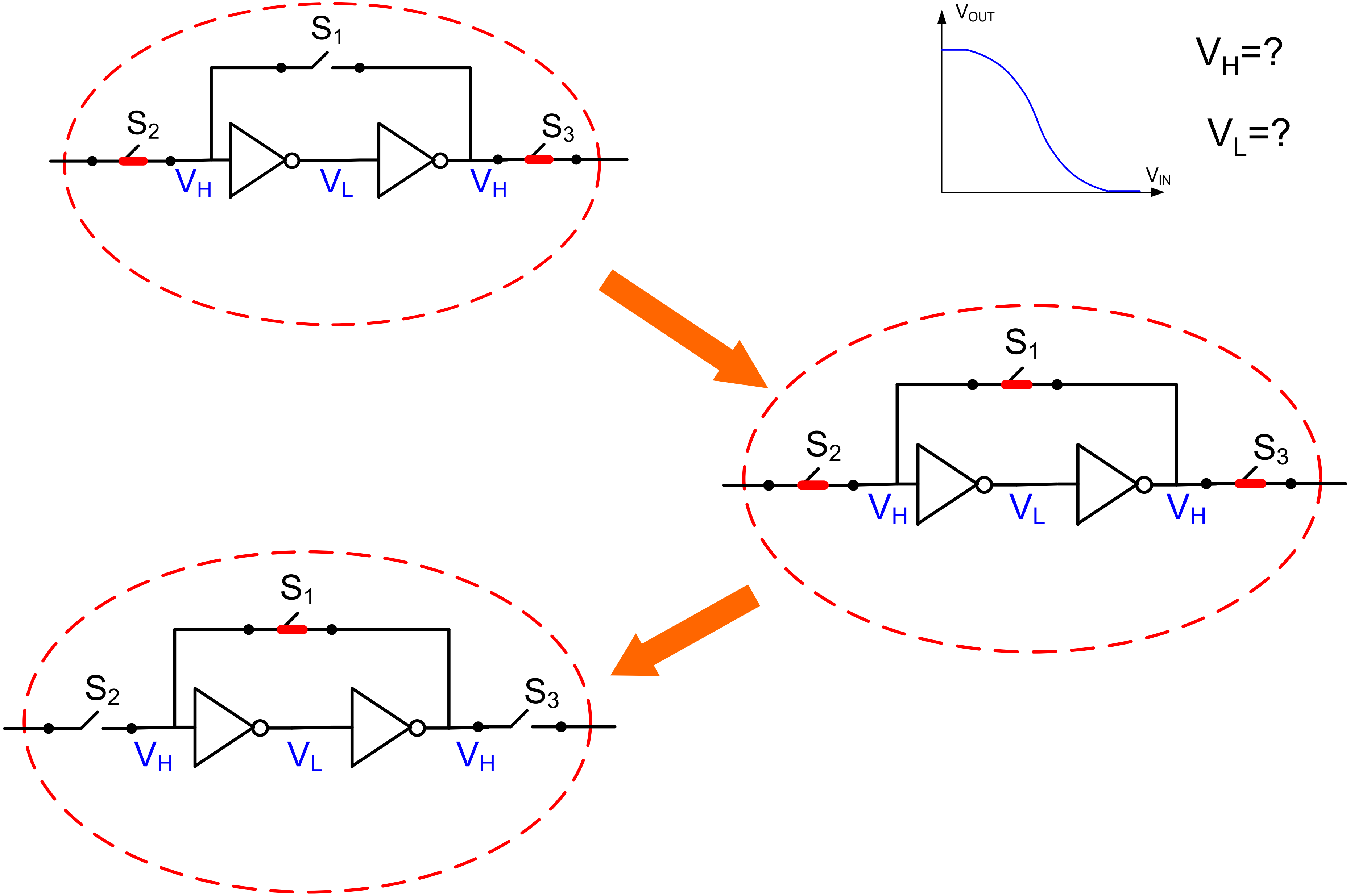

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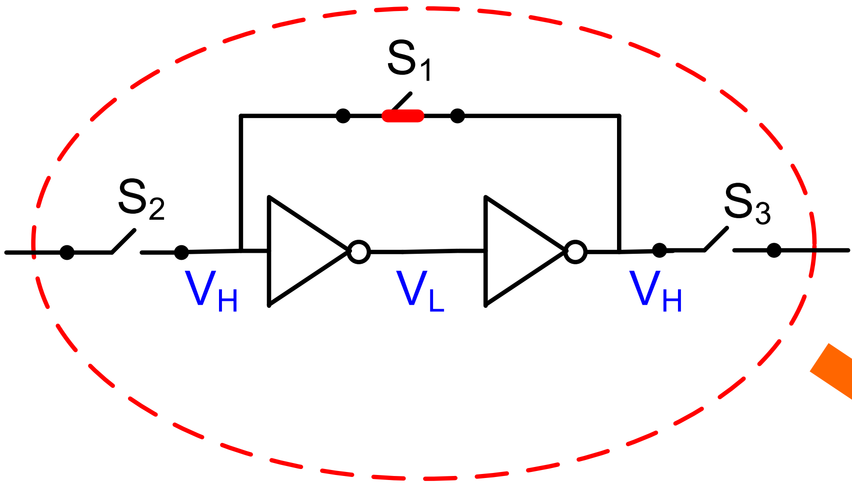
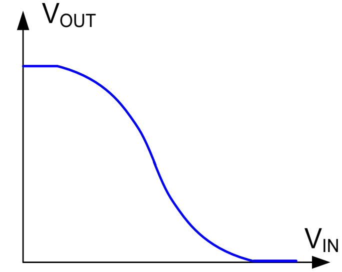
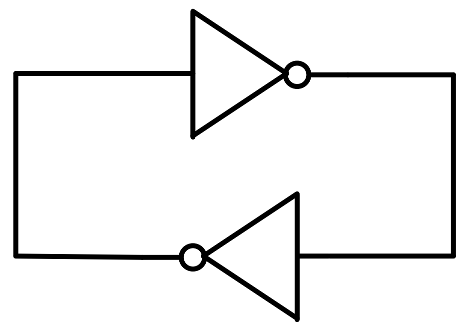




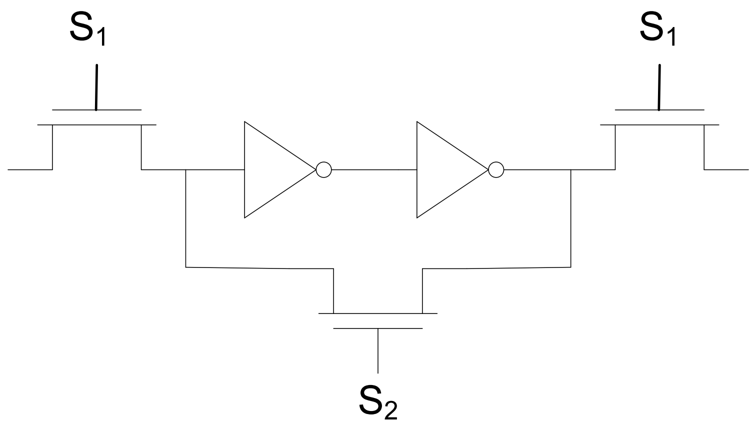
V_H=?

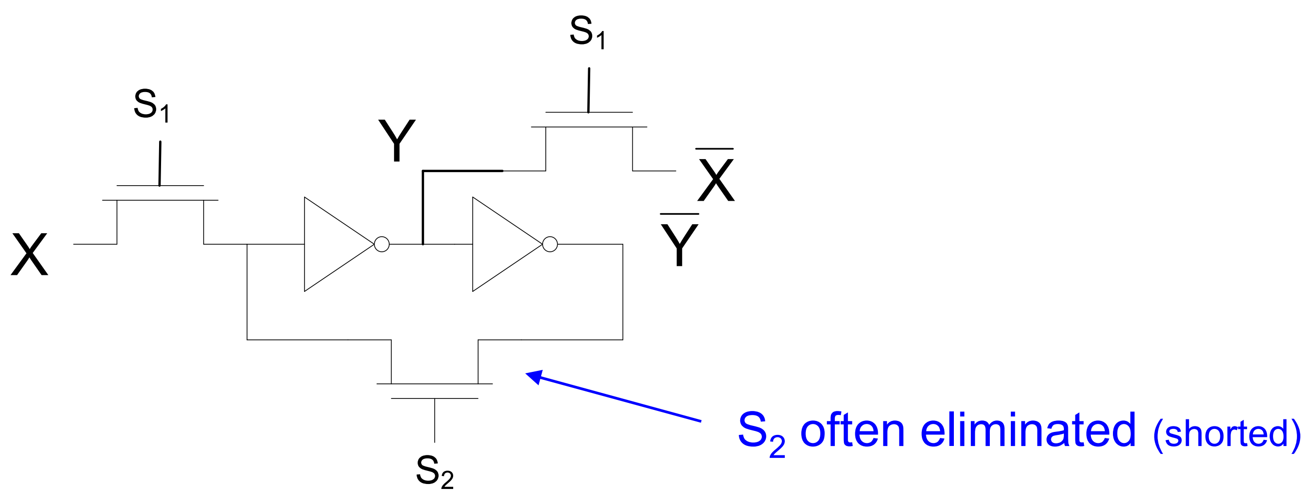
V_L=?



- Two inverter loop
- Very useful circuit !

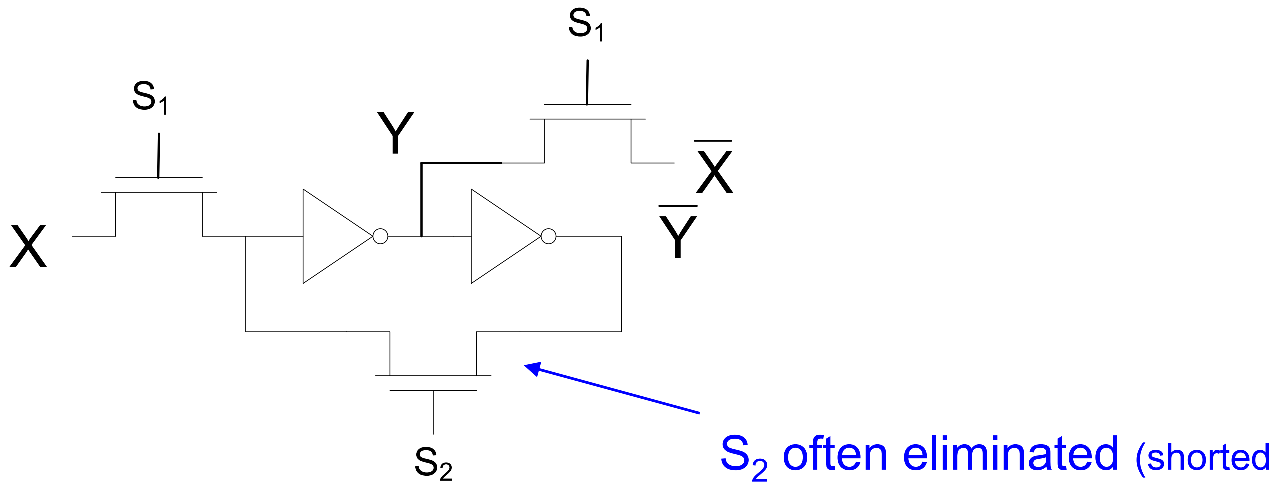
The two-inverter loop

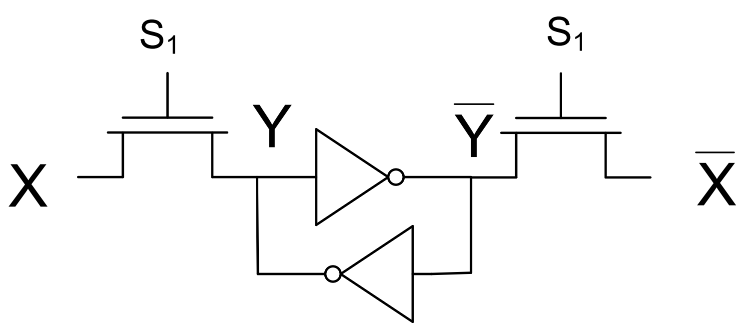




SRAM Cell

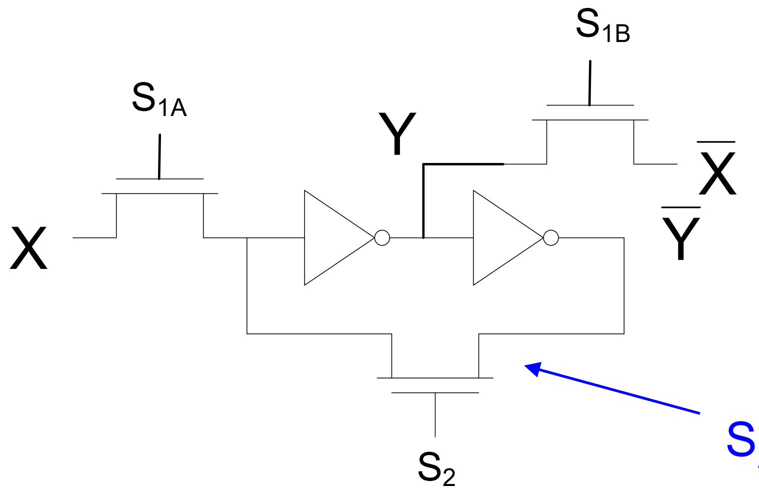
The two-inverter loop





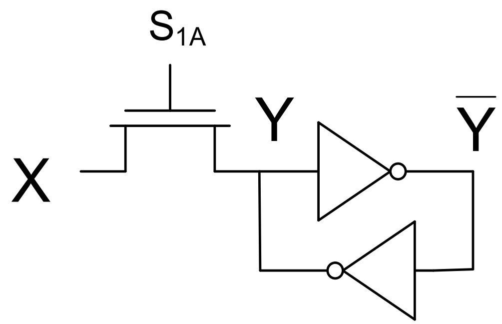
Standard 6-transistor SRAM Cell

The two-inverter loop



S_{1B} can also be eliminated (opened)

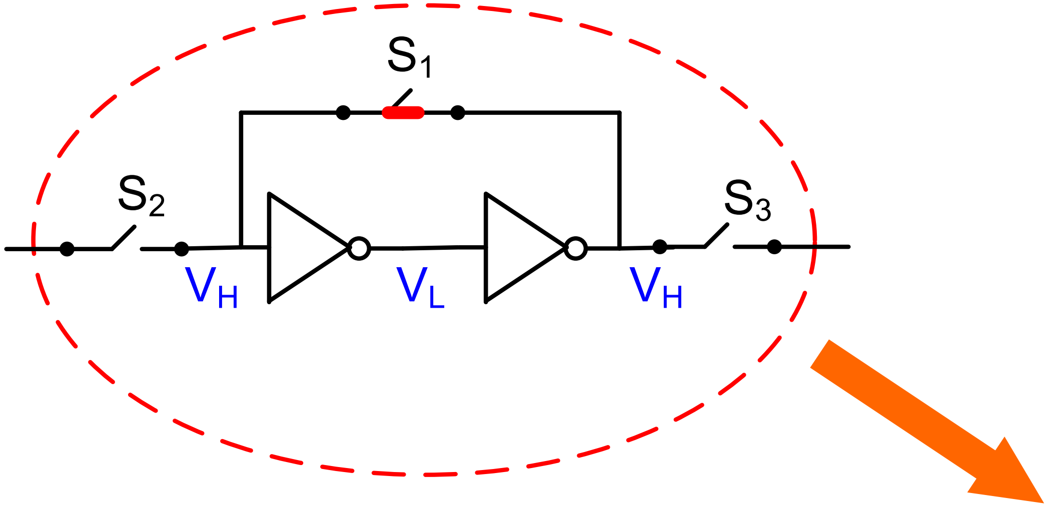
S_2 often eliminated (shorted)

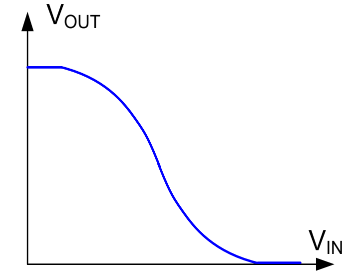


5-transistor SRAM Cell

Will also work but less common (less area but degraded performance)

Ask the inverter how it will interpret logic levels

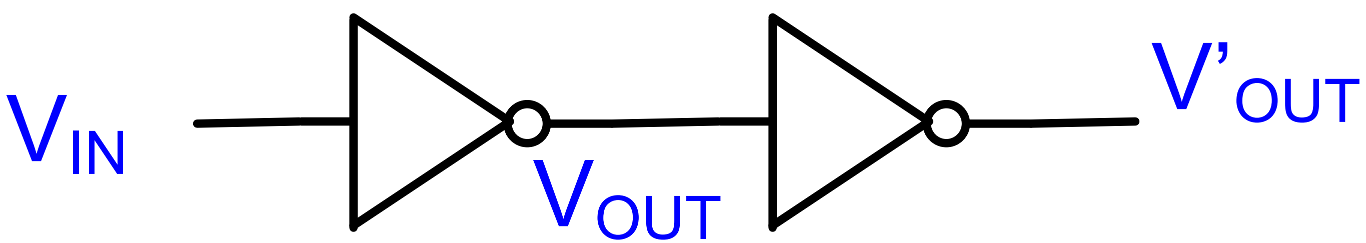




Inverter Characteristics

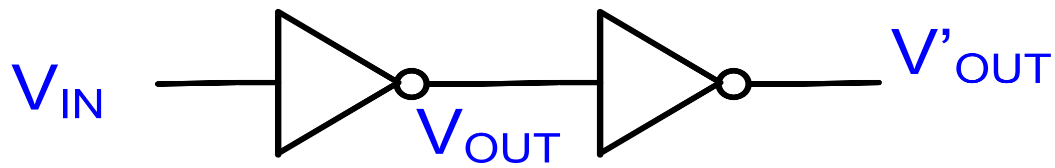
V_H=?

V_L=?

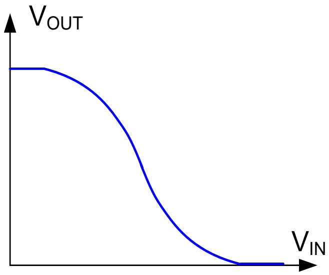


Thus, consider the inverter pair

Ask the inverter how it will interpret logic levels



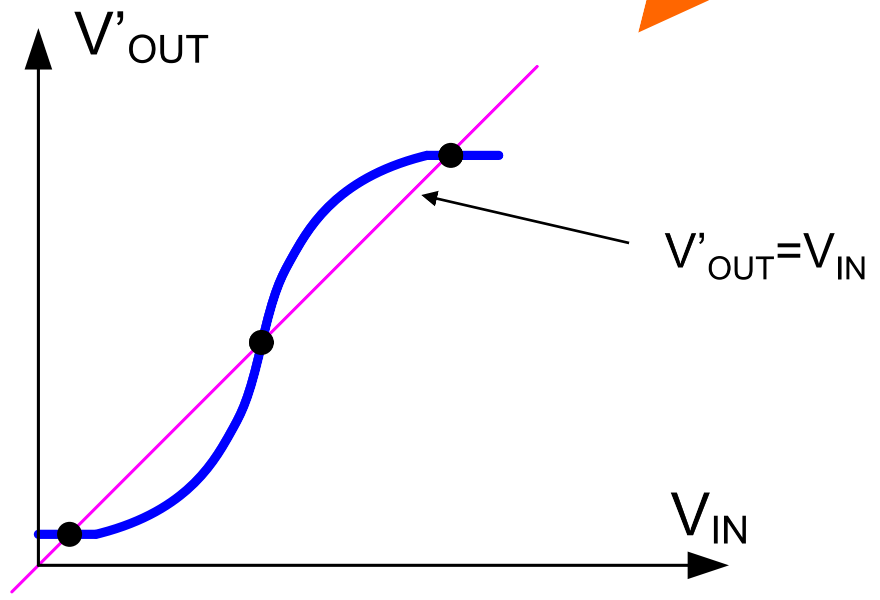
Inverter pair



V_H=?

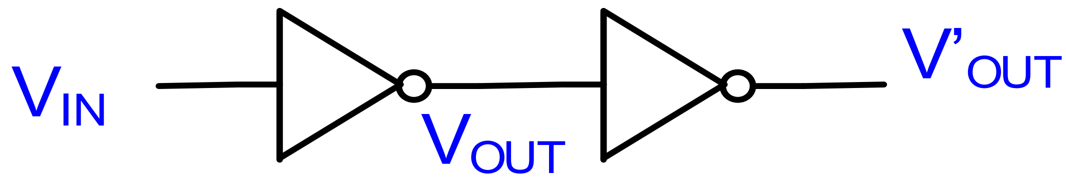
V_L=?

V_H and V_L will be on the intersection of the transfer characteristics of the inverter pair (IPTC) and the $V'_{OUT}=V_{IN}$ line

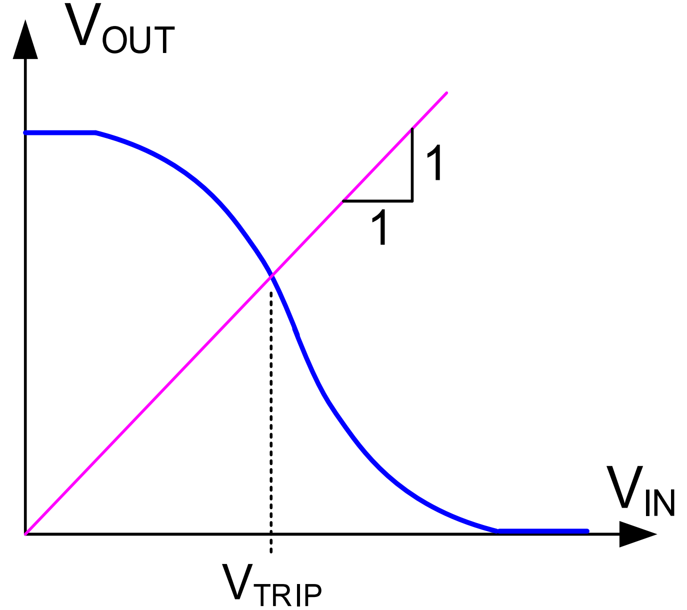


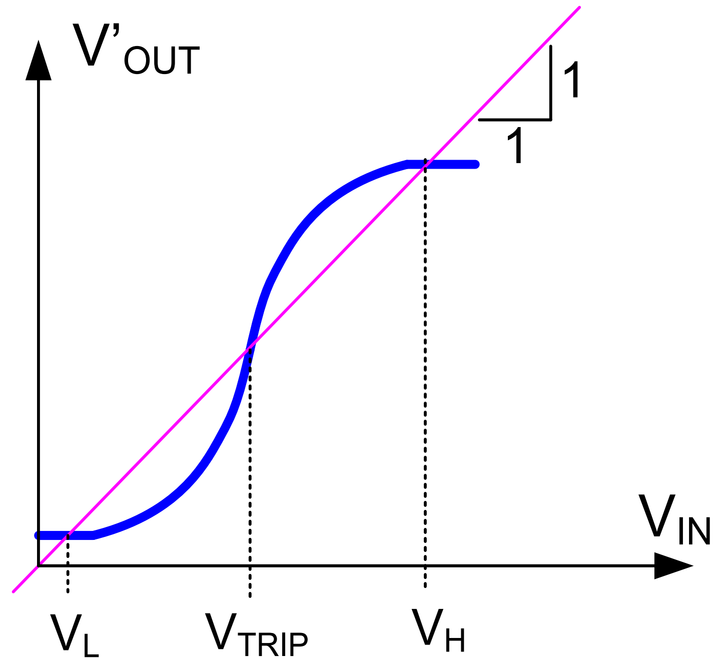
V_H and V_L often termed the “1” and “0” states

Observation



When V_{OUT}=V_{IN} for the inverter, V'_{OUT} is also equal to V_{IN} . Thus the intersection point for V_{OUT}=V_{IN} in the inverter transfer characteristics (ITC) is also an intersection point for V'_{OUT}=V_{IN} in the inverter-pair transfer characteristics (IPTC)





Implication: Inverter characteristics can be used directly to obtain V_{TRIP}

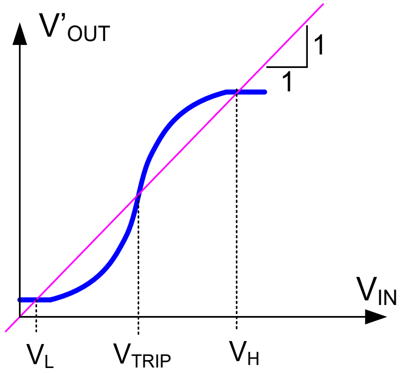
Logic Family Characteristics

What properties of an inverter are necessary for it to be useful for building a two-level logic family?

The inverter-pair transfer characteristics must have three unique intersection points with the $V'_{OUT} = V_{IN}$ line

What are the logic levels for a given inverter of for a given logic family?

The two extreme intersection points of the inverter-pair transfer characteristics with the $V'_{OUT} = V_{IN}$ line



Can we legislate V_H and V_L for a logic family ? No!

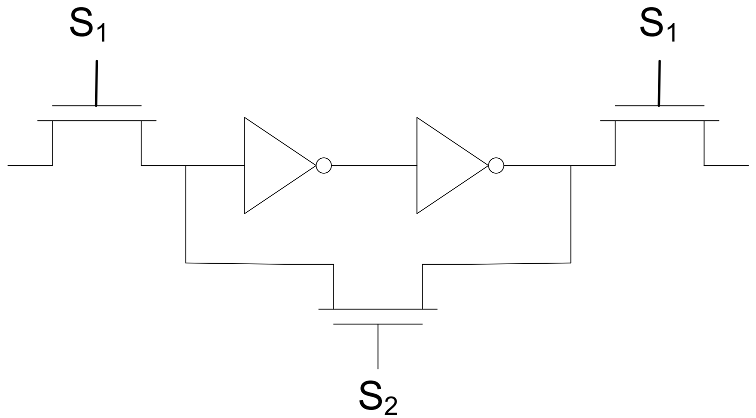
What other properties of the inverter are desirable?

Reasonable separation between V_H and V_L (enough separation so that noise does not cause circuit to interpret level incorrectly)

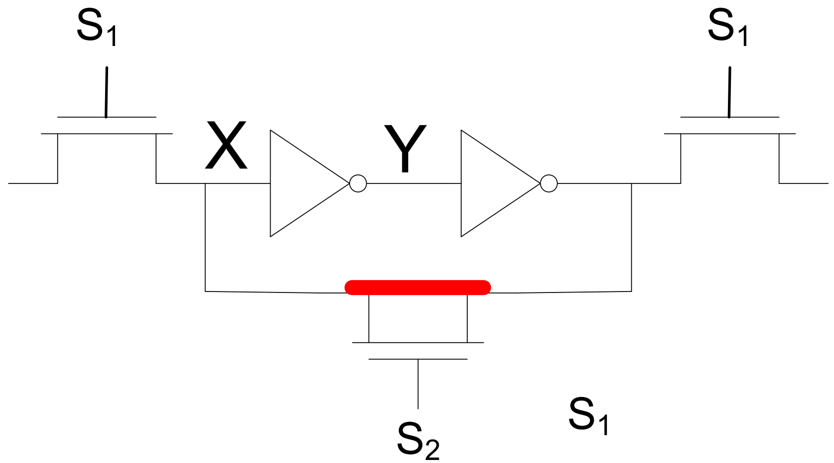
$$V_{TRIP} \cong \frac{V_H + V_L}{2}$$

(to provide adequate noise immunity and process insensitivity)

What happens near the quasi-stable operating point?

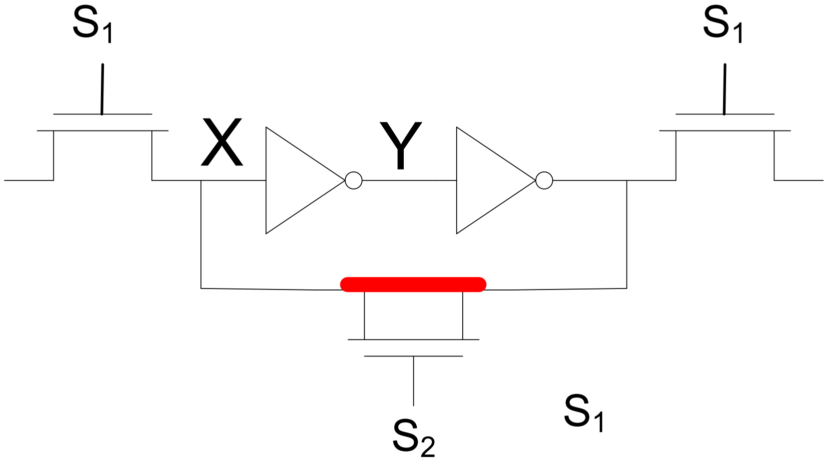


S_2 closed and $X=Y=V_{TRIP}$



What happens near the quasi-stable operating point?

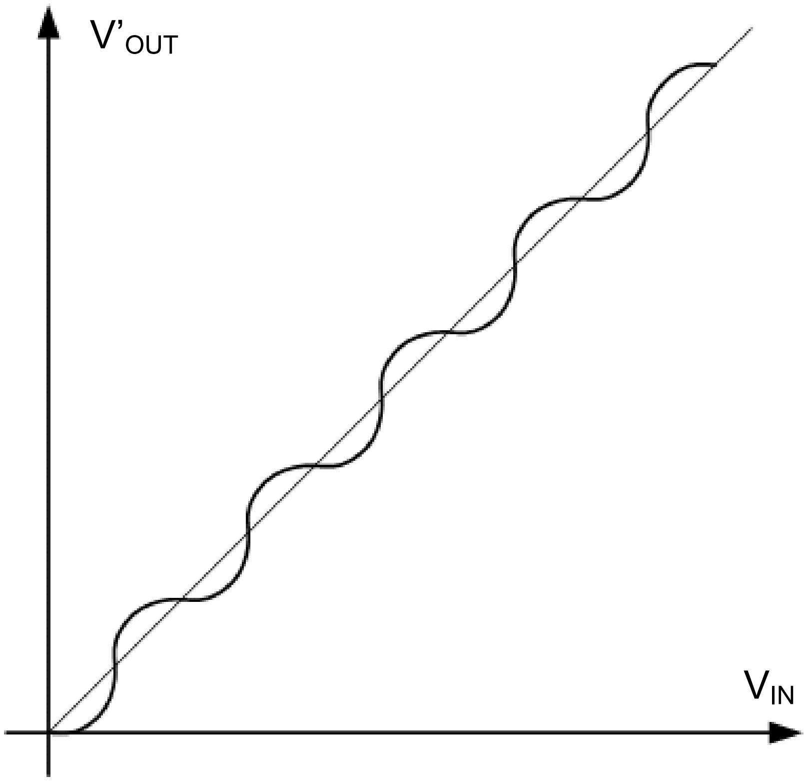
S_2 closed and $X=Y=V_{TRIP}$



If X decreases even very slightly, will move to the X=0, Y=1 state (very fast)

If X increases even very slightly, will move to the X=1, Y=0 state (very fast)

What if the inverter pair had the following transfer characteristics?



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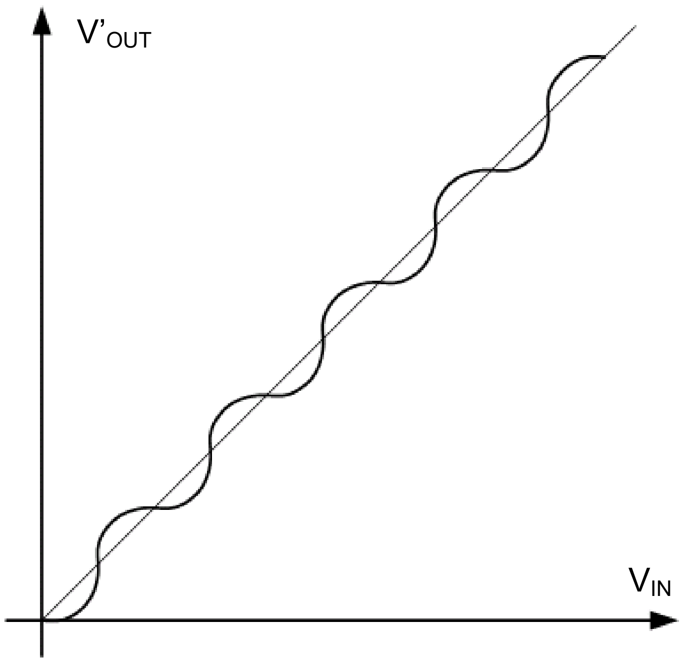
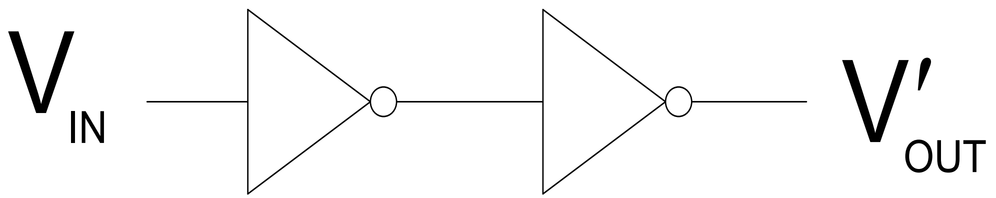
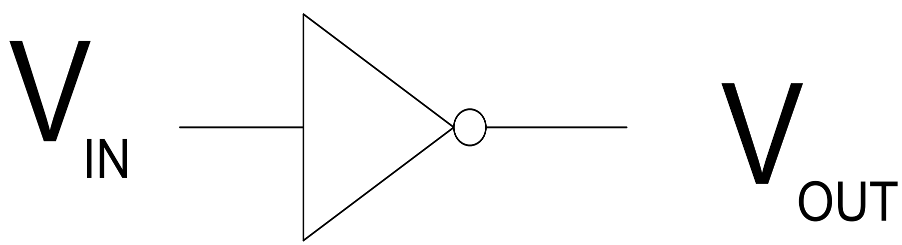


Multiple levels of logic
Every intersection point with slope <1 is a stable point
Every intersection point with slope >1 is a quasi-stable point

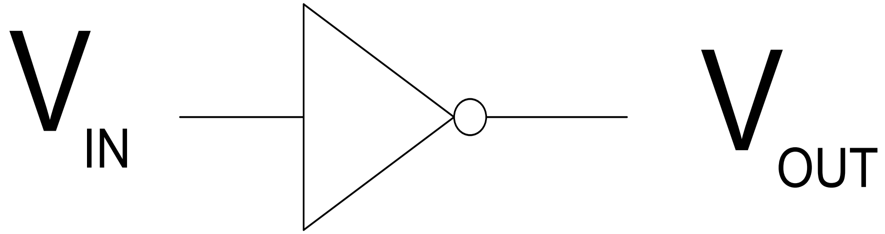
What are the transfer characteristics of the static CMOS inverter pair?

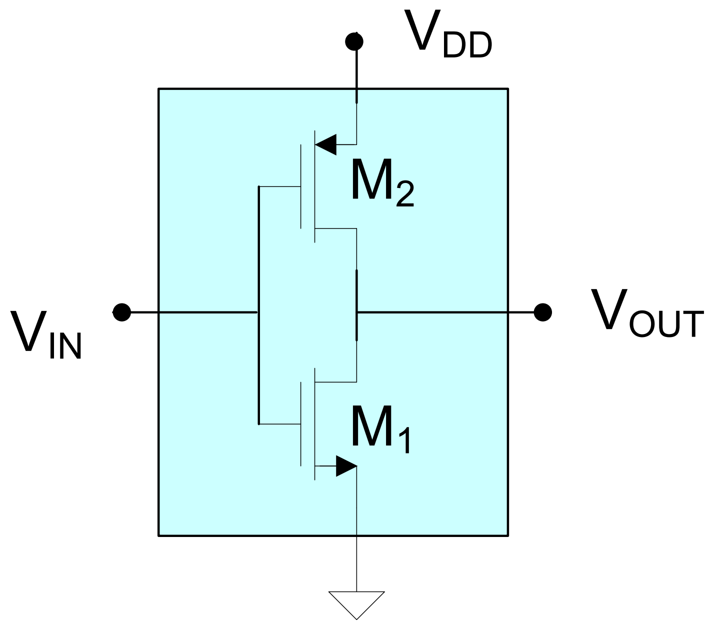


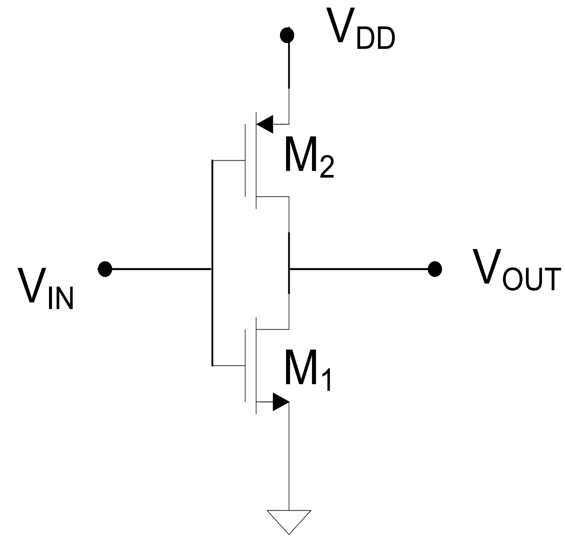
Consider first the inverter



Transfer characteristics of the static CMOS inverter





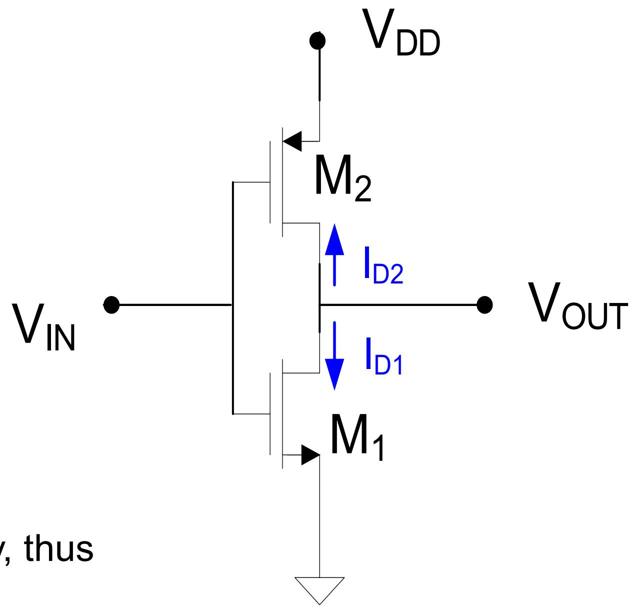


VDD
M2
VIN
VOUT
M1

Transfer characteristics of the static CMOS inverter

(Neglect λ effects)

Case 1 Vin is so high that M_1 triode, M_2 cutoff



$$I_{D1} = \mu_n C_{OXn} \frac{W_1}{L_1}\left(V_{IN} - V_{Tn} - \frac{V_{OUT}}{2}\right)V_{OUT}$$

$$I_{D2} = 0$$

Equating I_{D1} and $-I_{D2}$ we obtain:

$$0 = \mu_n C_{OXn} \frac{W_1}{L_1}\left(V_{IN} - V_{Tn} - \frac{V_{OUT}}{2}\right)V_{OUT}$$

It can be shown that setting the first product term to 0 will not verify, thus

$$V_{OUT} = 0$$

valid for:

$$V_{GS1} \geq V_{Tn} \qquad V_{DS1} < V_{GS1} - V_{Tn} \qquad V_{GS2} \geq V_{Tp}$$

thus, valid for:

$$V_{IN} \geq V_{Tn} \qquad V_{OUT} < V_{IN} - V_{Tn} \qquad V_{IN} - V_{DD} \geq V_{Tp}$$

Graphical Interpretation of these conditions:

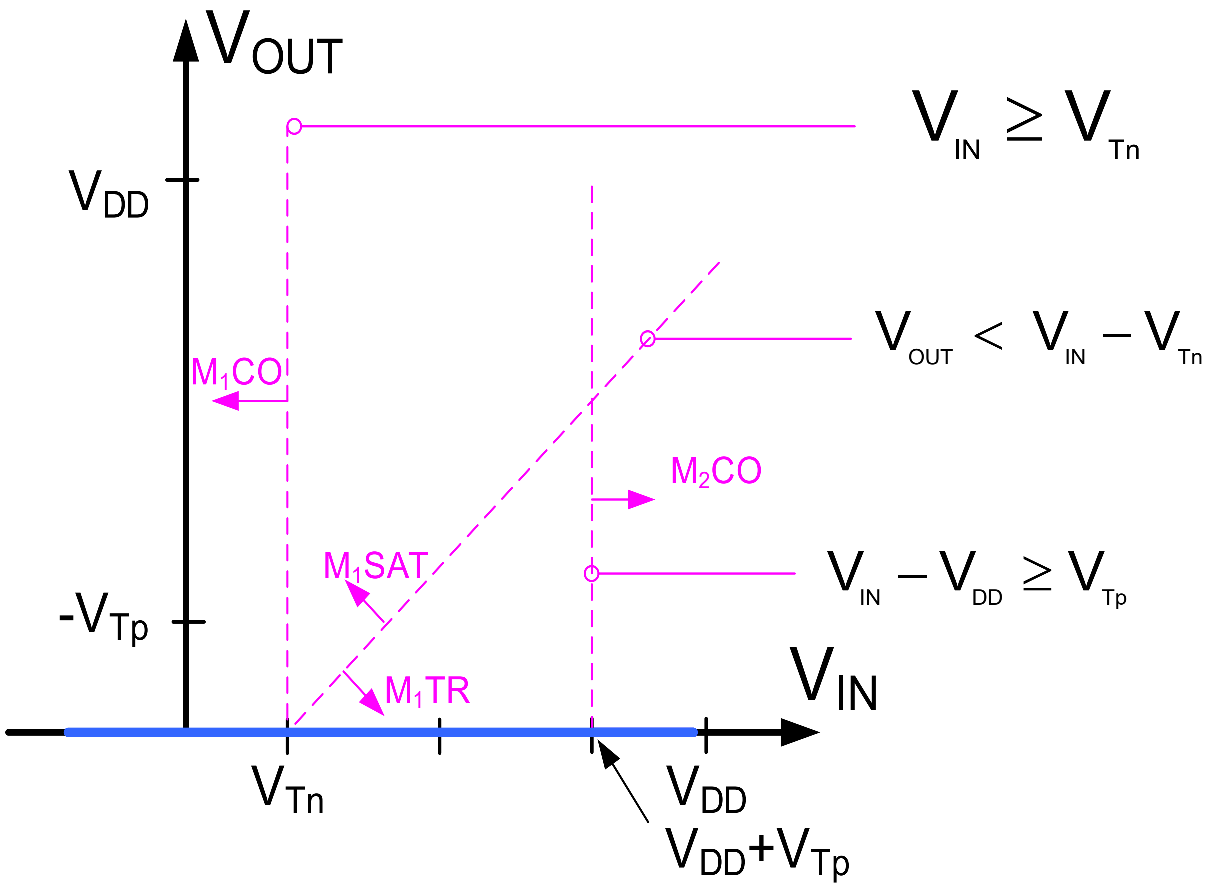
$V_{IN} \geq V_{Tn}$ $\quad$ $V_{OUT} < V_{IN} - V_{Tn}$ $\quad$ $V_{IN} - V_{DD} \geq V_{Tp}$

Transfer characteristics of the static CMOS inverter

(Neglect λ effects)

Case 1 M_1 triode, M_2 cutoff

$$V_{OUT} = 0$$

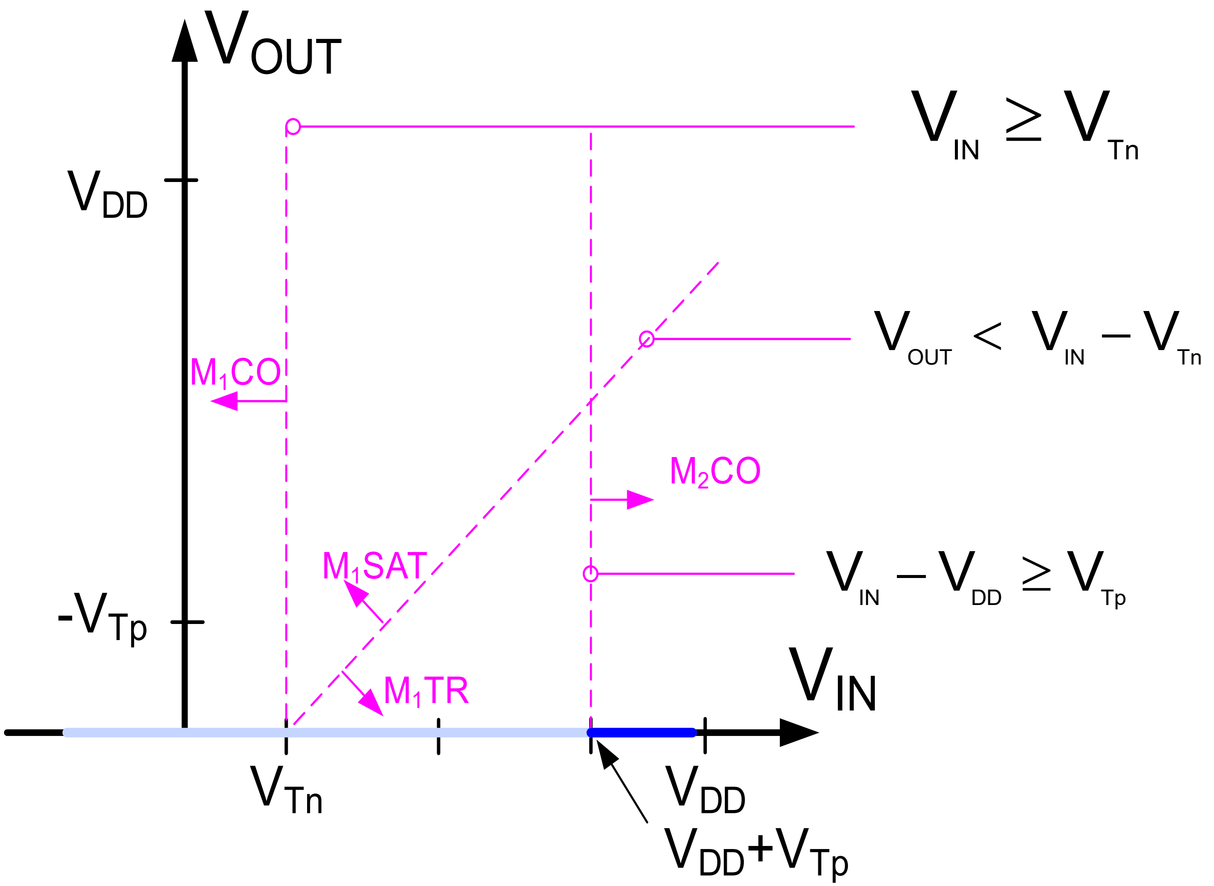


Transfer characteristics of the static CMOS inverter

(Neglect λ effects)

Case 1 M_1 triode, M_2 cutoff

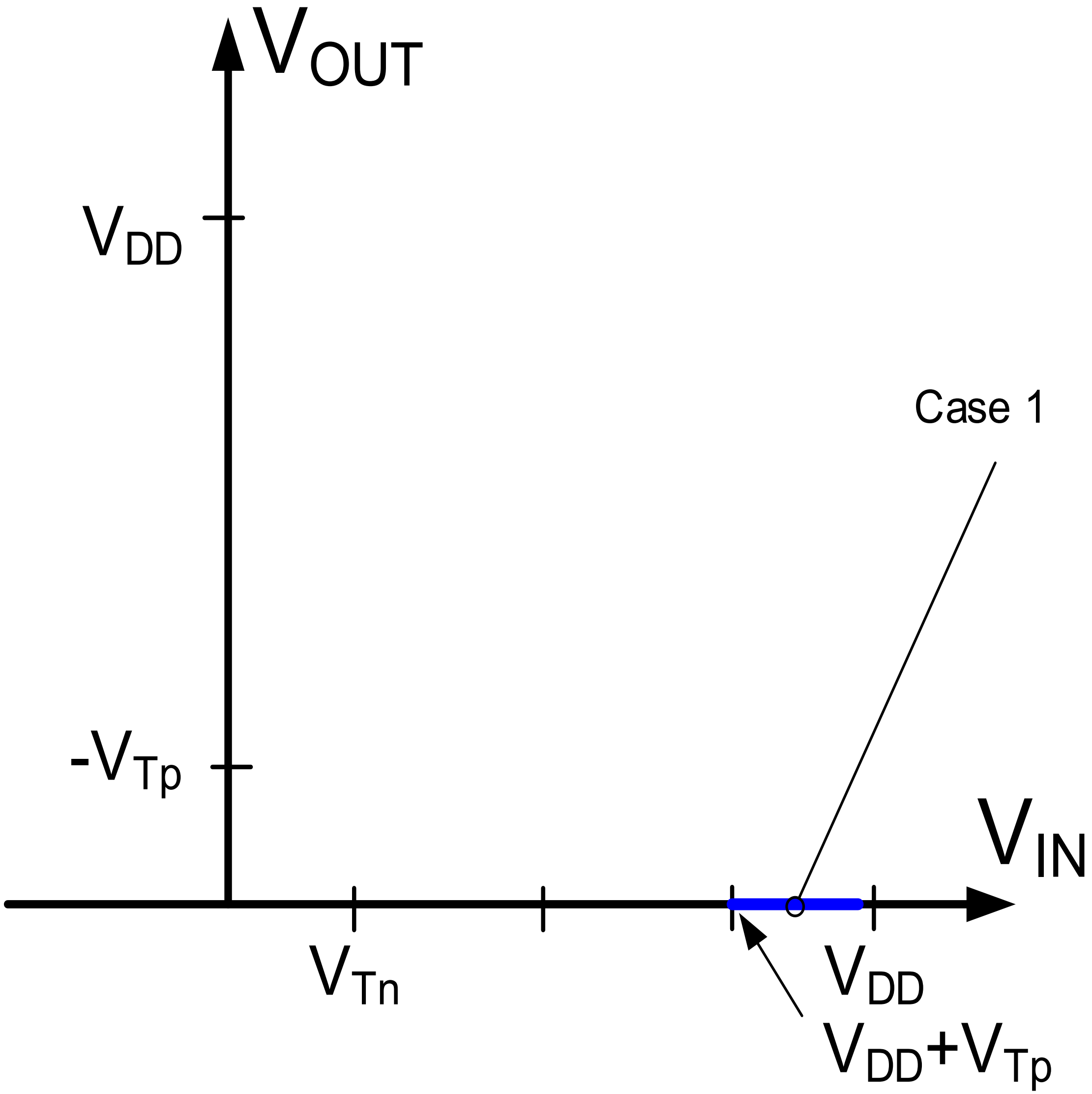
$$V_{OUT} = 0$$



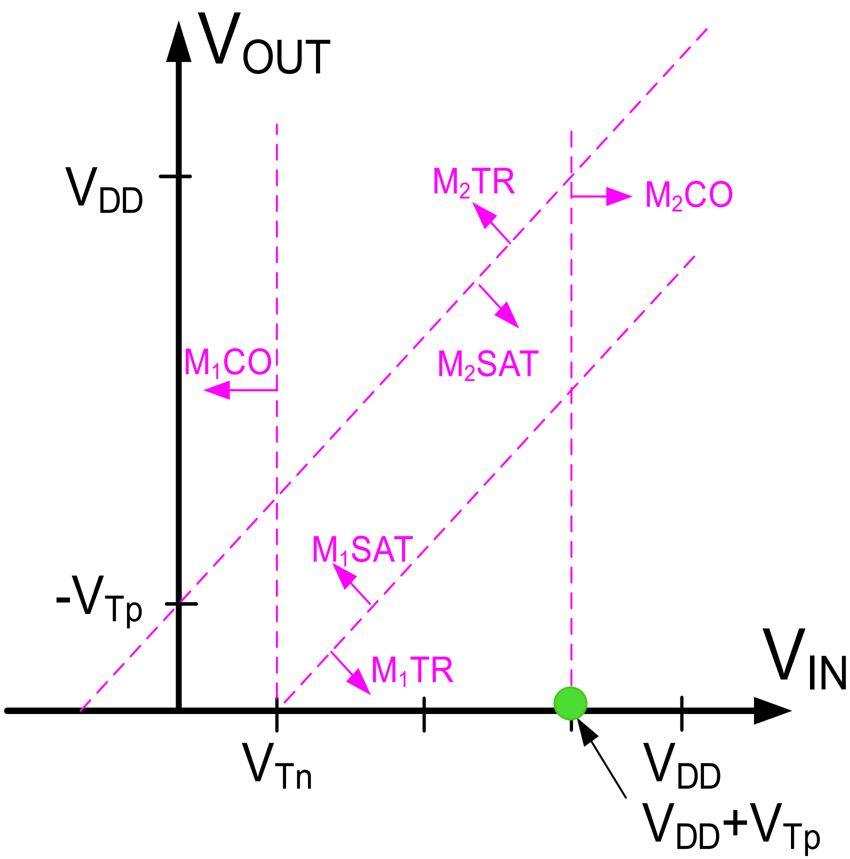
Transfer characteristics of the static CMOS inverter

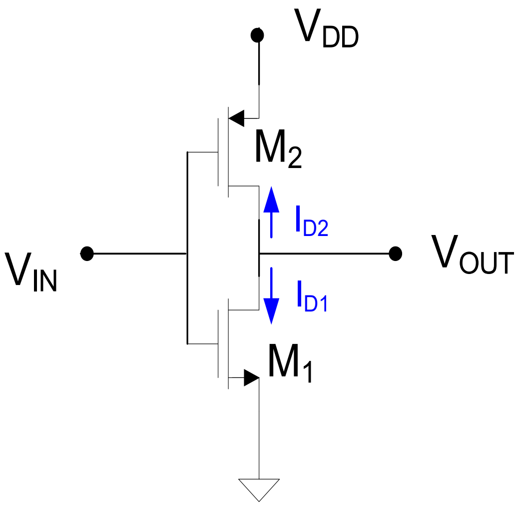
(Neglect λ effects)

Partial solution:



Regions of Operation for Devices in CMOS inverter

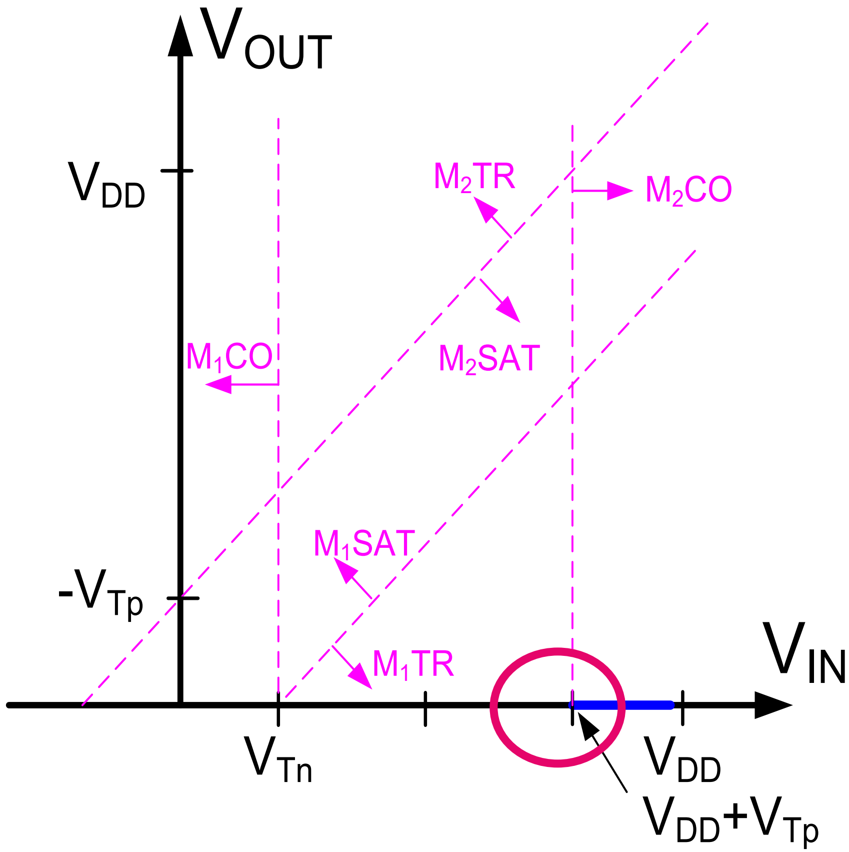




Transfer characteristics of the static CMOS inverter

(Neglect λ effects)

Case 2 M_1 triode, M_2 sat

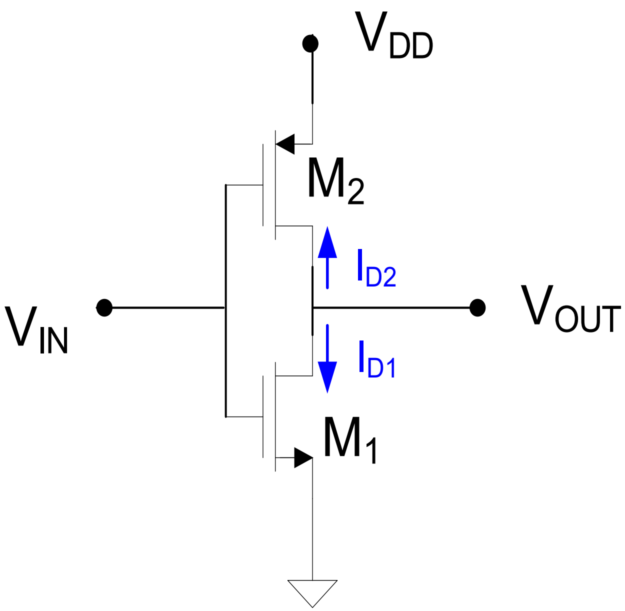


M_2: Square law I_D

M_1: like a resistor

Transfer characteristics of the static CMOS inverter

(Neglect λ effects)



Case 2 M_1 triode, M_2 sat

$$I_{D1}=\mu_n C_{OXn}\frac{W_1}{L_1}\left(V_{IN}-V_{Tn}-\frac{V_{OUT}}{2}\right)V_{OUT}$$

$$I_{D2}=-\frac{\mu_p C_{OXp}}{2}\frac{W_2}{L_2}\left(V_{IN}-V_{DD}-V_{Tp}\right)^2$$

Equating I_{D1} and $-I_{D2}$ we obtain:

$$\frac{\mu_p C_{OXp}}{2}\frac{W_2}{L_2}\left(V_{IN}-V_{DD}-V_{Tp}\right)^2=\mu_n C_{OXn}\frac{W_1}{L_1}\left(V_{IN}-V_{Tn}-\frac{V_{OUT}}{2}\right)V_{OUT}$$

valid for:

$$V_{GS1}\geq V_{Tn} \qquad V_{DS1}<V_{GS1}-V_{Tn} \qquad V_{GS2}\leq V_{Tp} \qquad V_{DS2}\leq V_{GS2}-V_{T2}$$

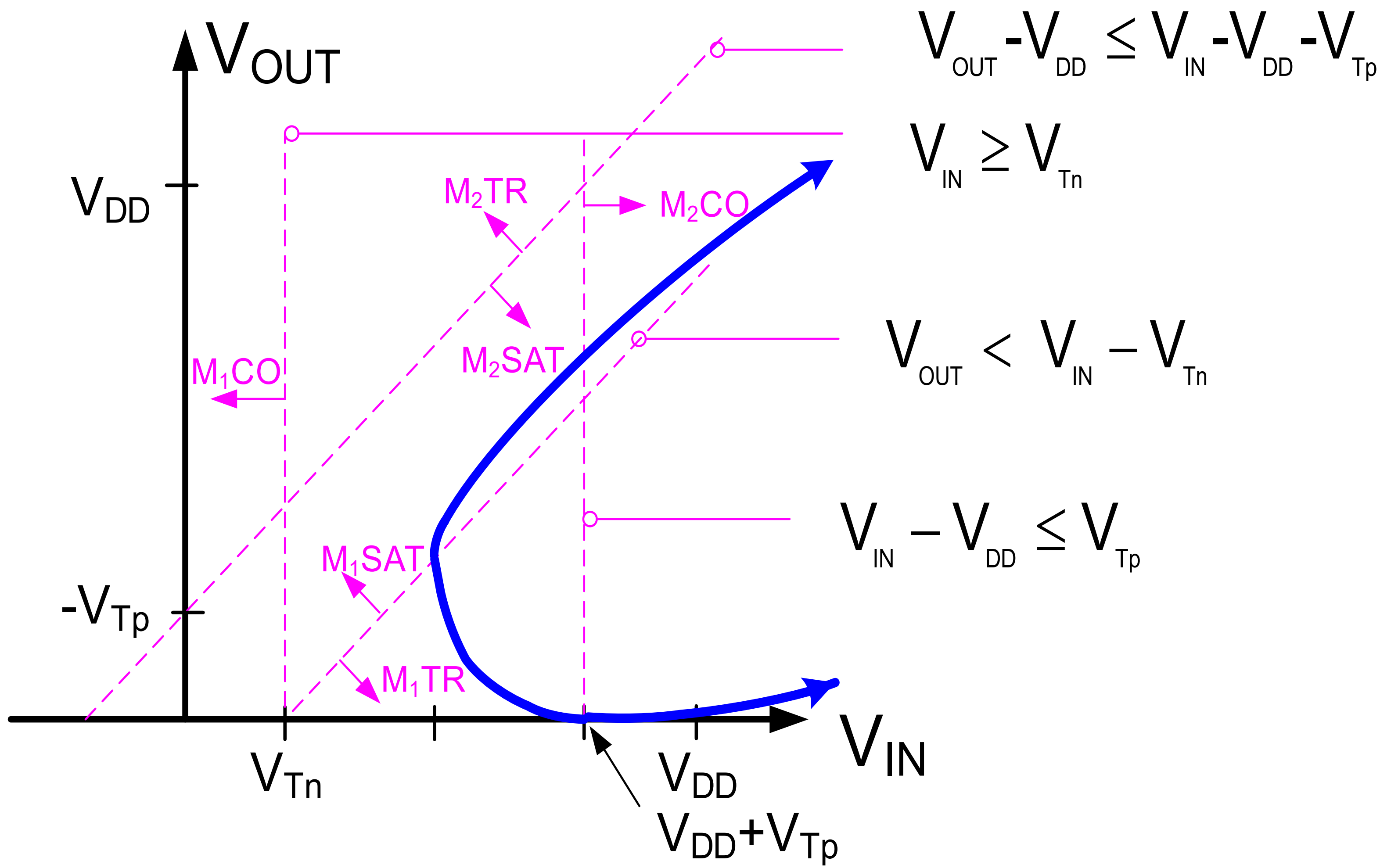
thus, valid for:

$$V_{IN}\geq V_{Tn} \qquad V_{OUT}<V_{IN}-V_{Tn} \qquad V_{IN}-V_{DD}\leq V_{Tp} \qquad V_{OUT}-V_{DD}\leq V_{IN}-V_{DD}-V_{Tp}$$

Transfer characteristics of the static CMOS inverter

(Neglect λ effects)

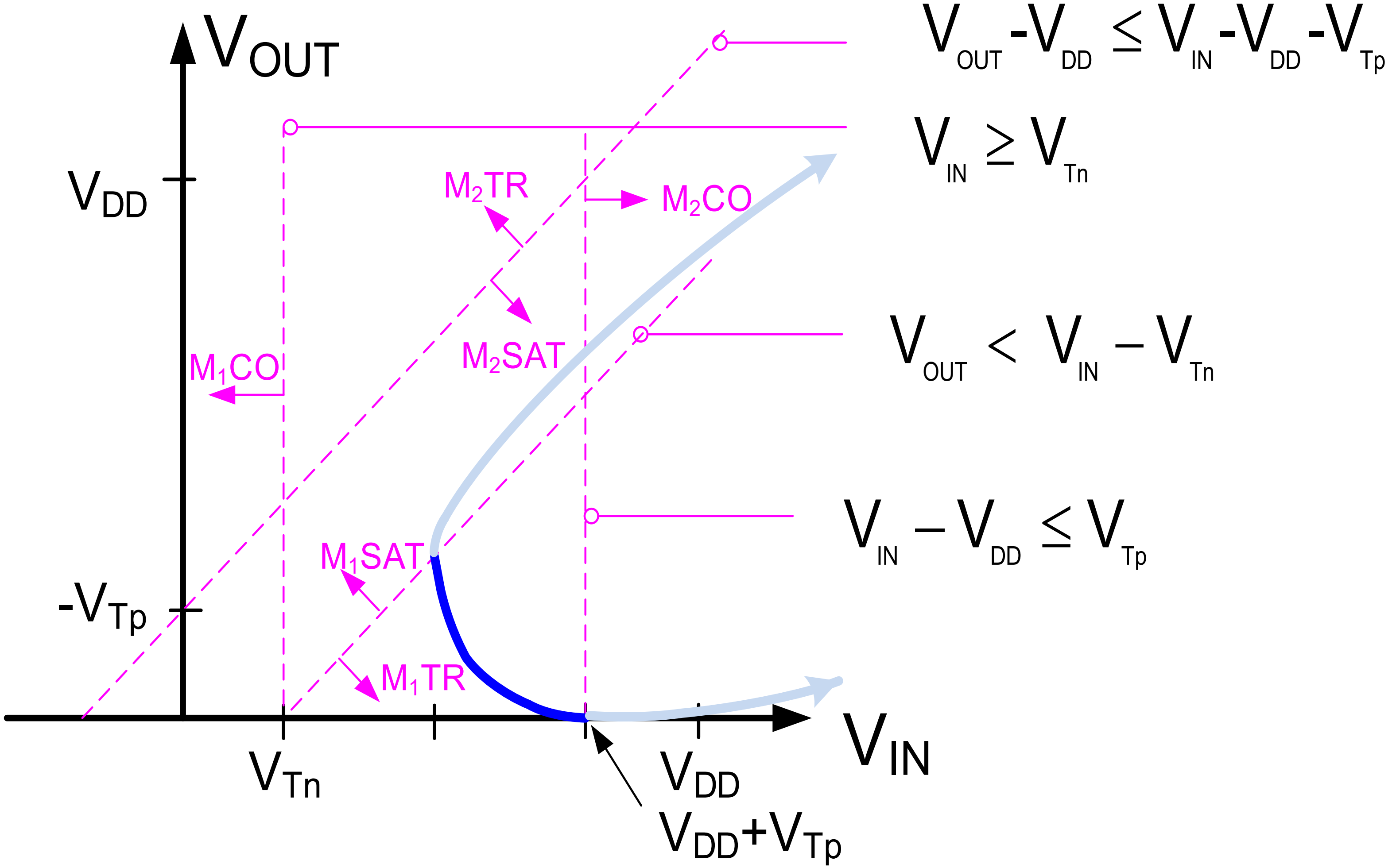
Case 2 M_1 triode, M_2 sat



Transfer characteristics of the static CMOS inverter

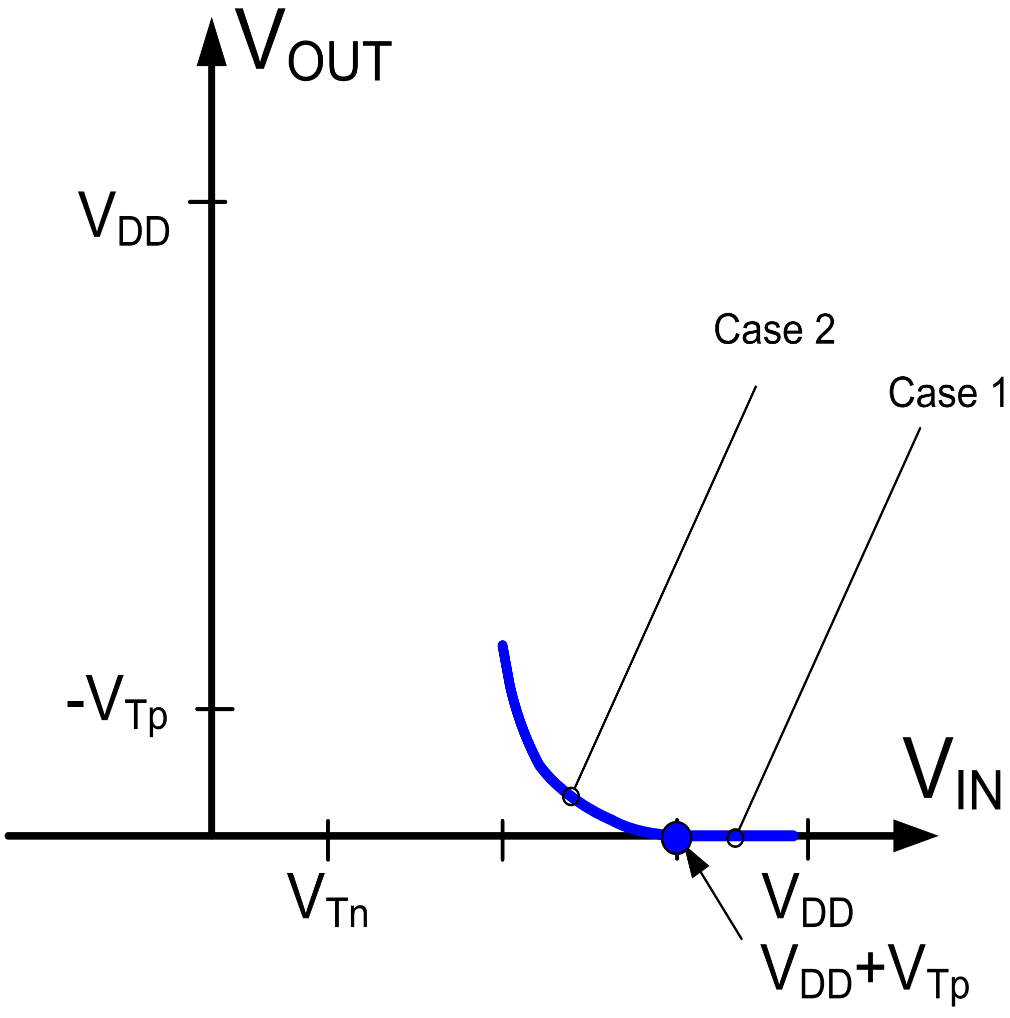
(Neglect λ effects)

Case 2 M_1 triode, M_2 sat



Transfer characteristics of the static CMOS inverter

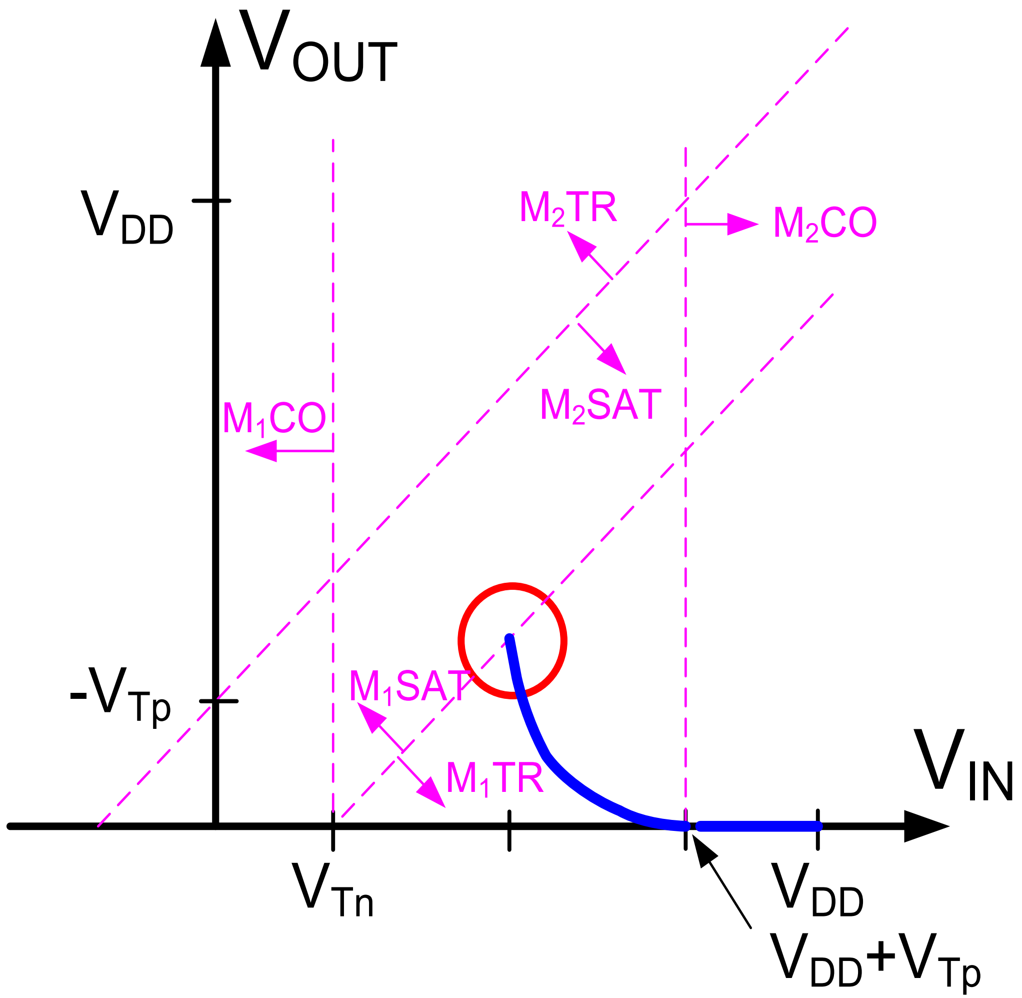
Partial solution:



Transfer characteristics of the static CMOS inverter

(Neglect λ effects)

Case 3 M_1 sat, M_2 sat



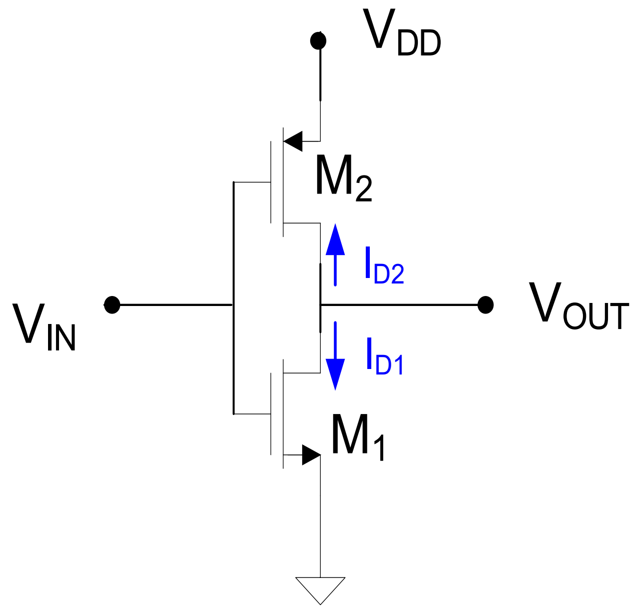
Transfer characteristics of the static CMOS inverter

(Neglect λ effects)

Case 3 M_1 sat, M_2 sat

$$I_{D1} = \frac{\mu_n C_{OXn}}{2}\frac{W_1}{L_1}\left(V_{IN} - V_{Tn}\right)^2$$

$$I_{D2} = \frac{\mu_p C_{OXp}}{2}\frac{W_2}{L_2}\left(V_{IN} - V_{DD} - V_{Tp}\right)^2$$



Equating I_{D1} and $-I_{D2}$ we obtain:

$$\frac{\mu_p C_{OXp}}{2}\frac{W_2}{L_2}\left(V_{IN} - V_{DD} - V_{Tp}\right)^2 = \frac{\mu_n C_{OXn}}{2}\frac{W_1}{L_1}\left(V_{IN} - V_{Tn}\right)^2$$

Which can be rewritten as:

$$\sqrt{\frac{\mu_p C_{OXp}}{2}\frac{W_2}{L_2}}\left(V_{DD} + V_{Tp} - V_{IN}\right) = \sqrt{\frac{\mu_n C_{OXn}}{2}\frac{W_1}{L_1}}\left(V_{IN} - V_{Tn}\right)$$

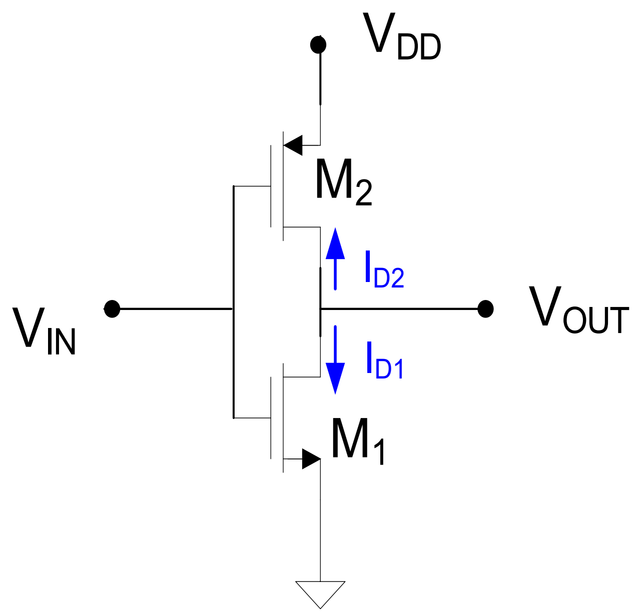
Which can be simplified to:

$$V_{IN} = \frac{\left(V_{Tn}\right)\sqrt{\frac{\mu_n C_{OXn}}{2}\frac{W_1}{L_1}} + \left(V_{DD} + V_{Tp}\right)\sqrt{\frac{\mu_p C_{OXp}}{2}\frac{W_2}{L_2}}}{\sqrt{\frac{\mu_n C_{OXn}}{2}\frac{W_1}{L_1}} + \sqrt{\frac{\mu_p C_{OXp}}{2}\frac{W_2}{L_2}}}$$

This is a vertical line

Transfer characteristics of the static CMOS inverter

(Neglect λ effects)



Case 3 M_1 sat, M_2 sat

$$V_{IN}=\frac{(V_{Tn})\sqrt{\frac{\mu_n C_{OXn}}{2}\frac{W_1}{L_1}}+(V_{DD}+V_{Tp})\sqrt{\frac{\mu_p C_{OXp}}{2}\frac{W_2}{L_2}}}{\sqrt{\frac{\mu_n C_{OXn}}{2}\frac{W_1}{L_1}}+\sqrt{\frac{\mu_p C_{OXp}}{2}\frac{W_2}{L_2}}}$$

Since $C_{OXn} \cong C_{OXp} = C_{OX}$ this can be simplified to:

$$V_{IN}=\frac{(V_{Tn})\sqrt{\frac{W_1}{L_1}}+(V_{DD}+V_{Tp})\sqrt{\frac{\mu_p}{\mu_n}\frac{W_2}{L_2}}}{\sqrt{\frac{W_1}{L_1}}+\sqrt{\frac{\mu_p}{\mu_n}\frac{W_2}{L_2}}}$$

valid for:

$V_{GS1} \geq V_{Tn}$ $\quad V_{DS1} \geq V_{GS1} - V_{Tn}$ $\quad V_{GS2} \leq V_{Tp}$ $\quad V_{DS2} \leq V_{GS2} - V_{T2}$

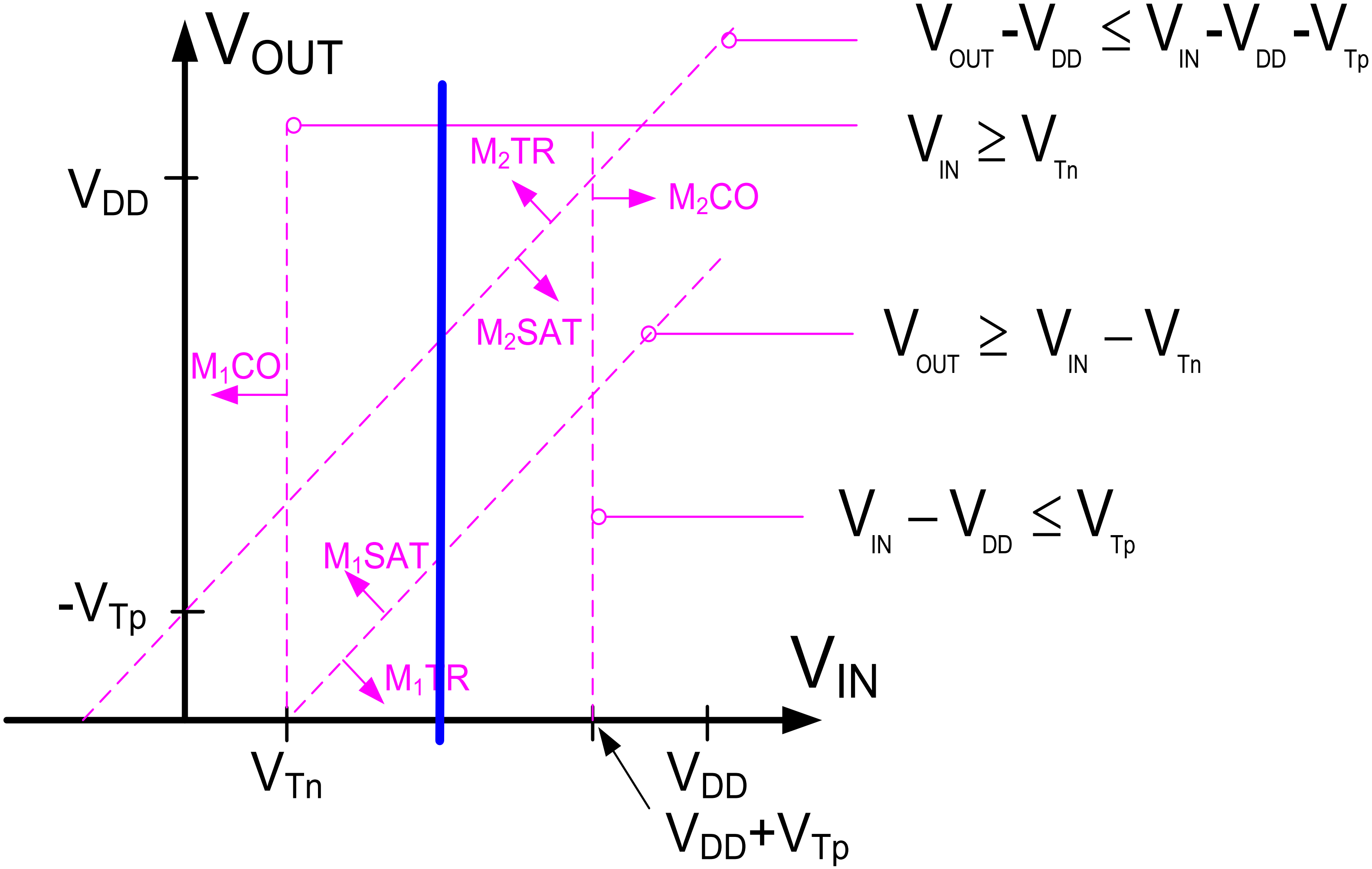
thus, valid for:

$V_{IN} \geq V_{Tn}$ $\quad V_{OUT} \geq V_{IN} - V_{Tn}$ $\quad V_{IN} - V_{DD} \leq V_{Tp}$ $\quad V_{OUT} - V_{DD} \leq V_{IN} - V_{DD} - V_{Tp}$

Transfer characteristics of the static CMOS inverter

(Neglect λ effects)

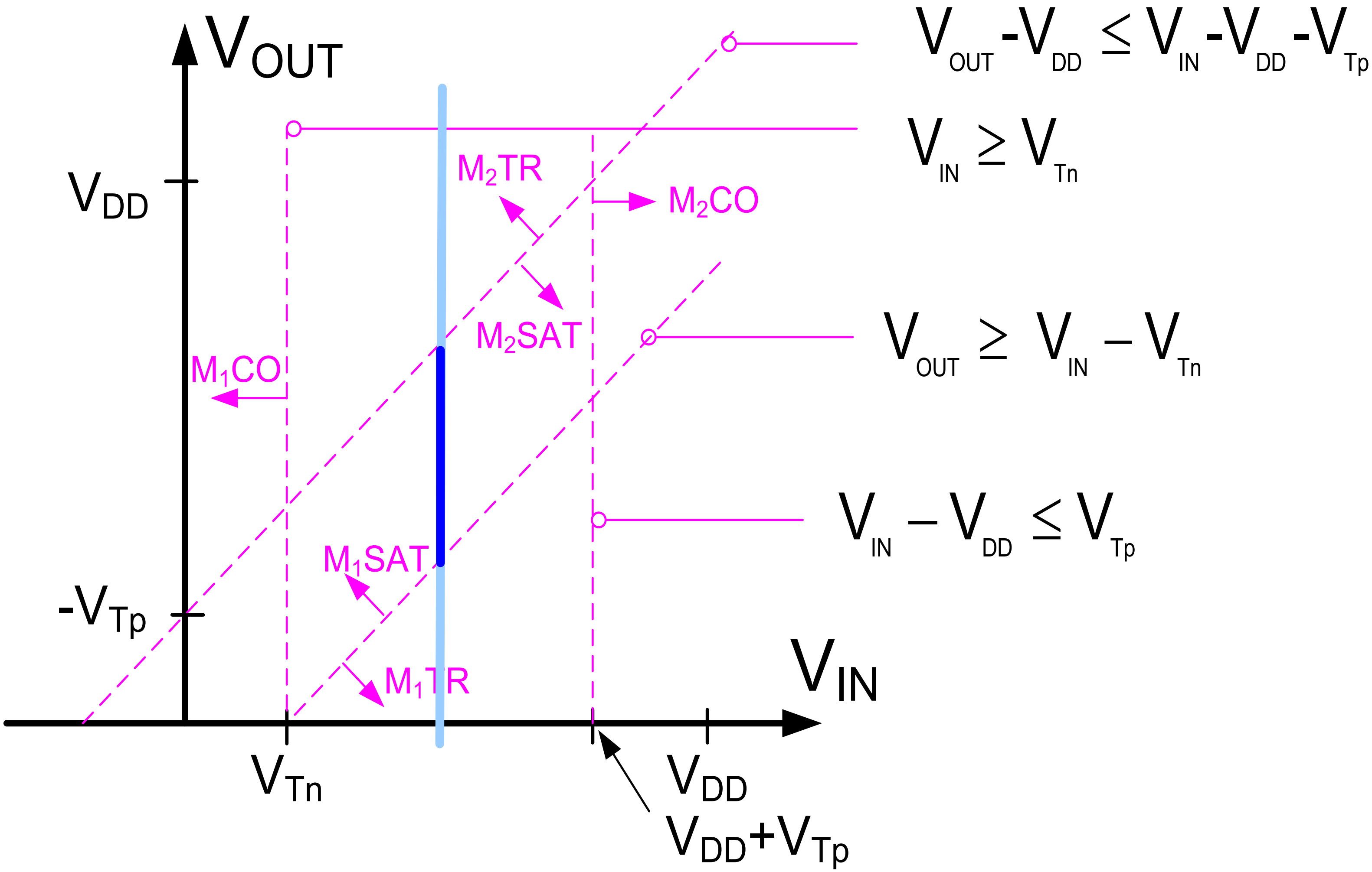
Case 3 M_1 sat, M_2 sat



Transfer characteristics of the static CMOS inverter

(Neglect λ effects)

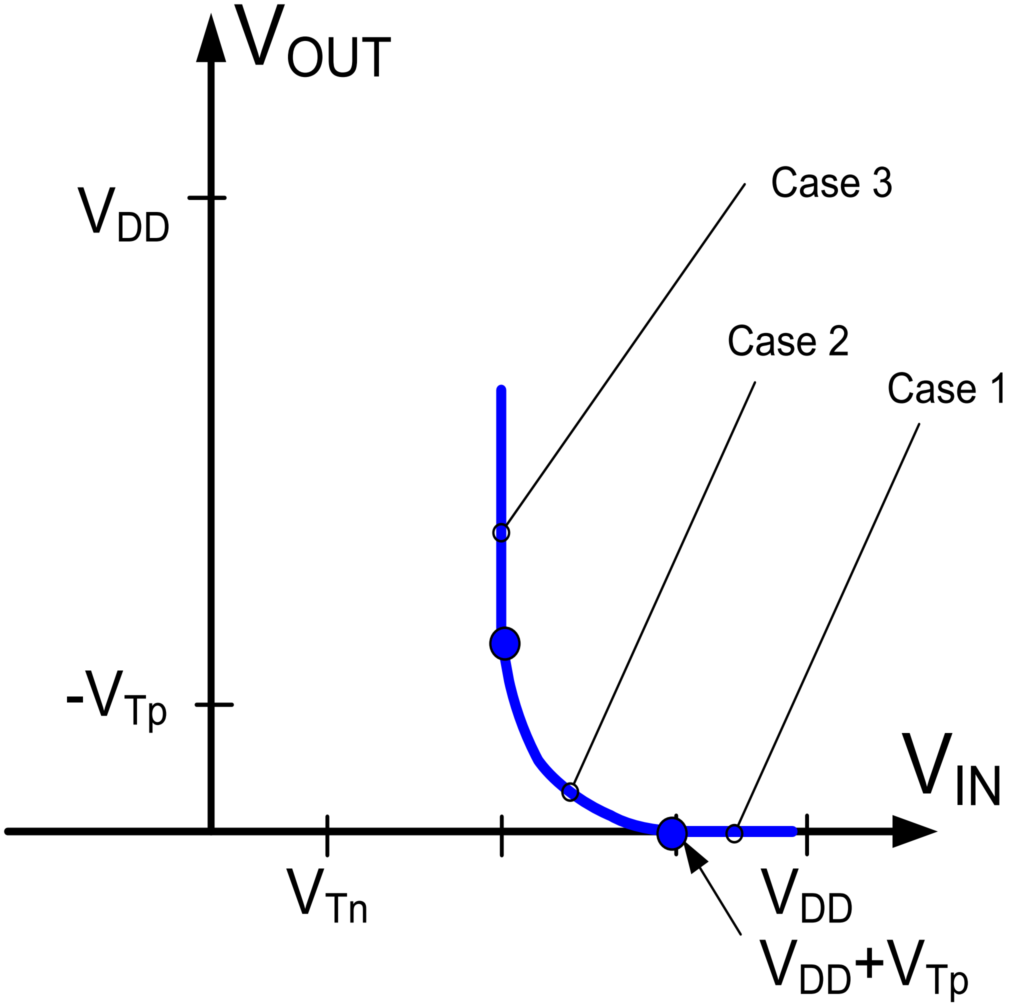
Case 3 M_1 sat, M_2 sat



Transfer characteristics of the static CMOS inverter

(Neglect λ effects)

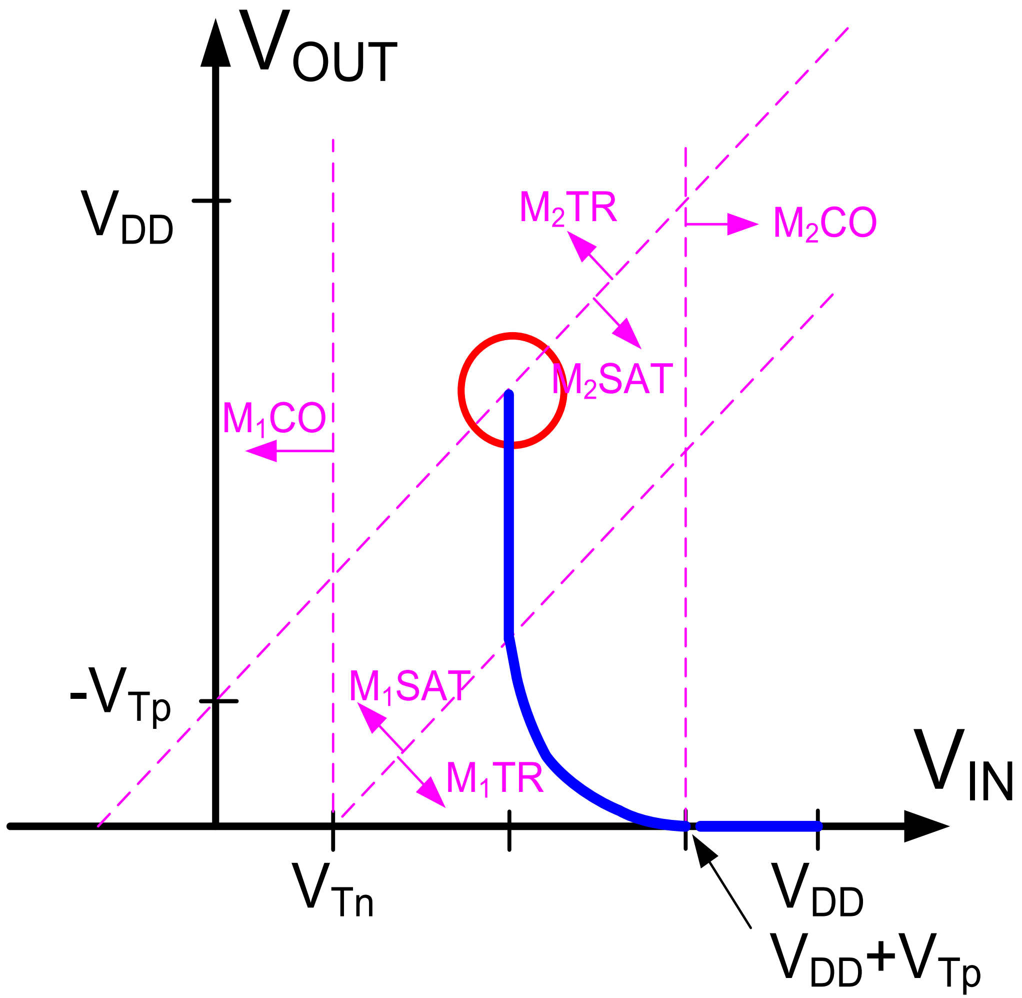
Partial solution:



Transfer characteristics of the static CMOS inverter

(Neglect λ effects)

Case 4 M_1 sat, M_2 triode



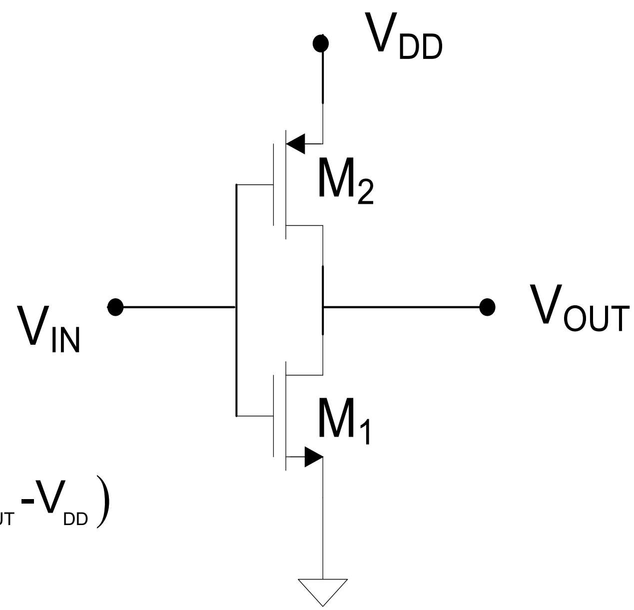
Transfer characteristics of the static CMOS inverter

(Neglect λ effects)

Case 4 M_1 sat, M_2 triode

$$I_{D1}=\frac{\mu_n C_{OXn}}{2}\frac{W_1}{L_1}\left(V_{IN}-V_{Tn}\right)^2$$

$$I_{D2}=-\mu_p C_{OXp}\frac{W_2}{L_2}\left(V_{IN}-V_{DD}-V_{Tp}-\frac{V_{OUT}\text{-}V_{DD}}{2}\right)\bullet\left(V_{OUT}\text{-}V_{DD}\right)$$



Equating I_{D1} and $-I_{D2}$ we obtain:

$$\frac{\mu_n C_{OXn}}{2}\frac{W_1}{L_1}\left(V_{IN}-V_{Tn}\right)^2=\mu_p C_{OXp}\frac{W_2}{L_2}\left(V_{IN}-V_{DD}-V_{Tp}-\frac{V_{OUT}\text{-}V_{DD}}{2}\right)\bullet\left(V_{OUT}\text{-}V_{DD}\right)$$

valid for:

$$V_{GS1}\geq V_{Tn} \qquad V_{DS1}\geq V_{GS1}-V_{Tn} \qquad V_{GS2}\leq V_{Tp} \qquad V_{DS2}>V_{GS2}\text{-}V_{T2}$$

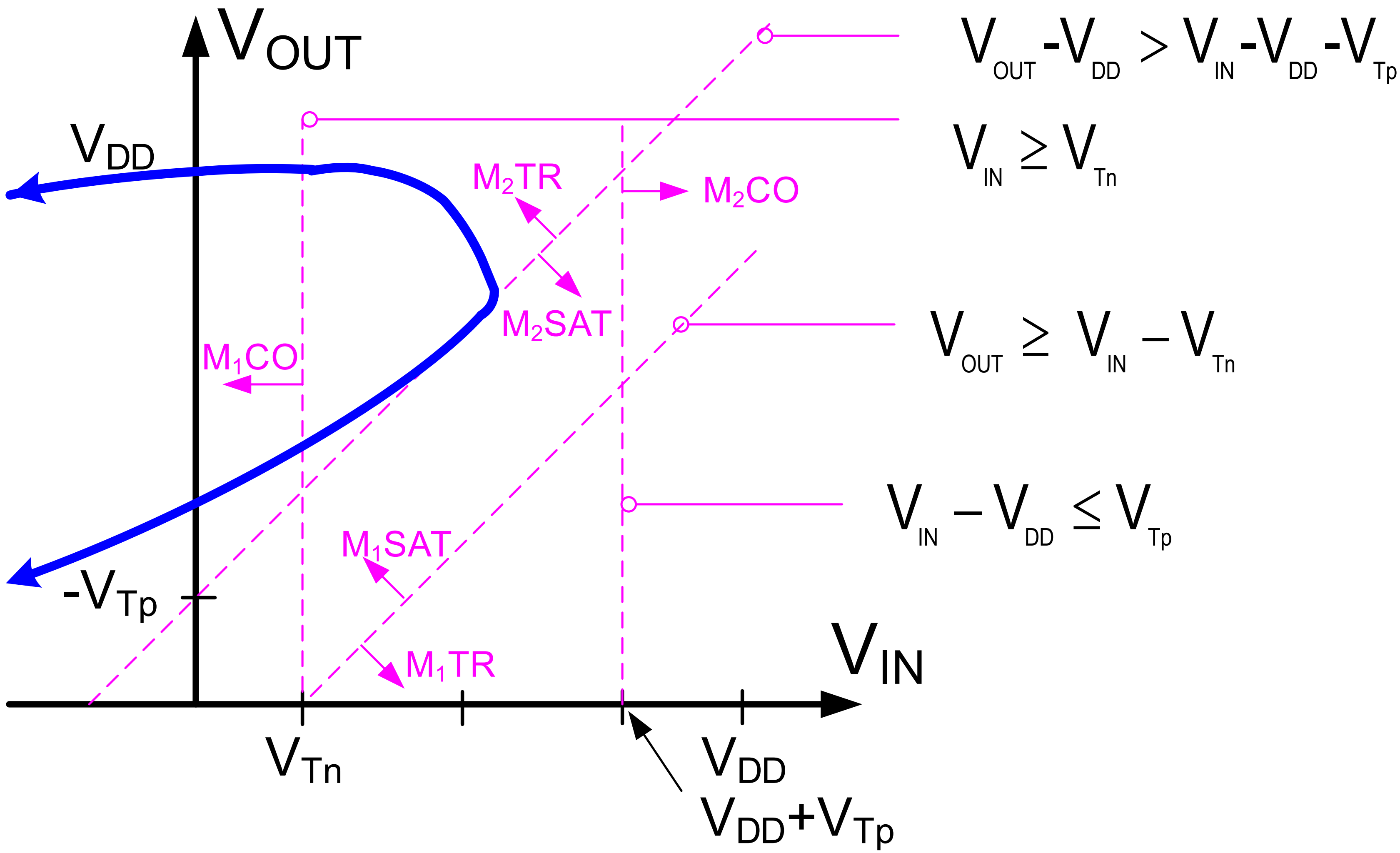
thus, valid for:

$$V_{IN}\geq V_{Tn} \qquad V_{OUT}\geq V_{IN}-V_{Tn} \qquad V_{IN}-V_{DD}\leq V_{Tp} \qquad V_{OUT}\text{-}V_{DD}>V_{IN}\text{-}V_{DD}\text{-}V_{Tp}$$

Transfer characteristics of the static CMOS inverter

(Neglect λ effects)

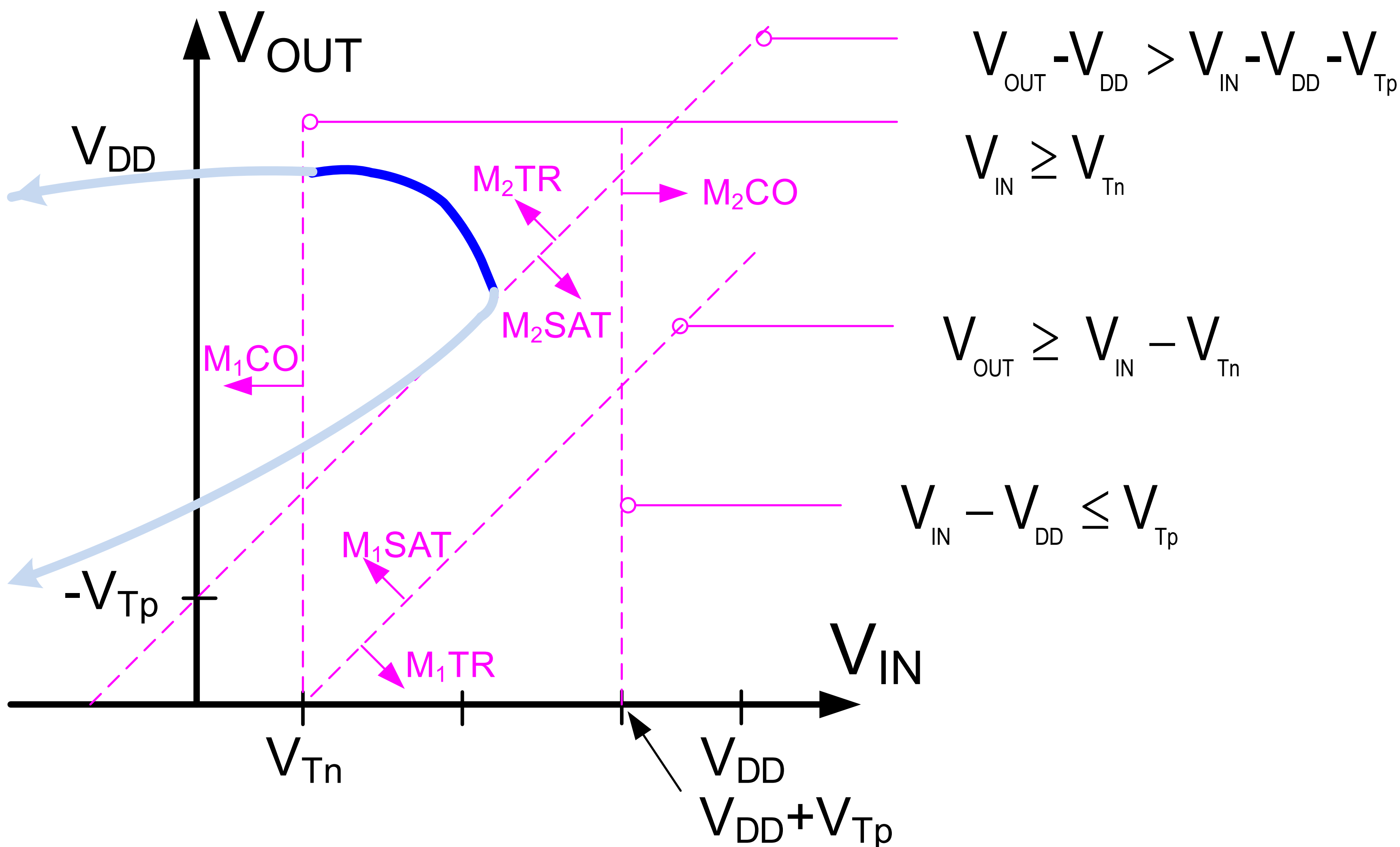
Case 4 M_1 sat, M_2 triode



Transfer characteristics of the static CMOS inverter

(Neglect λ effects)

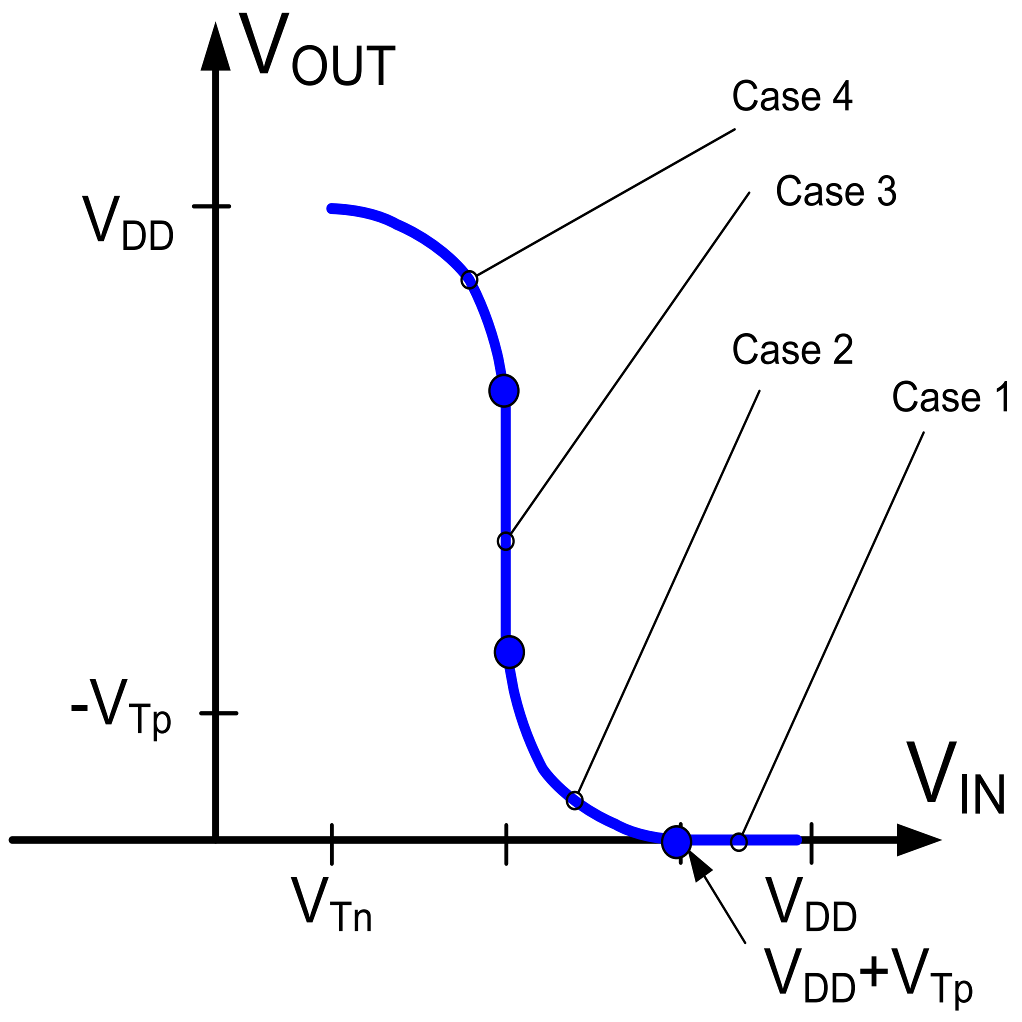
Case 4 M_1 sat, M_2 triode



Transfer characteristics of the static CMOS inverter

(Neglect λ effects)

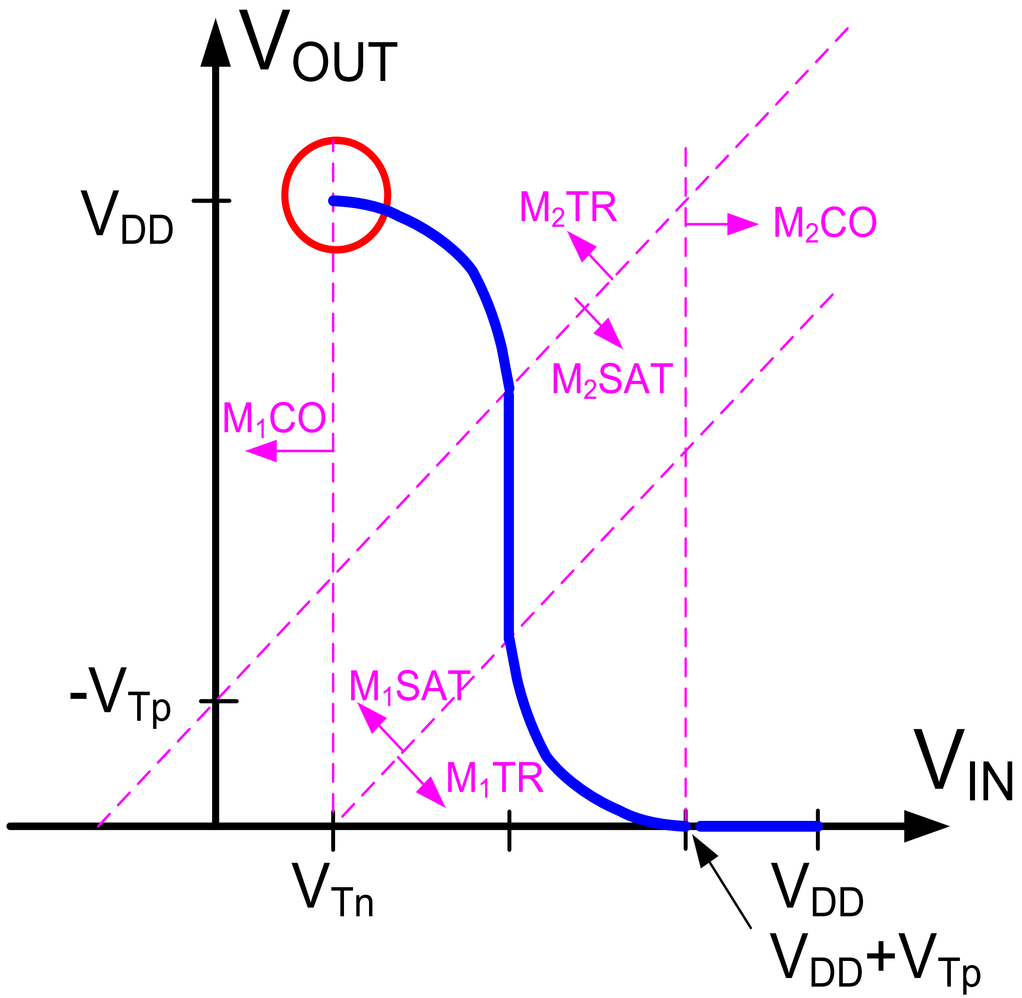
Partial solution:



Transfer characteristics of the static CMOS inverter

(Neglect λ effects)

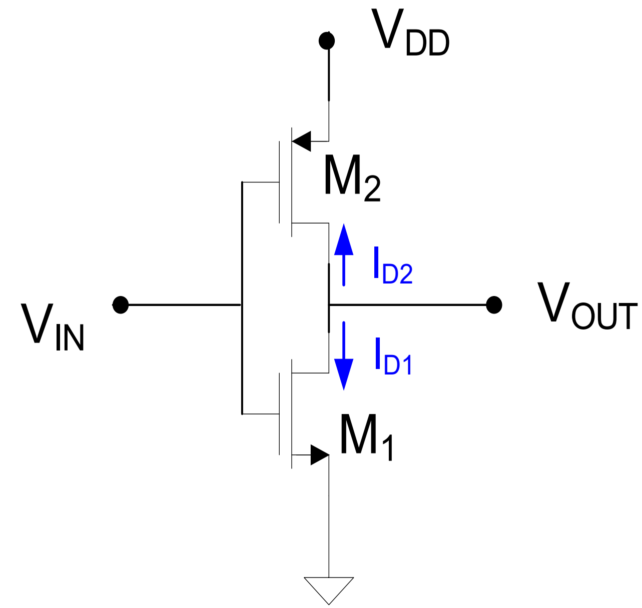
Case 4 M_1 cutoff, M_2 triode



Transfer characteristics of the static CMOS inverter

(Neglect λ effects)

Case 5 M_1 cutoff, M_2 triode



$$I_{D1} = 0$$

$$I_{D2} = -\mu_p C_{OXp} \frac{W_2}{L_2}\left(V_{IN} - V_{DD} - V_{Tp} - \frac{V_{OUT}-V_{DD}}{2}\right) \bullet \left(V_{OUT}-V_{DD}\right)$$

Equating I_{D1} and $-I_{D2}$ we obtain:

$$\mu_p C_{OXp} \frac{W_2}{L_2}\left(V_{IN} - V_{DD} - V_{Tp} - \frac{V_{OUT}-V_{DD}}{2}\right) \bullet \left(V_{OUT}-V_{DD}\right) = 0$$

valid for:

$$V_{GS1} < V_{Tn} \qquad V_{GS2} \le V_{Tp} \qquad V_{DS2} > V_{GS2}-V_{T2}$$

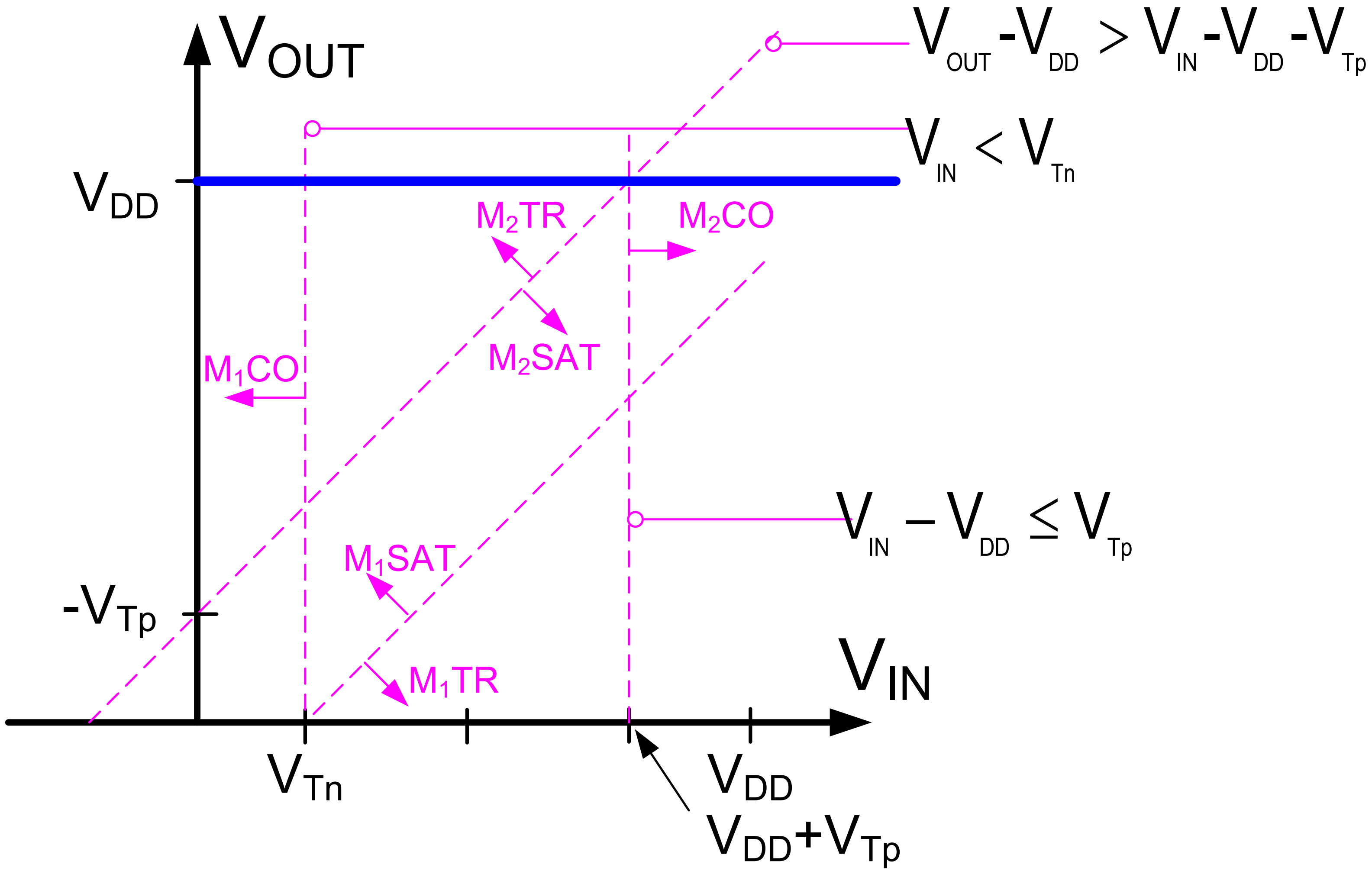
thus, valid for:

$$V_{IN} < V_{Tn} \qquad V_{IN} - V_{DD} \le V_{Tp} \qquad V_{OUT}-V_{DD} > V_{IN}-V_{DD}-V_{Tp}$$

Transfer characteristics of the static CMOS inverter

(Neglect λ effects)

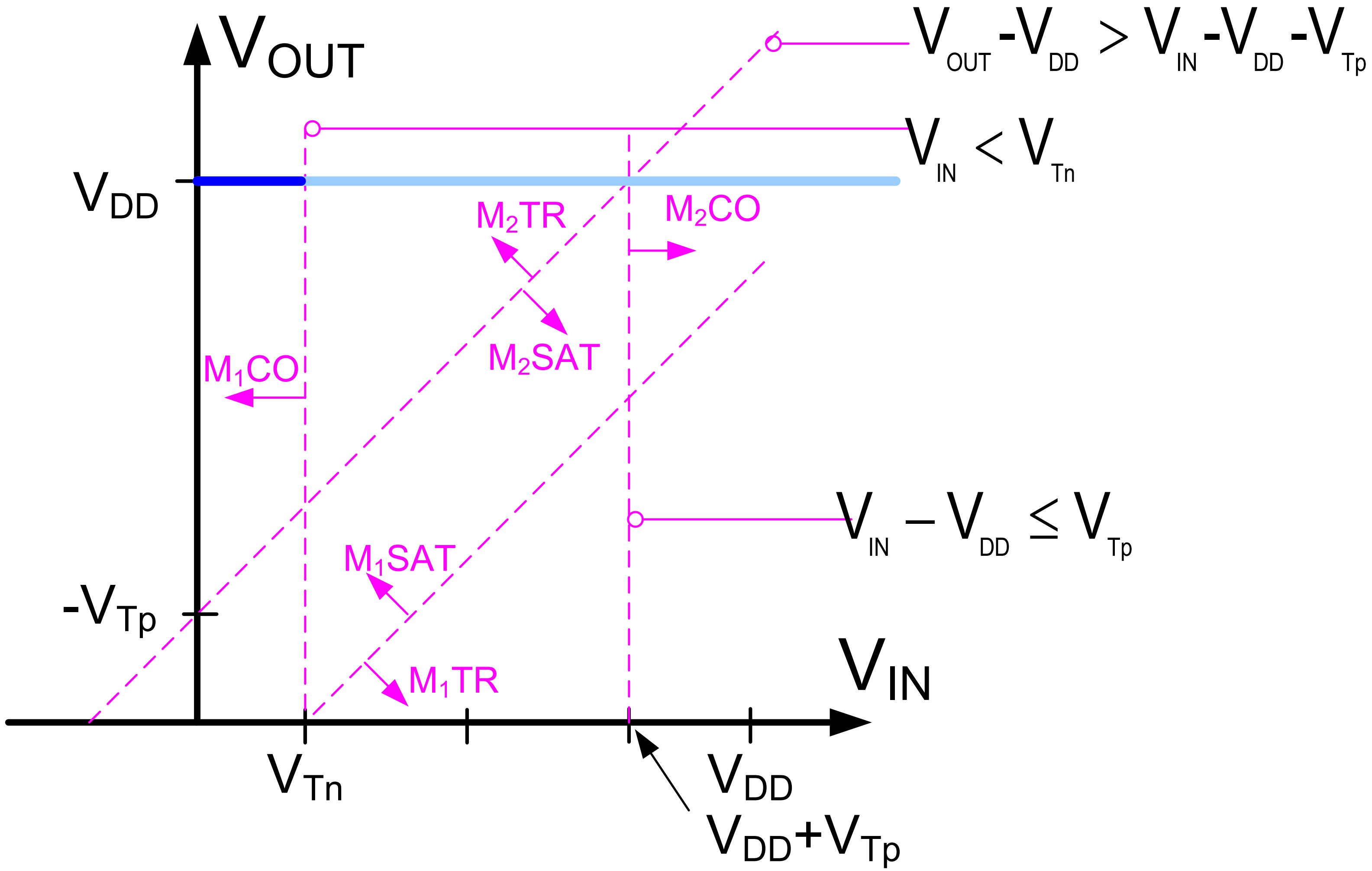
Case 5 M_1 cutoff, M_2 triode



Transfer characteristics of the static CMOS inverter

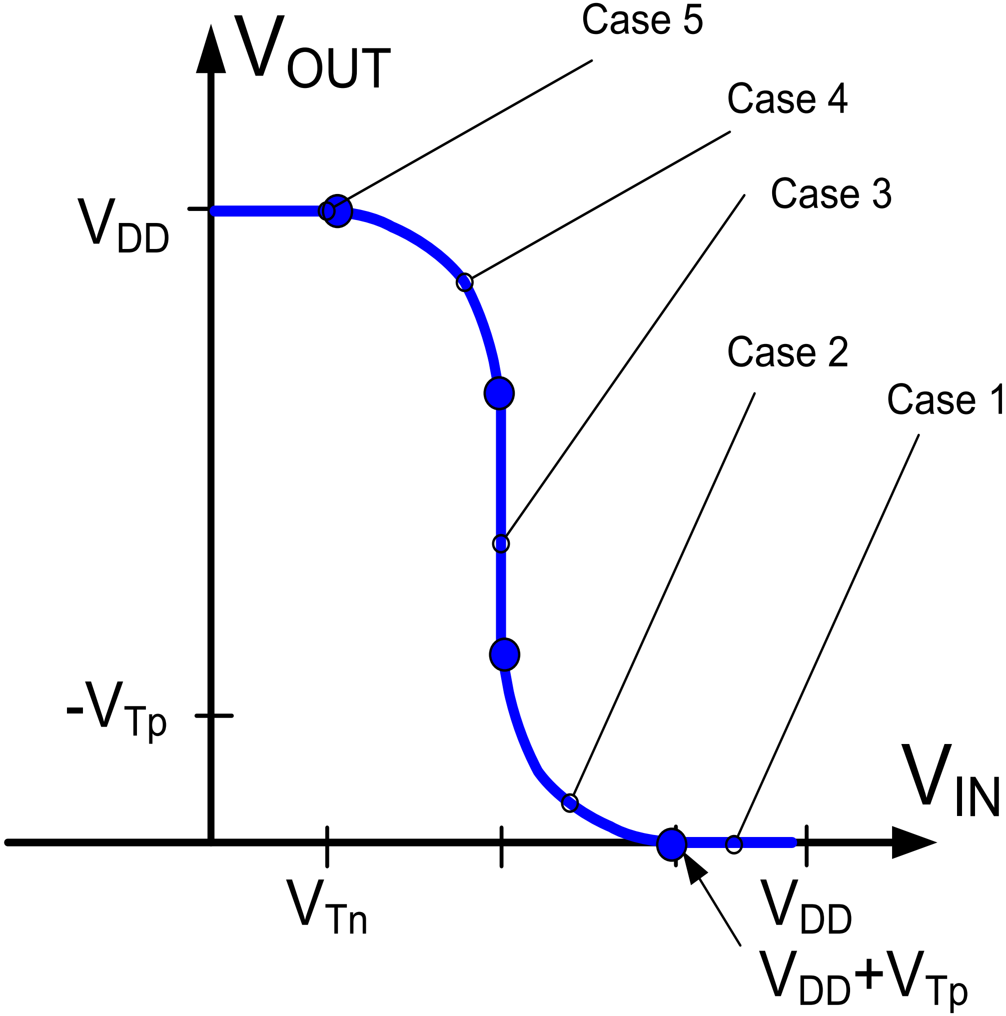
(Neglect λ effects)

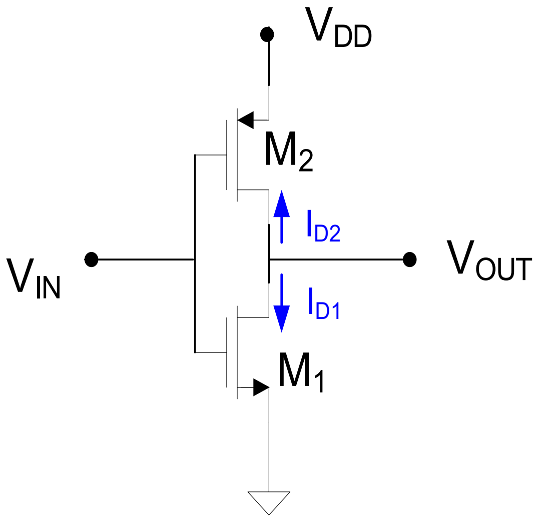
Case 5 M_1 cutoff, M_2 triode



Transfer characteristics of the static CMOS inverter

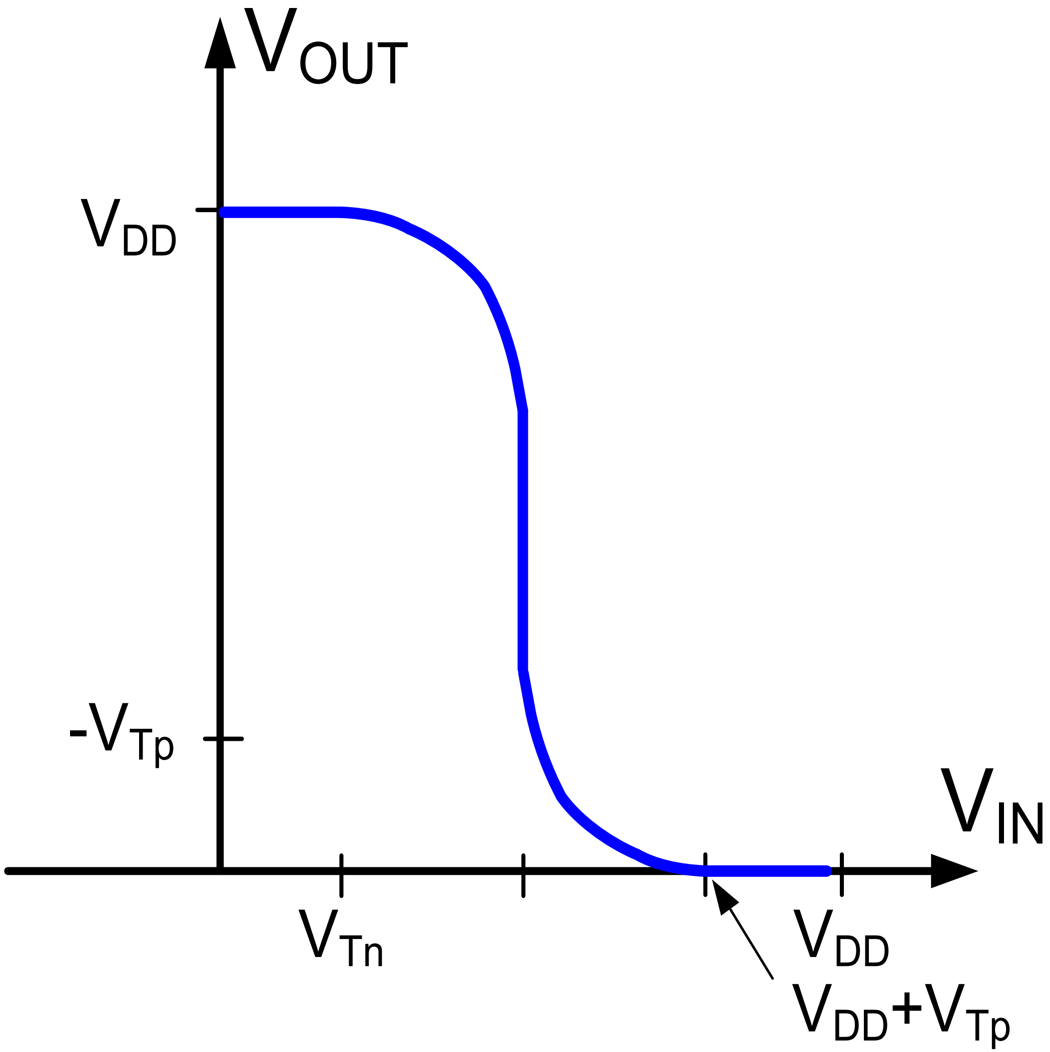
(Neglect λ effects)





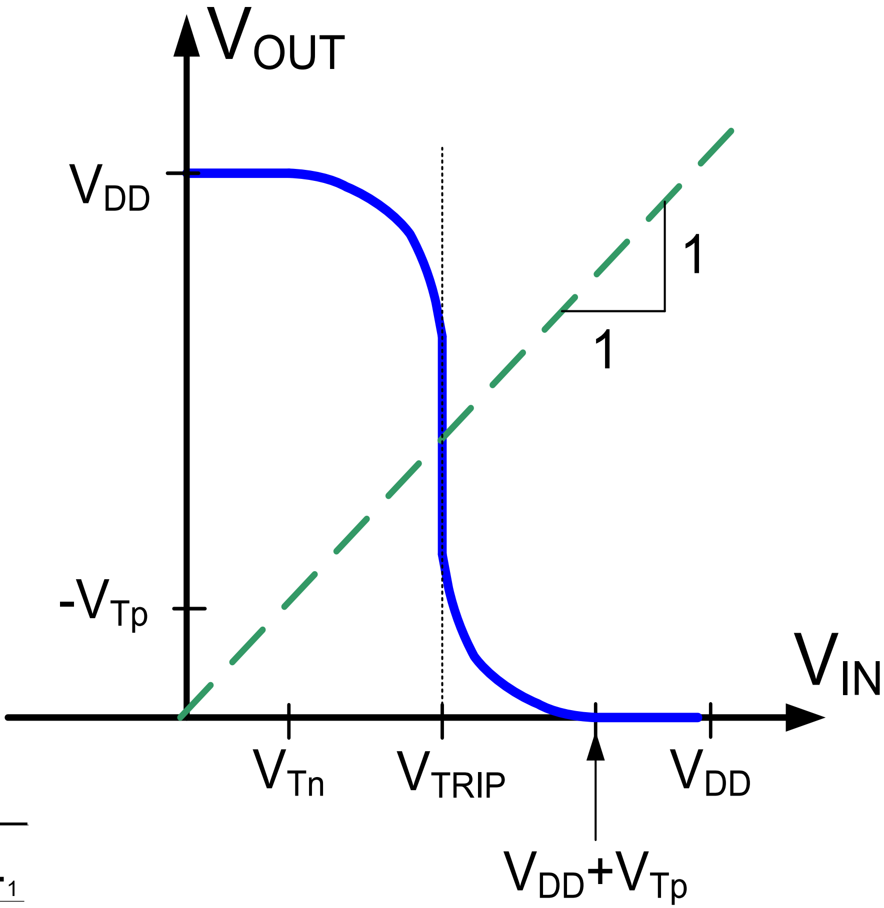
Transfer characteristics of the static CMOS inverter

(Neglect λ effects)



Transfer characteristics of the static CMOS inverter

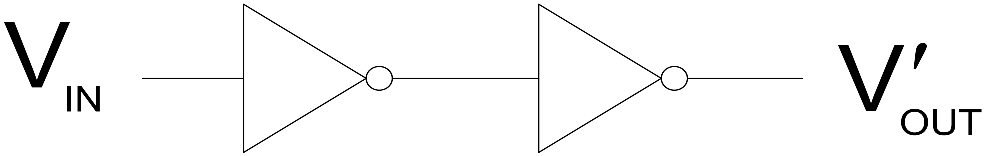
(Neglect λ effects)



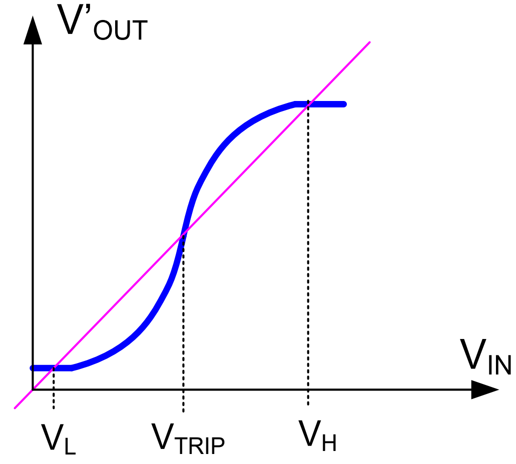
From Case 3 analysis:

$$V_{IN} = \frac{(V_{Tn}) + (V_{DD} + V_{Tp})\sqrt{\frac{\mu_p}{\mu_n}\frac{W_2}{W_1}\frac{L_1}{L_2}}}{1 + \sqrt{\frac{\mu_p}{\mu_n}\frac{W_2}{W_1}\frac{L_1}{L_2}}}$$

Inverter Transfer Characteristics of Inverter Pair

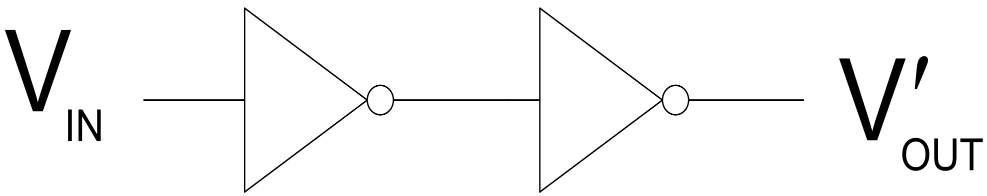


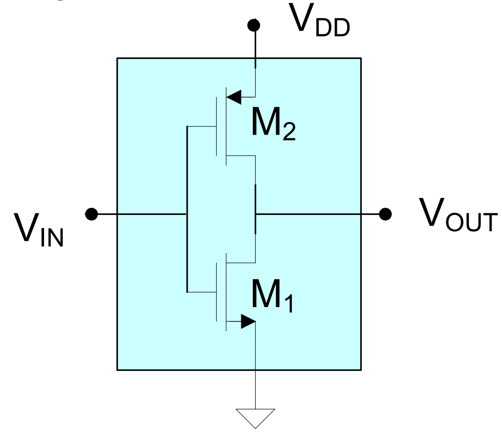
What are V_H and V_L?

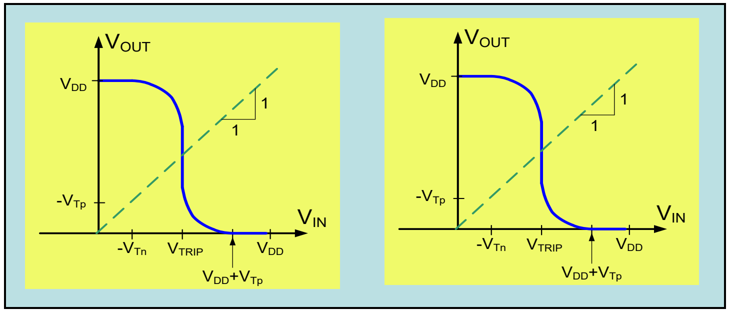


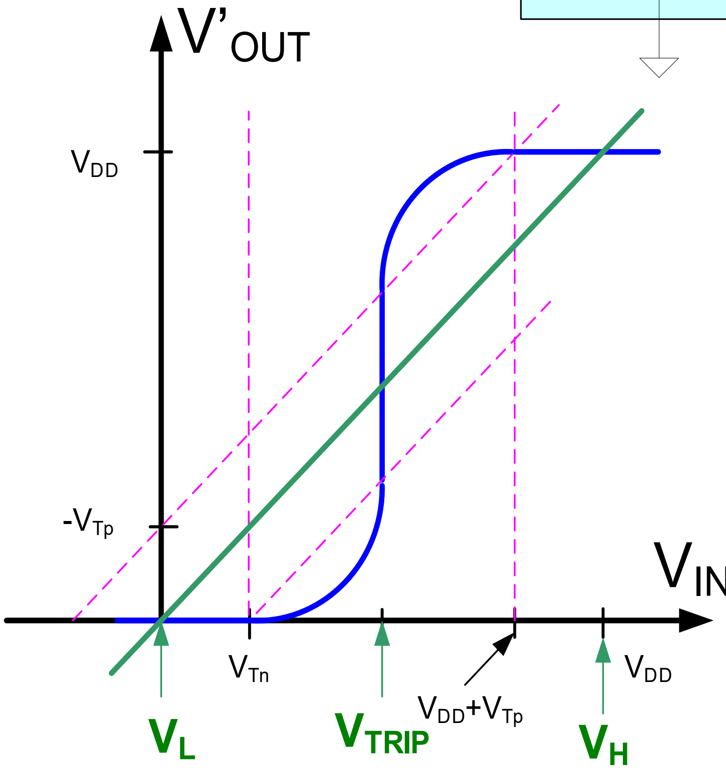
Find the points on the inverter pair transfer characteristics where $V_{OUT}'=V_{IN}$ and the slope is less than 1

Inverter Transfer Characteristics of Inverter Pair for <u>THIS</u> Logic Family









$V_H=V_{DD}$ and $V_L=0$

Note this is independent of device sizing for THIS logic family !!

Designer can use sizing to achieve other desirable properties !!!

Stay Safe and Stay Healthy !

End of Lecture 38