Lecture21:
NMOS inverter

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Why digital?

- You know the answer.
  - And you know what it actually is. (Binary)
- Today, we will consider the following questions:
  - How can we treat the arithmetic operations (Addition, subtraction, multiplication, …)
  - What is the elemental operation?
  - Then, what are the essential circuits to build such a system?
  - (It will be a short review on *Digital Design*.)
- Inverter and NAND gates

Addition

- Once you can add two numbers, x and y, you can do
  - Addition, $x + y$ (of course)
  - Subtraction, $x - y = x + (-y)$
    - A simple example) 4-digit binary numbers, $a = 0110$ and $b = 0011$.
    - The 1's complement of b is 1100.
    - The 2's complement of b is 1101.
    - Sum of 0110 and 1101 is 10011.
    - Discarding the end carry gives us the correct answer, 0011.
  - Multiplication, $x \times y$

Even in addition,

- You can recognize that
  - Addition of two 1-bit binary numbers is the core operation!
  - There are only four possible cases!

$$0 + 0 = 0$$
$$0 + 1 = 1$$
$$1 + 0 = 1$$
$$1 + 1 = 10 \longleftarrow \text{Carry}$$

Inclusion of carry-bit

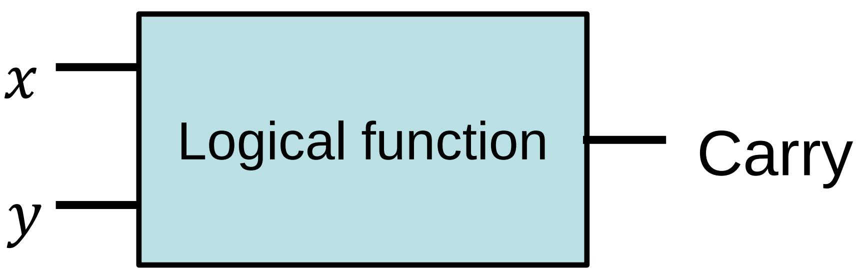
- We introduce a separate bit for representing the carry.
  - Carry-bit & sum-bit

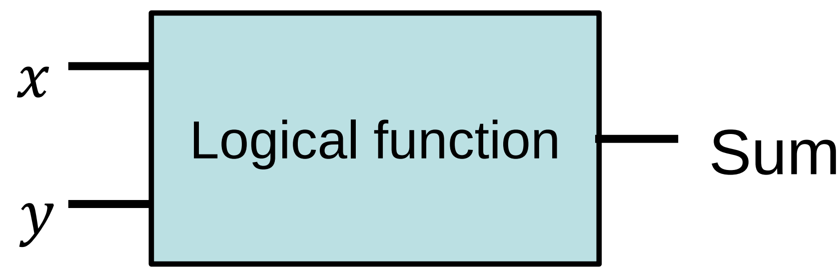
Carry

$$0 + 0 = 00$$
$$0 + 1 = 01$$
$$1 + 0 = 01$$
$$1 + 1 = 10$$

Sum

  - Treat them separately!





Relation btw x, y, and sum

- Concentrate on the sum-bit.
  - A table can be made.
  - It is called a **truth table**.

x	y	sum
0	0	0
0	1	1
1	0	1
1	1	0

  - Yes, it is the exclusive OR, $x \text{ XOR } y$.

Relation btw x, y, and carry

- Concentrate on the carry-bit.
  - A table can be made, again.

x	y	carry
0	0	0
0	1	0
1	0	0
1	1	1

  - Yes, it is the AND operation, $x \text{ AND } y$

After all,

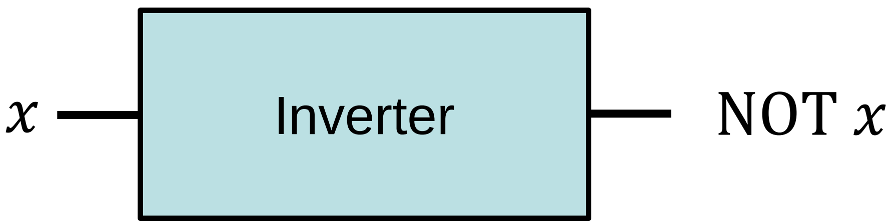
- As much as we have AND, OR, and NOT gates, we can implement any Boolean function.
  - For example,

$$x \text{ XOR } y = \big(x \text{ AND } (\text{NOT } y)\big) \text{ OR } \big((\text{NOT } x) \text{ AND } y\big)$$

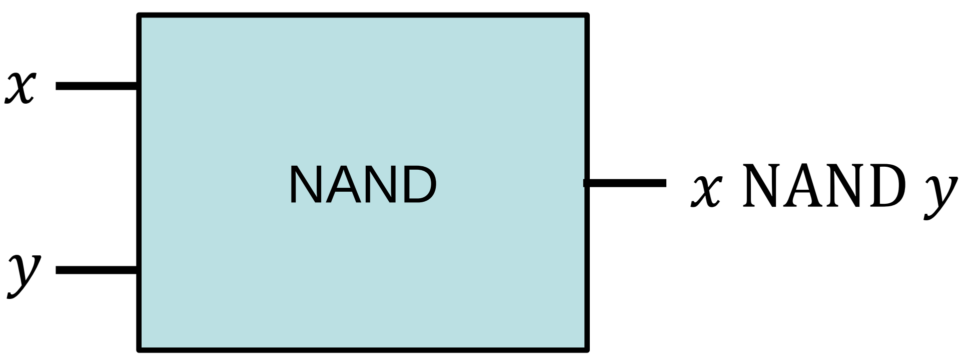
  - *With NAND, NOR, and NOT gates, we can, too.*

Inverter and NAND

- NOR can be implemented similarly.



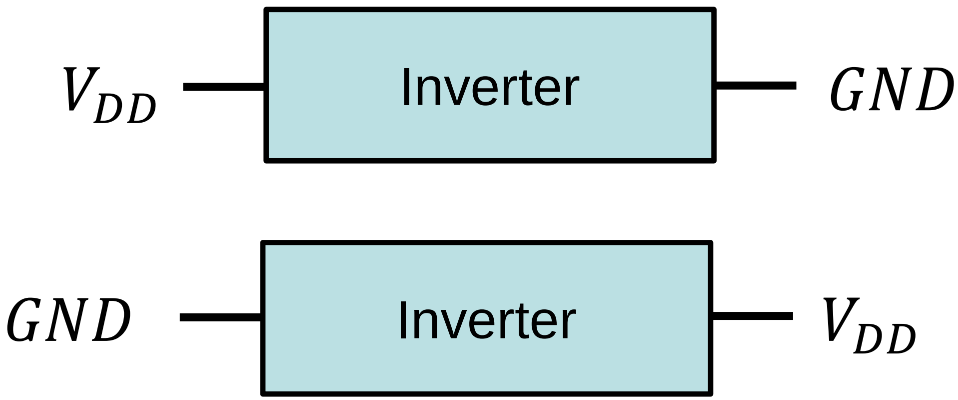
x	NOT
0	1
1	0

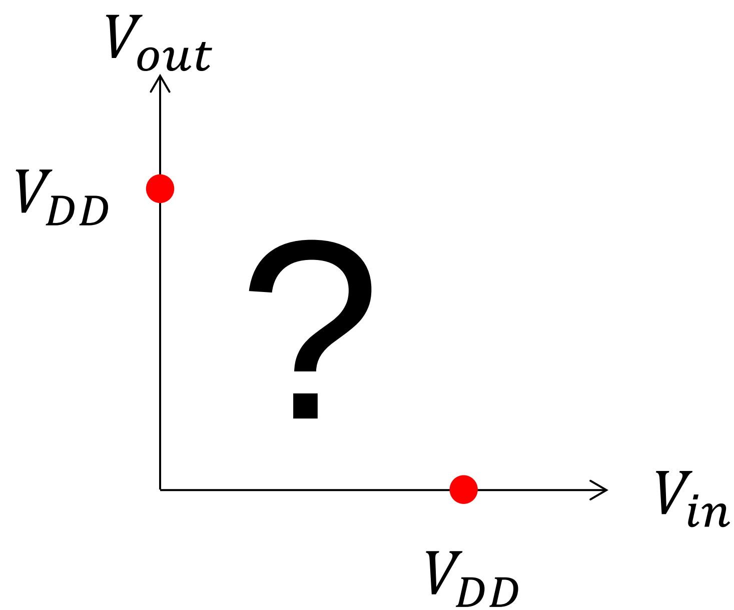


x	y	NAND
0	0	1
0	1	1
1	0	1
1	1	0

In circuit,

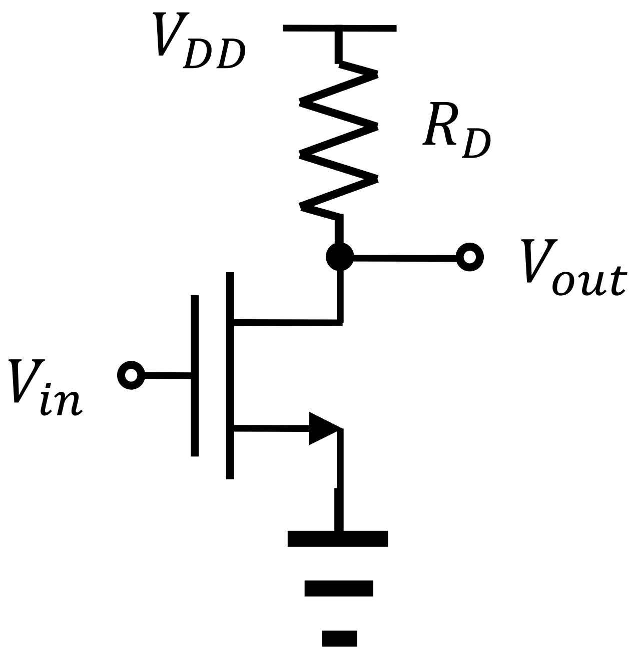
- How can we represent 0 and 1?
  - V_{DD} is assigned to the logical value, 1.
  - GND is assigned to the logical value, 0.





NMOS inverter

- How can we have an output, 0?
  - Only when the input is high. *You have seen it before!*



Vin	Vout
0	1
1	0

Voltage transfer

- When $V_{in} < V_{TH}$, trivially, $V_{out} = V_{DD}$.
- When V_{in} is slightly larger than V_{TH}, the NMOSFET is in the saturation region.

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

$$V_{out} = V_{DD} - \frac{1}{2}\mu_n C_{ox}\frac{W}{L}R_D(V_{in} - V_{TH})^2$$

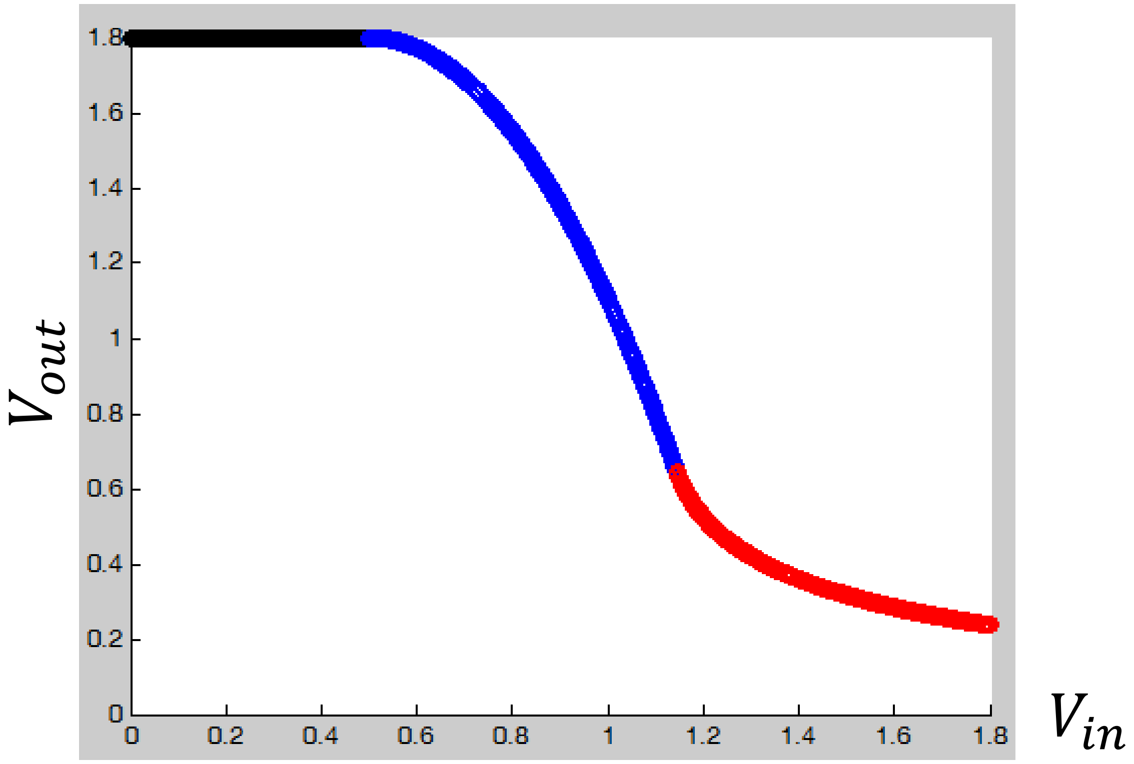
- When V_{in} is further increased, the NMOSFET is in the triode region.

$$V_{out} = V_{DD} - \frac{1}{2}\mu_n C_{ox}\frac{W}{L}R_D[2(V_{in} - V_{TH})V_{out} - V_{out}^2]$$

Draw it! (1/2)

- Parameters in Example 17. 14 (Razavi) w/o modification.

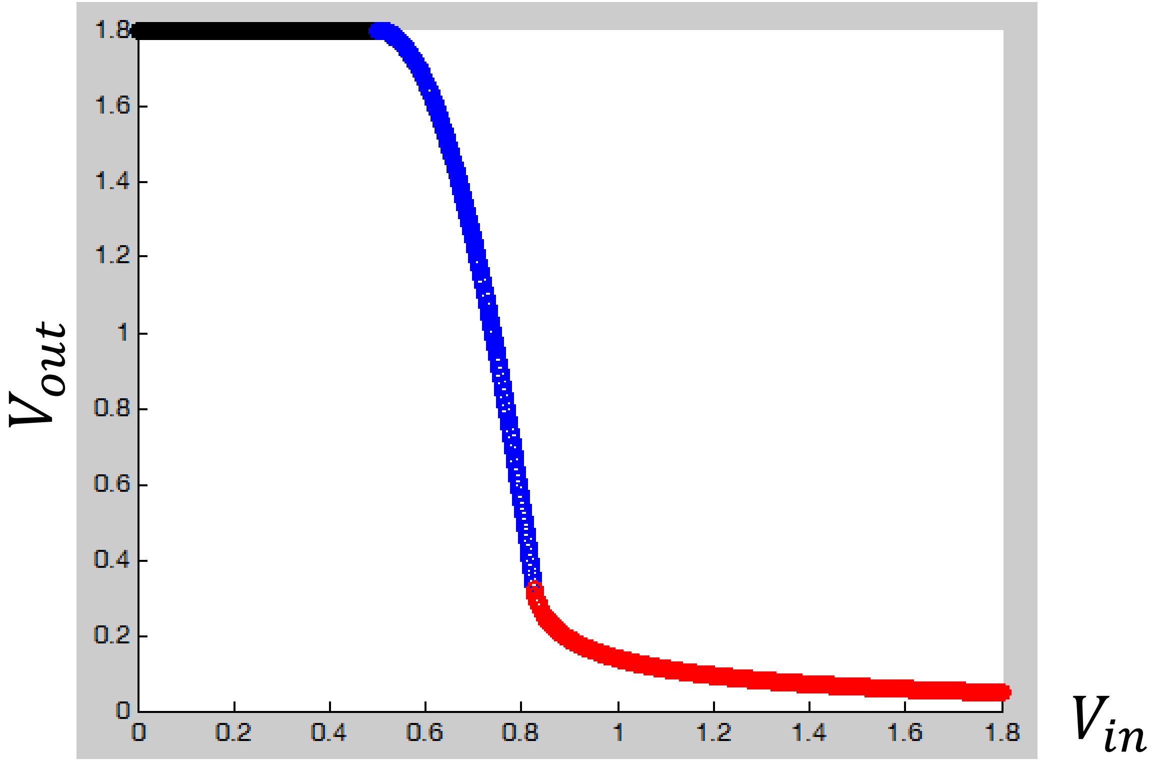
$\mu_n C_{ox} = 100\ \mu\mathrm{A/V^2}$, $V_{TH} = 0.5\ \mathrm{V}$, $\frac{W}{L} = \frac{10}{0.18}$, $R_D = 1k\Omega$ and $V_{DD} = 1.8\ \mathrm{V}$



Draw it! (2/2)

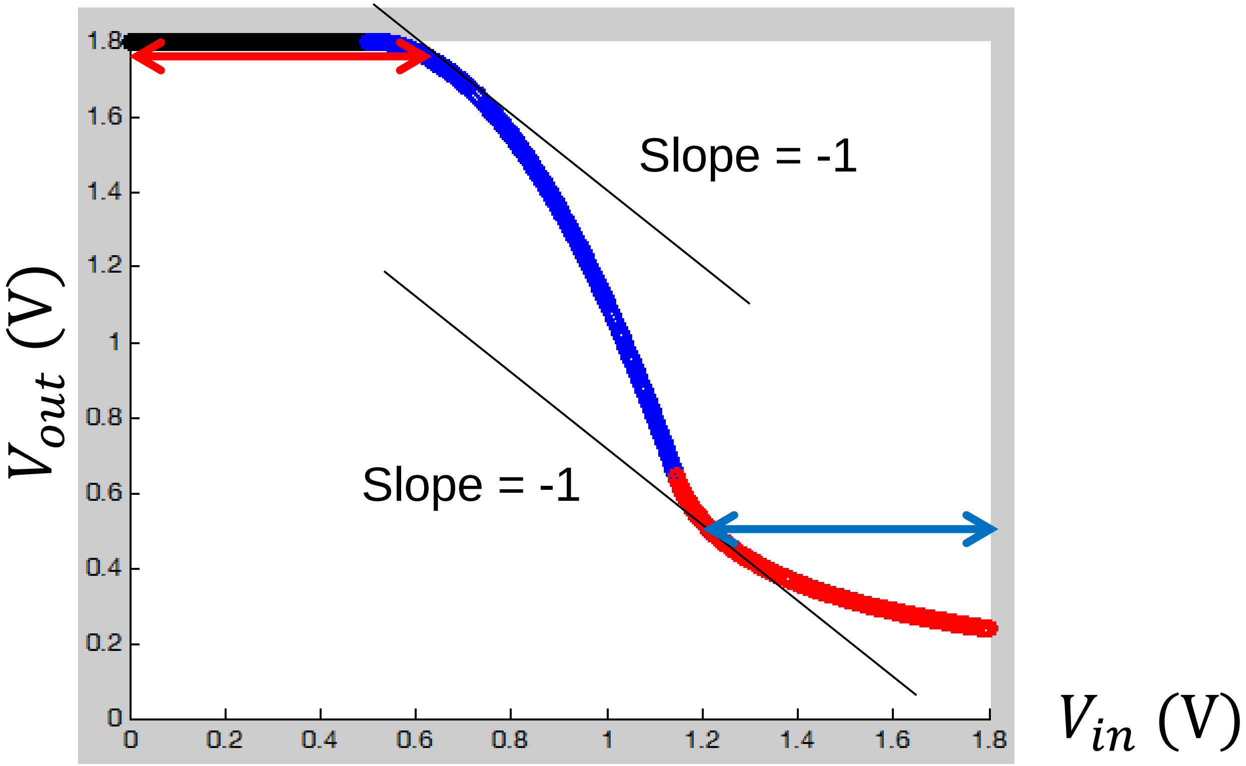
- With a wider NMOSFET

$\mu_n C_{ox} = 100\ \mu\text{A/V}^2$, $V_{TH} = 0.5\ \text{V}$, $\frac{W}{L} = \frac{50}{0.18}$, $R_D = 1k\Omega$ and $V_{DD} = 1.8\ \text{V}$



Noise margin

- Verbatim
  - "(It) is the maximum amount of degradation (noise) at the input that can be tolerated before the output is affected significantly."

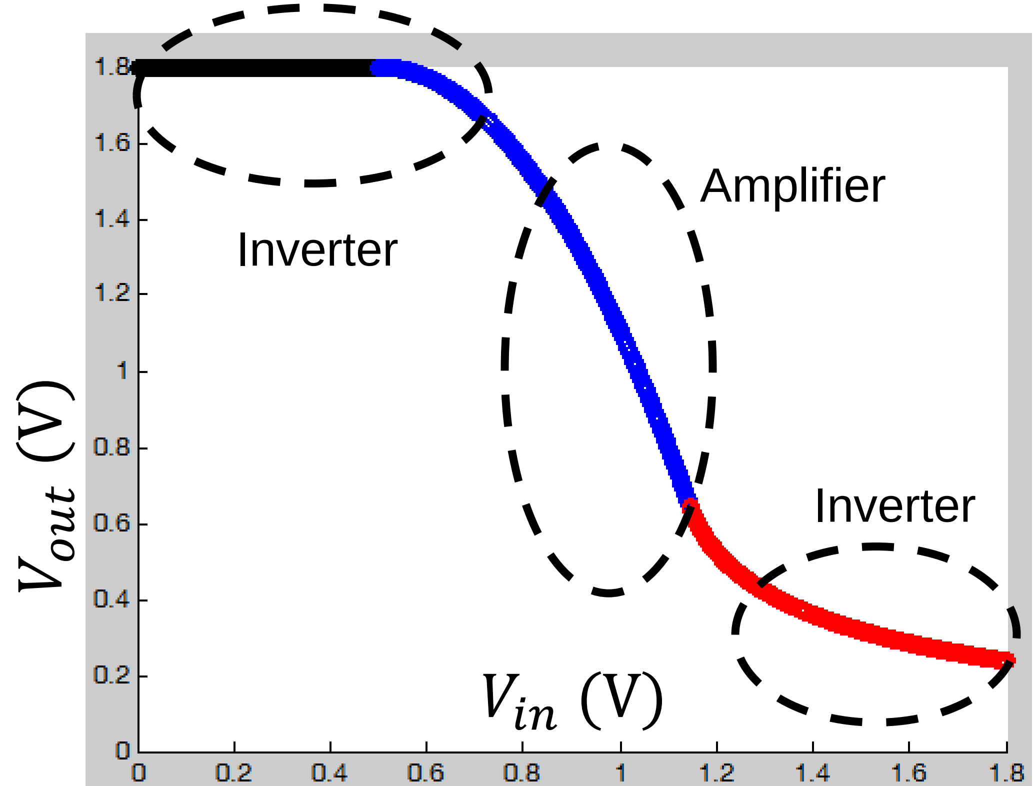


Noise margin of CS stage

- Let's calculate $NM_L = V_{IL}$.
  - In this case, (blue curve)
$$V_{out} = V_{DD} - \frac{1}{2}\mu_n C_{ox}\frac{W}{L}R_D(V_{in} - V_{TH})^2$$
  - Taking the differentiation w. r. t. V_{in},
$$\frac{\partial V_{out}}{\partial V_{in}} = -\mu_n C_{ox}\frac{W}{L}R_D(V_{in} - V_{TH})$$
  - At $V_{in} = V_{IL}$, the slope becomes -1,
$$NM_L = V_{IL} = \frac{1}{\mu_n C_{ox}\frac{W}{L}R_D} + V_{TH}$$
  - (Stronger NMOS yields a reduces NM_L.)

Common-source

- Common-source configuration
  - It can be used as an inverter.
  - It can be used as an amplifier.
  - $\frac{dV_{out}}{dV_{in}}$ is the voltage gain.



Homework#9

- Due: 09:00, **May 27 (Mon)**
- Solve the following problems of the final exam in 2018.
  - P9
  - P10
  - P11
  - P12
  - P13
  - P14