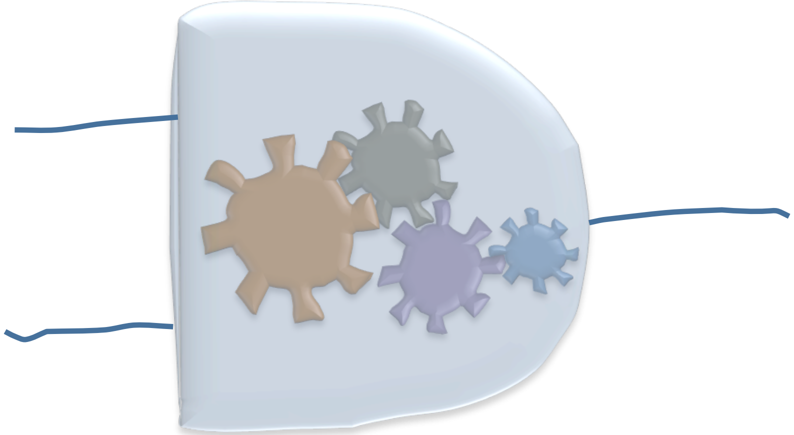
6.002x CIRCUITS AND ELECTRONICS

Inside the Digital Gate



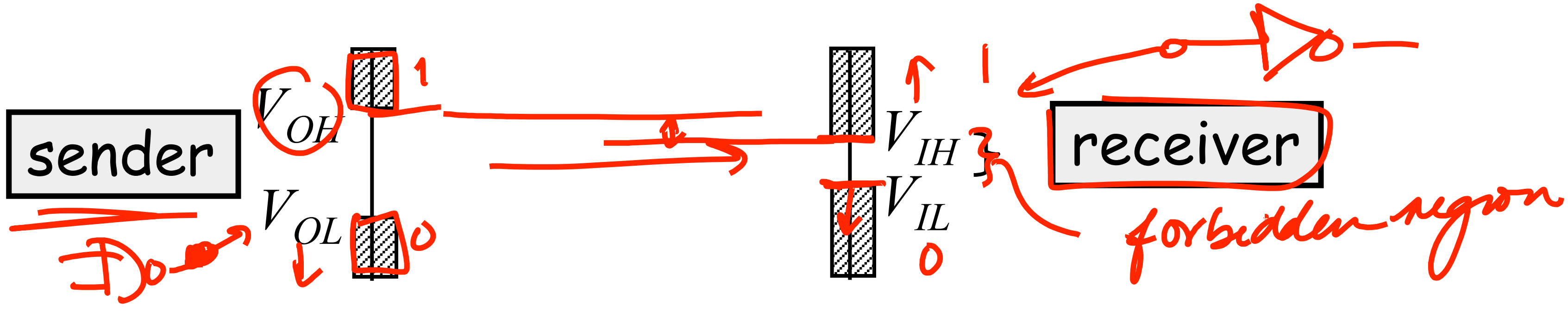
Reading: Chapter 6 of A&L

Review

The Digital Abstraction

EECS
digital
0, 1
linear
SD1
SD2

- Discretize value: 0, 1
- Static discipline -- digital devices meet voltage thresholds

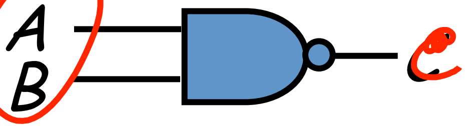


Specifies how gates must be designed

Review

Combinational gate abstraction

- outputs function of input alone
- satisfies static discipline



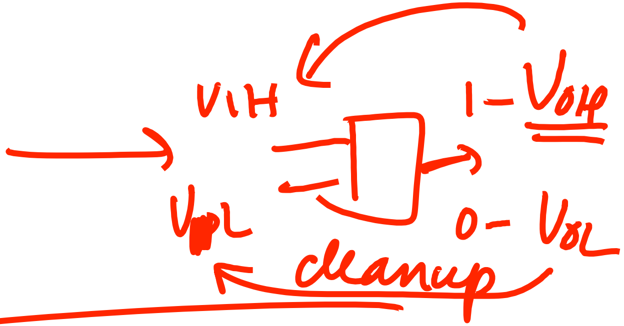
NAND

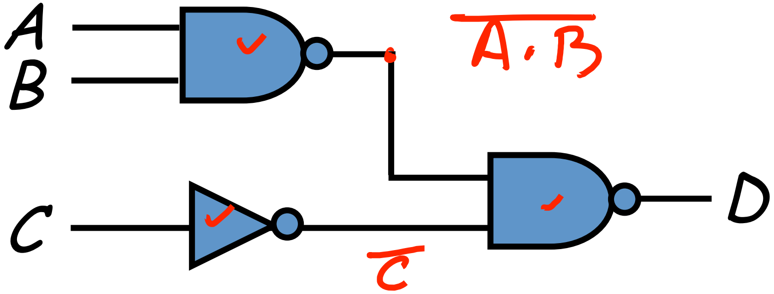
A	B	C
0	0	1
0	1	1
1	0	1
1	1	0

Truth tables

Review

A digital circuit





$\overline{\left(\overline{A\cdot B}\right)\cdot \bar{C}}$

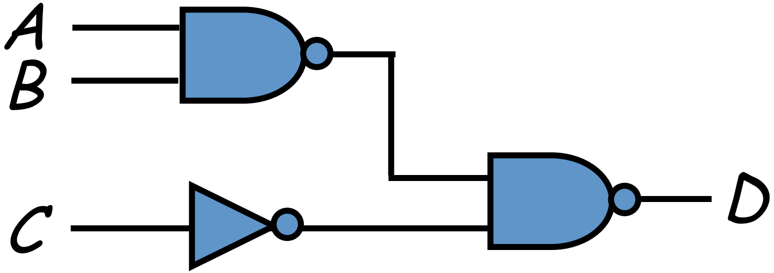
3 gates here

- A Nehalem class microprocessor from Intel has approx 1 billion gates
- The RAW multicore chip (http://groups.csail.mit.edu/cag/raw/) built by students at CSAIL, MIT, had about 3 million gates
- The 64-core Tile processor from Tilera has approx a half billion gates

Review

A digital circuit

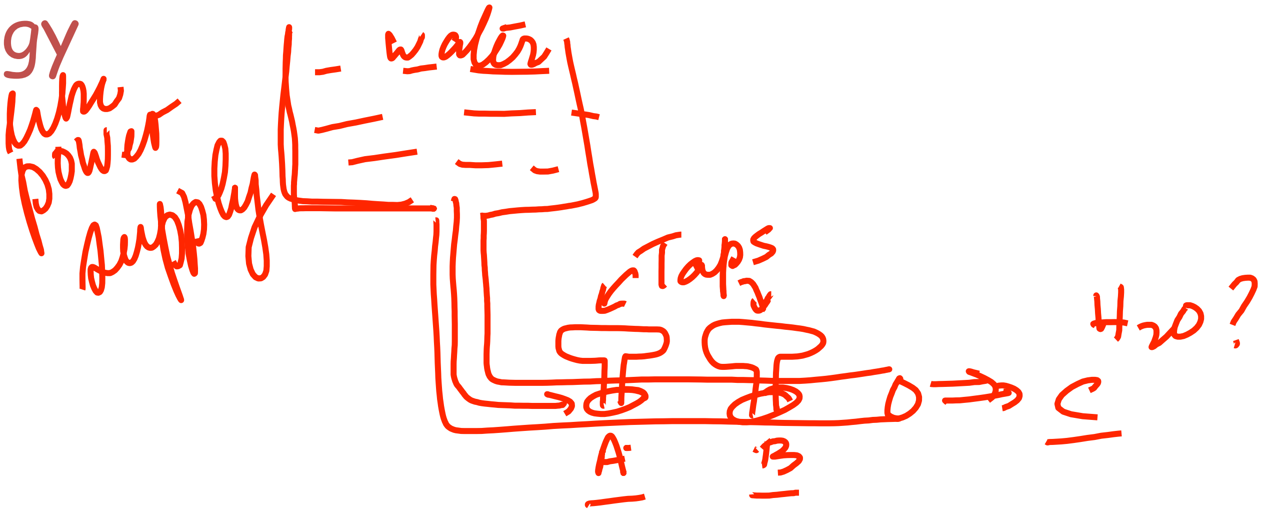
Demo



http://localhost:8000/static/book/p027.jpg

How to build a digital gate

Analogy

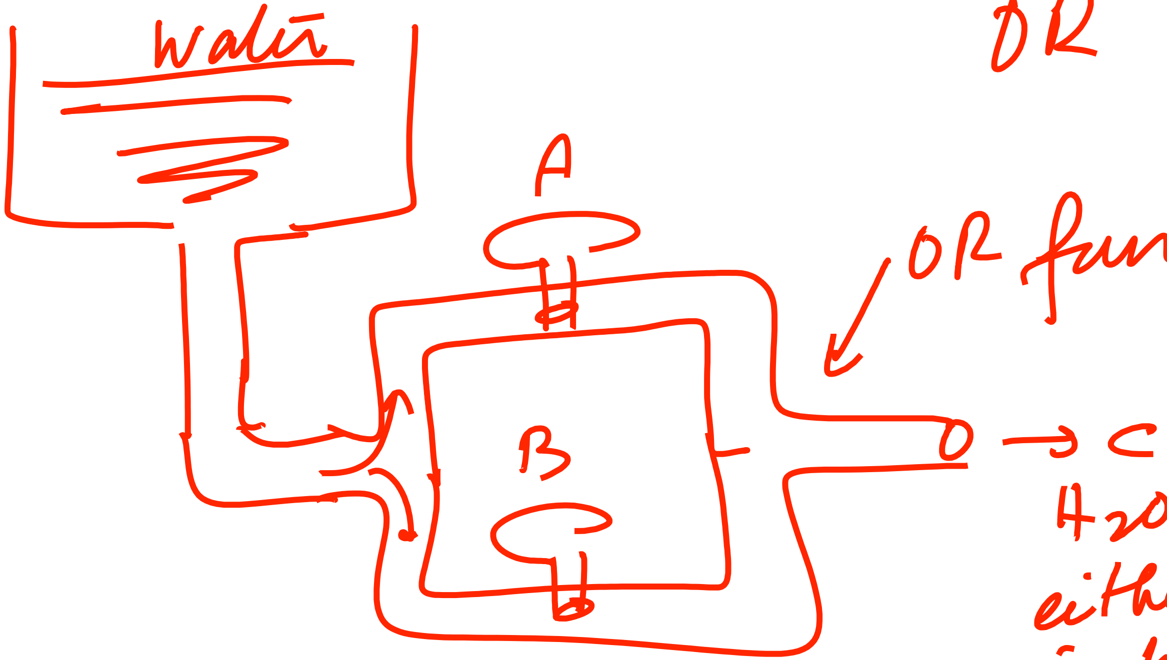


If A = ON AND B = ON
THEN C has H_2O
else C has no H_2O

Use this insight to build an AND gate.

How to build a digital gate

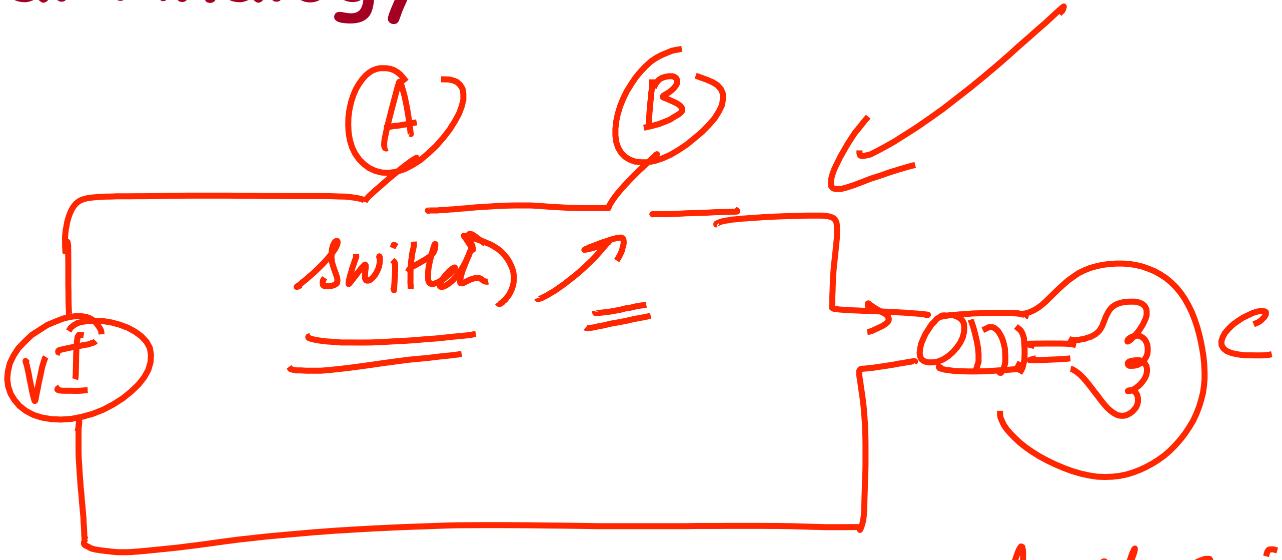
OR



OR function

H_2O if either A or B is turned ON

Electrical Analogy



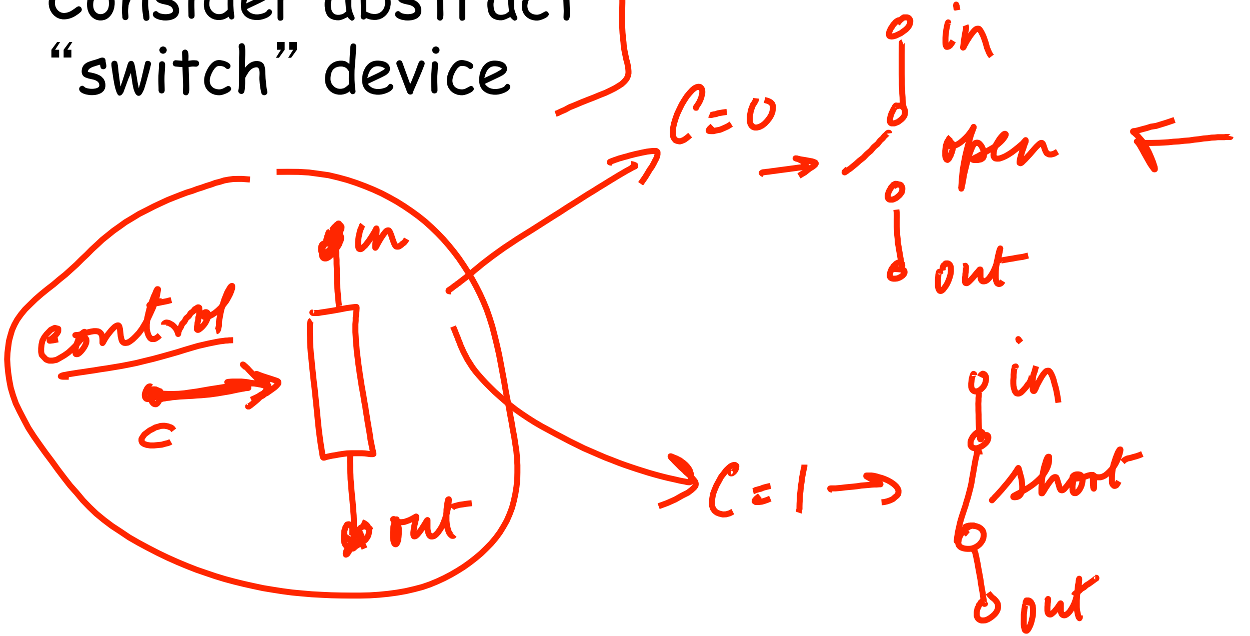
If A AND B are ON, bulb C is ON
else bulb C is off

Key: we need a "switch" device

New Switch Element

Consider abstract "switch" device

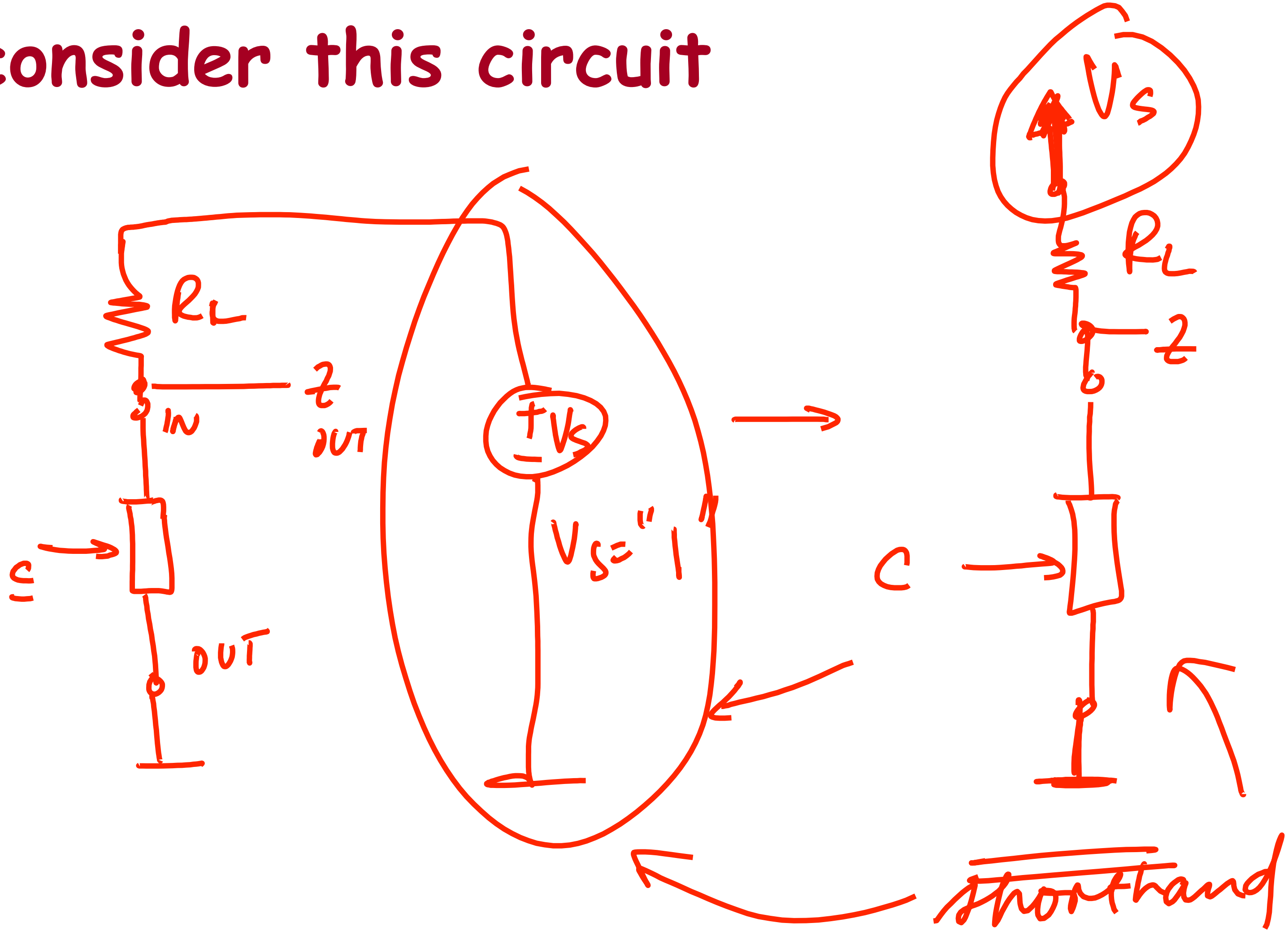
Equivalent ckt



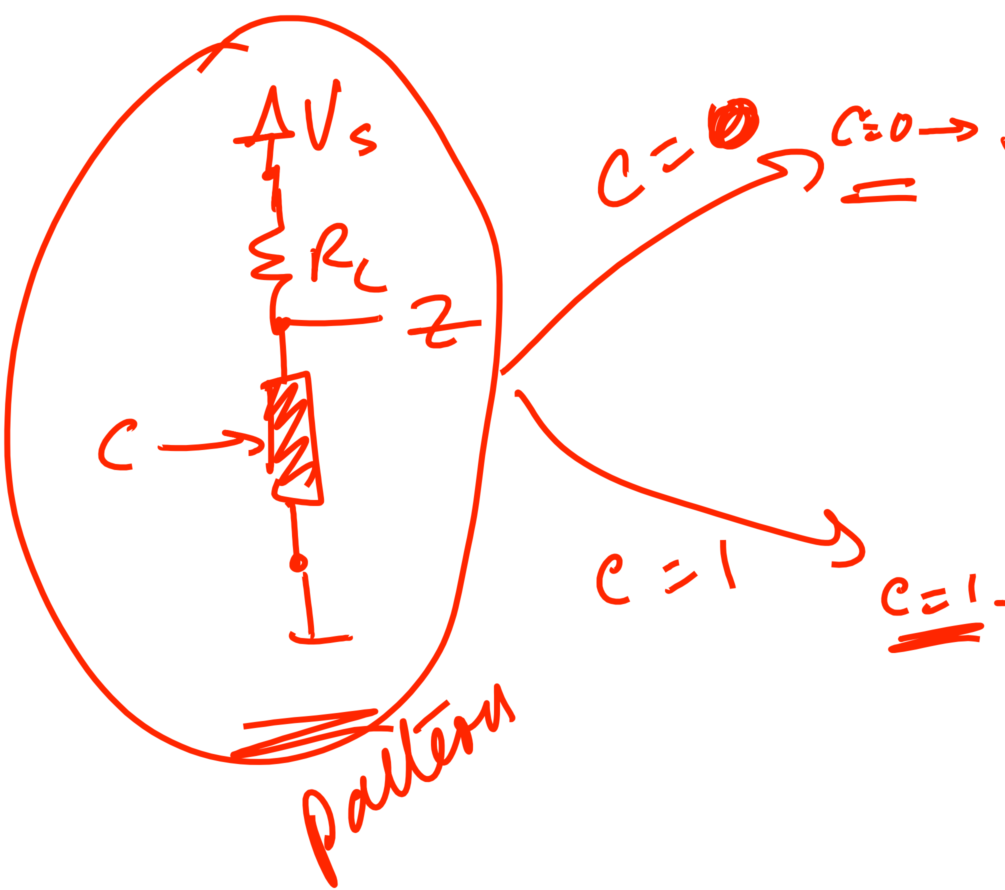
For mechanical switch, control mechanical pressure

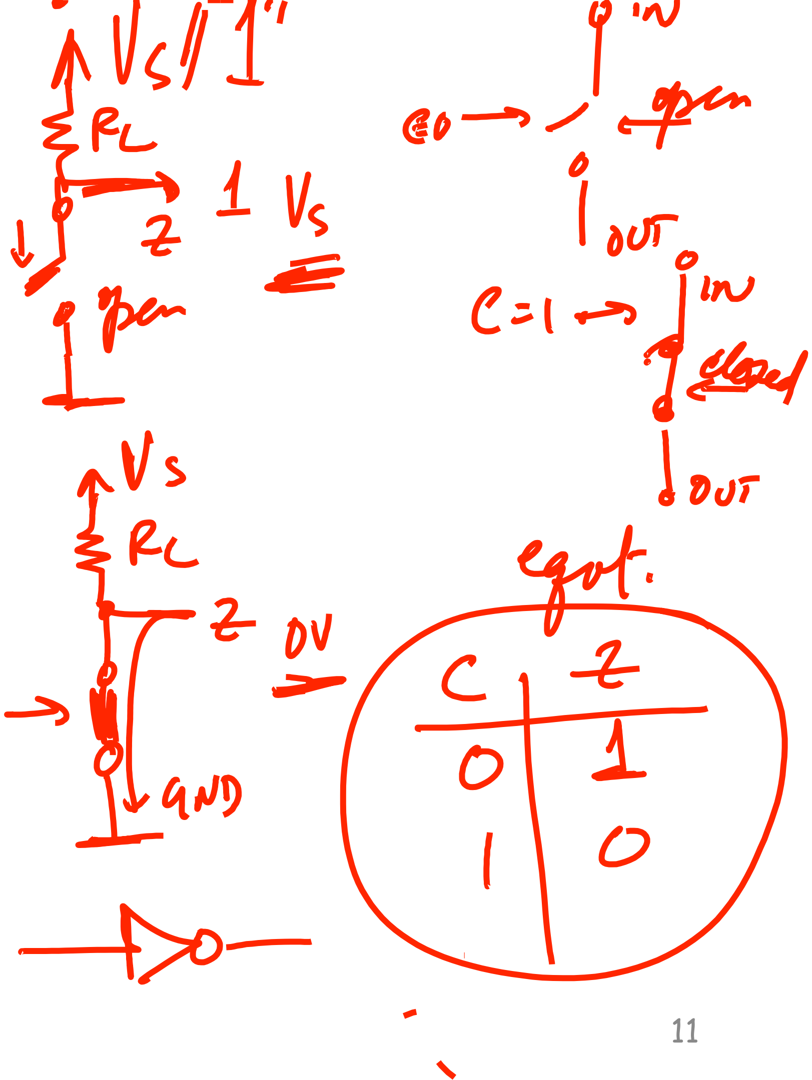
3-Terminal device
if C = ~~0~~ 1: short circuit between in and out
else: open circuit between in and out → C=0

Now, consider this circuit



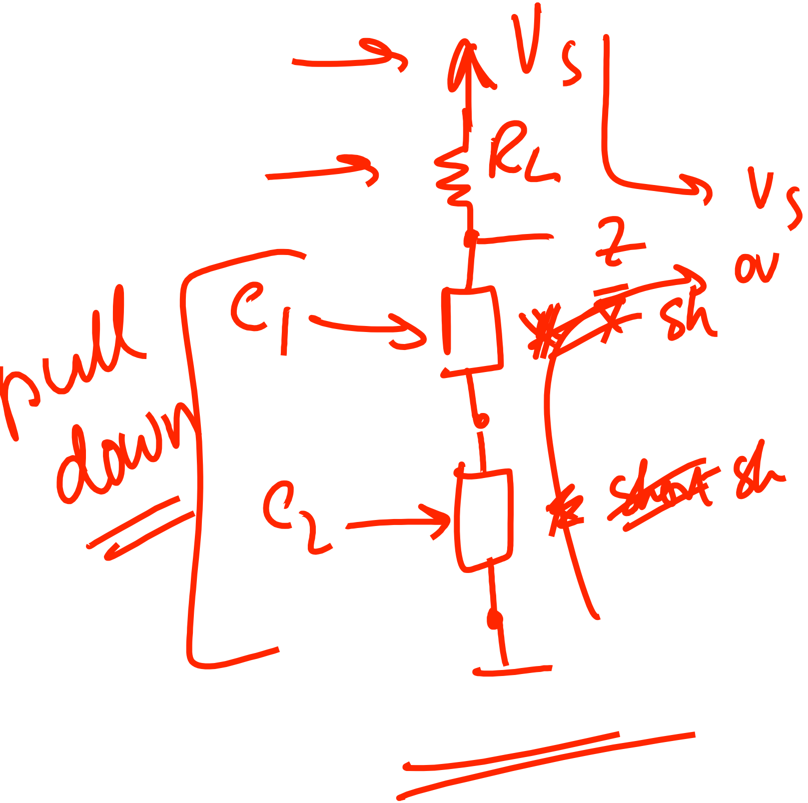
Behavior of this circuit





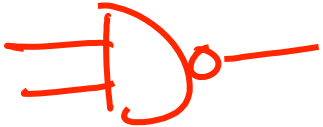
C	Z
0	1
1	0

What about?

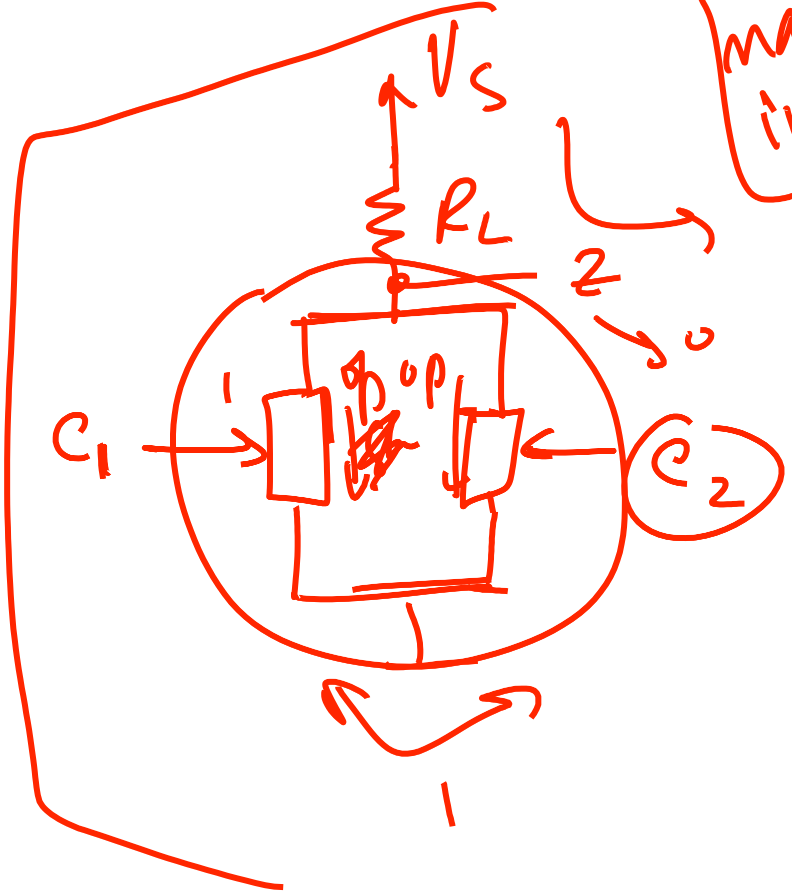


C_1	C_2	Z
0	0	1
0	1	1
1	0	1
1	1	0

Truth table for



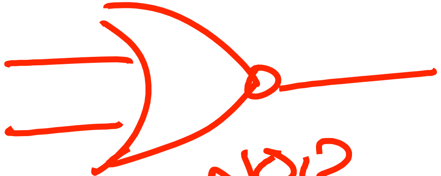
What about?



natural inversion

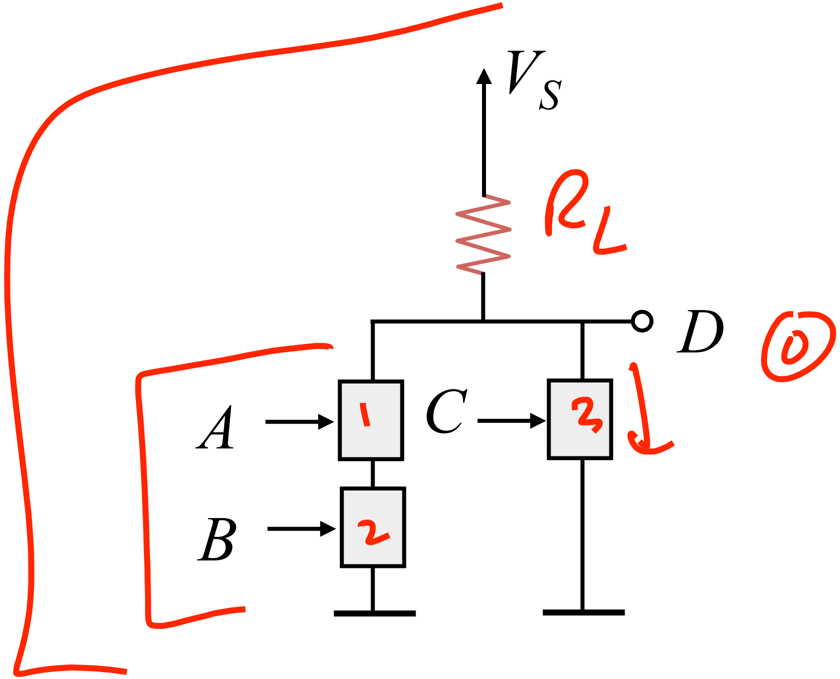
C_1	C_2	Z
0	0	1
0	1	0
1	0	0
1	1	0

Truth table for ?

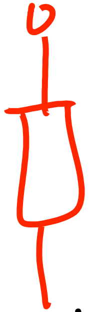


NOR

We can also build compound gates



$$D = \overline{(A \cdot B) + C}$$

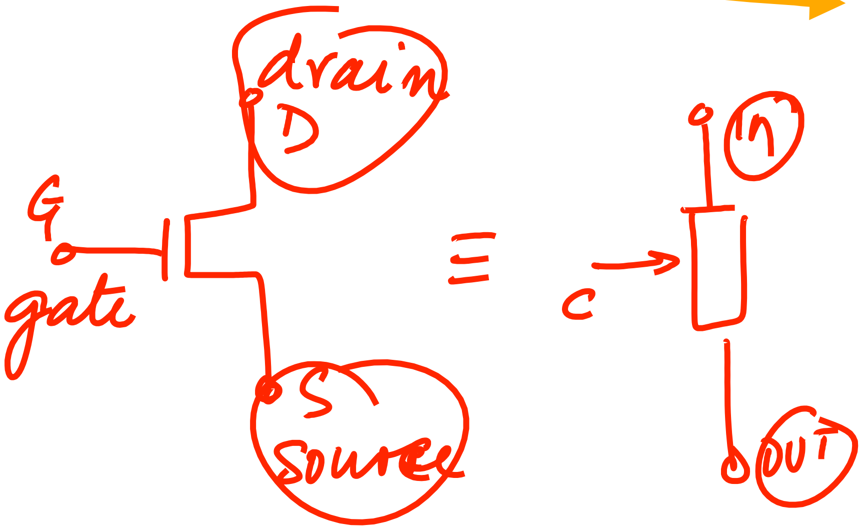


magical abstract switch!

Now let's get back to reality… we need a physical switch

The MOSFET Device

Metal-Oxide Semiconductor
Field-Effect Transistor



3 terminal lumped element
behaves like a switch

G: control terminal

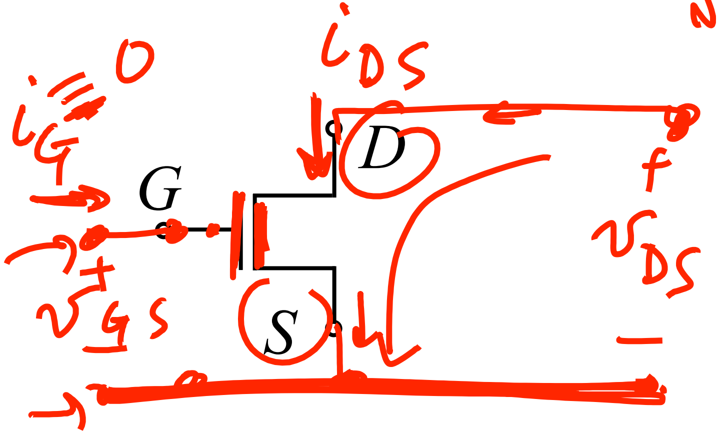
D, S: behave in a symmetric
manner (for our needs)

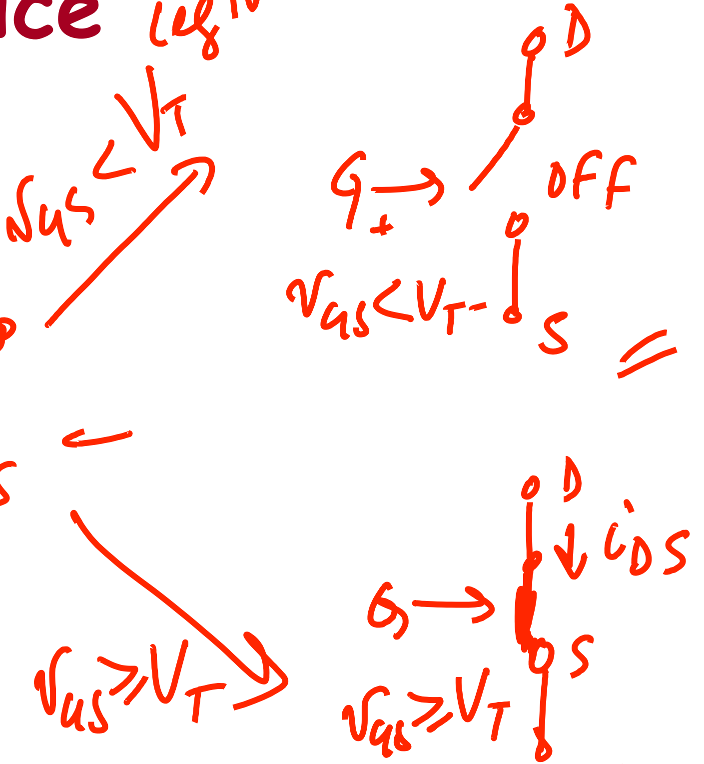
6.002x

Chap 6.7

The MOSFET Device (eg 1V)

Understand its operation by viewing it as a two-port element





Check out the textbook for its internal structure Sec 6.7

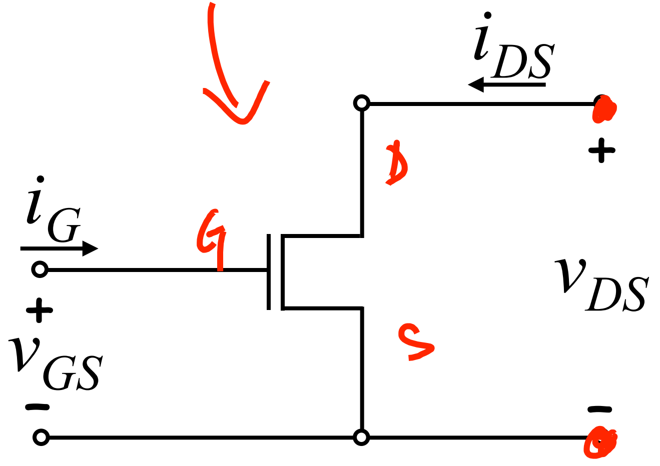
$V_T \sim 1V$
for example

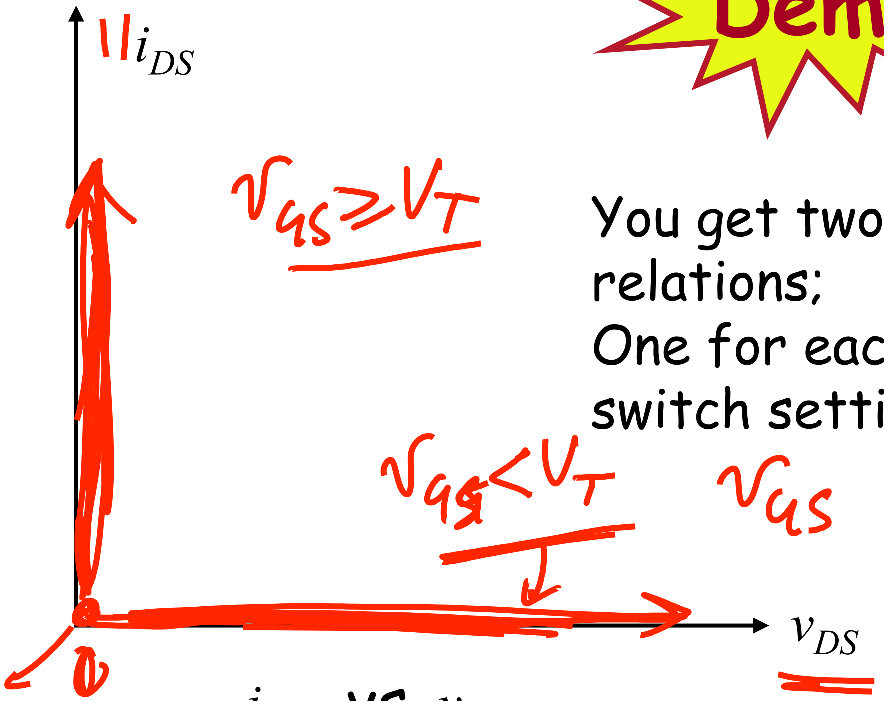
MOSFET actually more complex!

"Switch" model (S model) of the MOSFET

Check the MOS device on a scope

Demo





i_{DS} **VS** v_{DS}

You get two v-i relations;
One for each switch setting

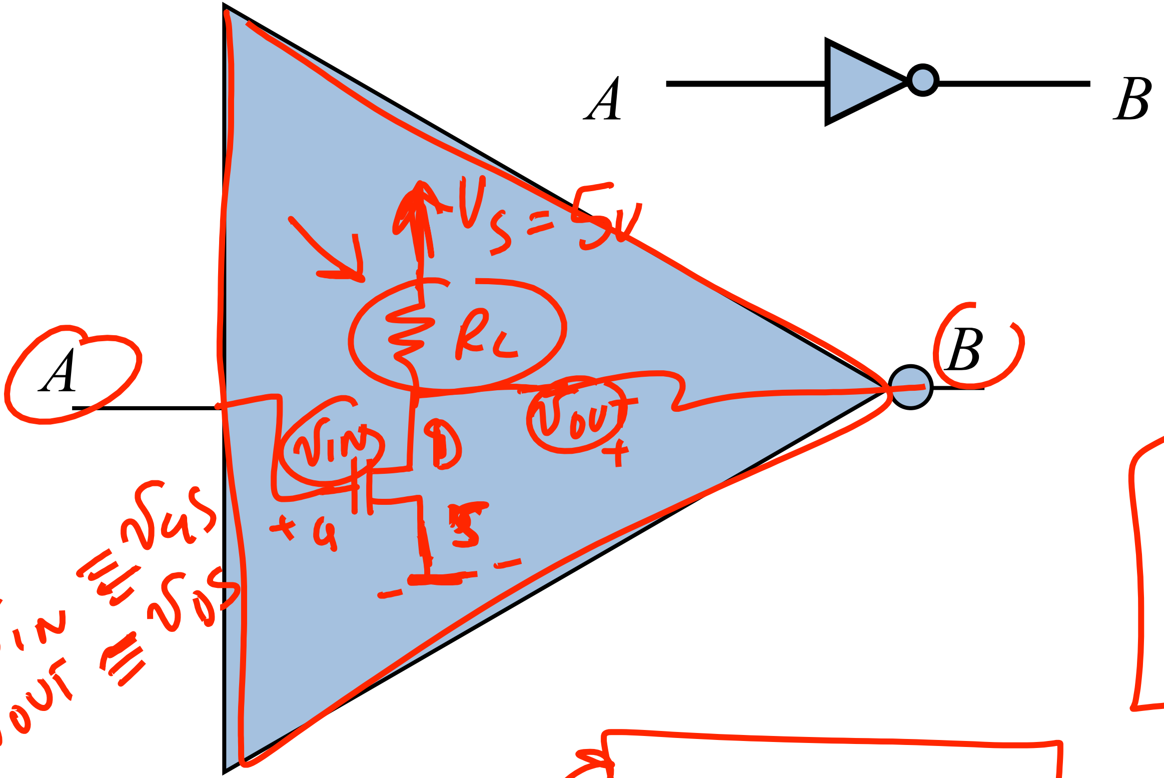
V_{GS}

open

short

(As we will see soon, note that the actual MOSFET behavior is quite a bit more complex. The above switch characterization is a gross simplification. If you cannot wait, check out Section 7.3 of the textbook for the actual MOSFET characteristics)

A MOSFET Inverter



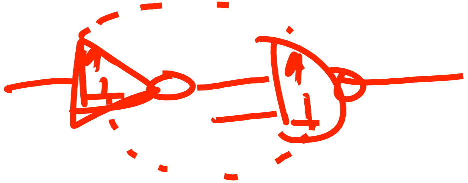
$v_{IN} \equiv v_{GS}$
$v_{OUT} \equiv v_{DS}$

Note the power of abstraction:

The abstract inverter gate representation hides internal details such as power supply connections, R_L, GND, etc. When we build digital circuits, the ↑ and ⊥ are common across all gates!

A, B: Logic value 0, 1

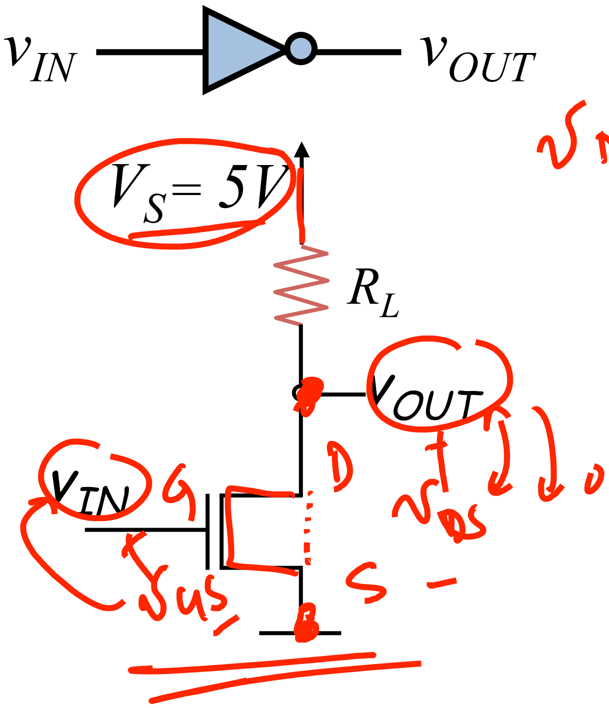
v_{IN}: Voltage value

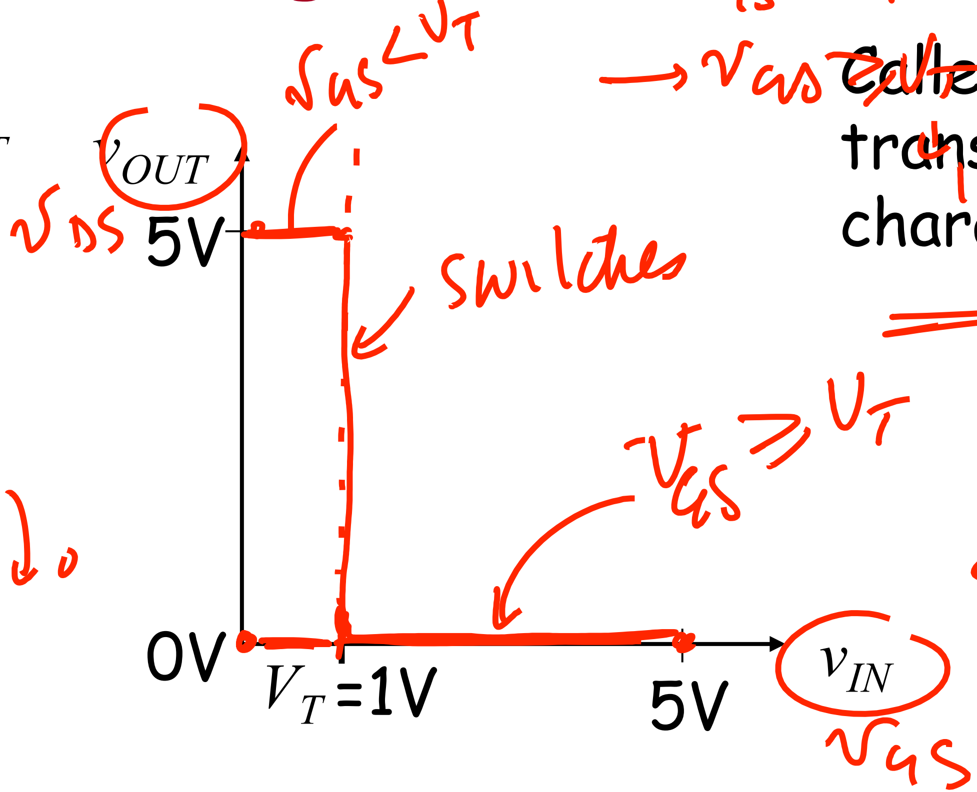


We can plot the relationship between the input and output voltages

→ $v_{GS} < V_T$ open D-S

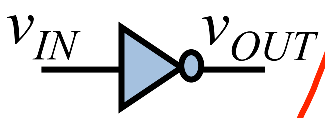
→ $v_{GS} \geq V_T$ short D-S





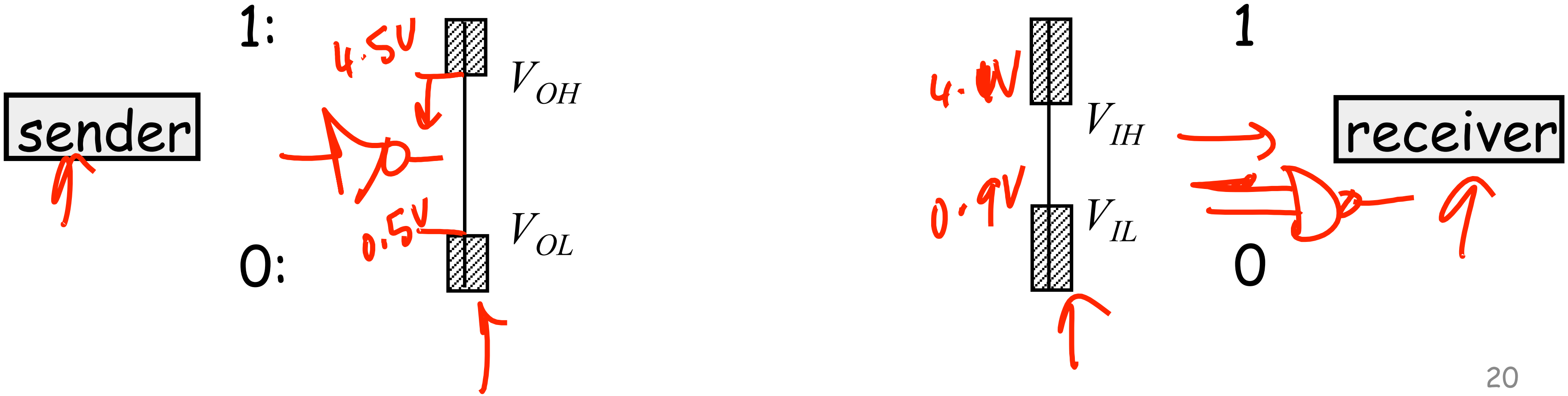
Called voltage transfer characteristic

Question: The T1000 model laptop needs gates that satisfy a static discipline with voltage thresholds given below. Does our inverter qualify?

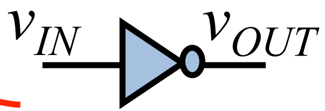


V_{OL} = 0.5V $\quad$ V_{IL} = 0.9V

V_{OH} = 4.5V $\quad$ V_{IH} = 4.1V

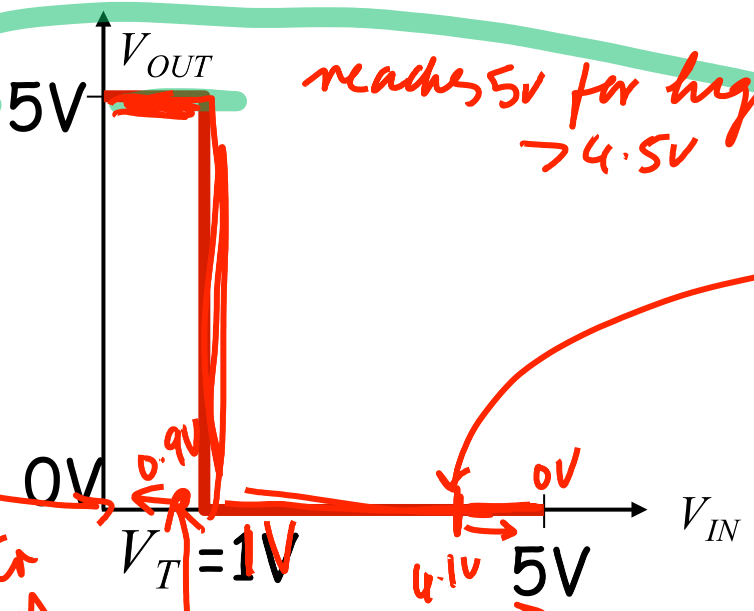


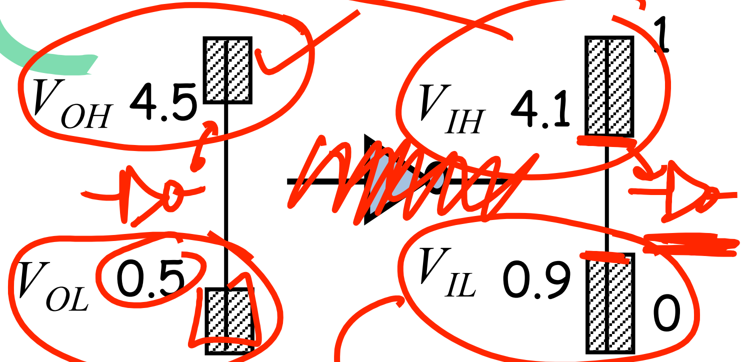
Does our inverter satisfy the voltage thresholds for this static discipline?



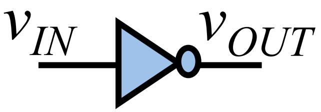
V_{OL} = 0.5V V_{IL} = 0.9V

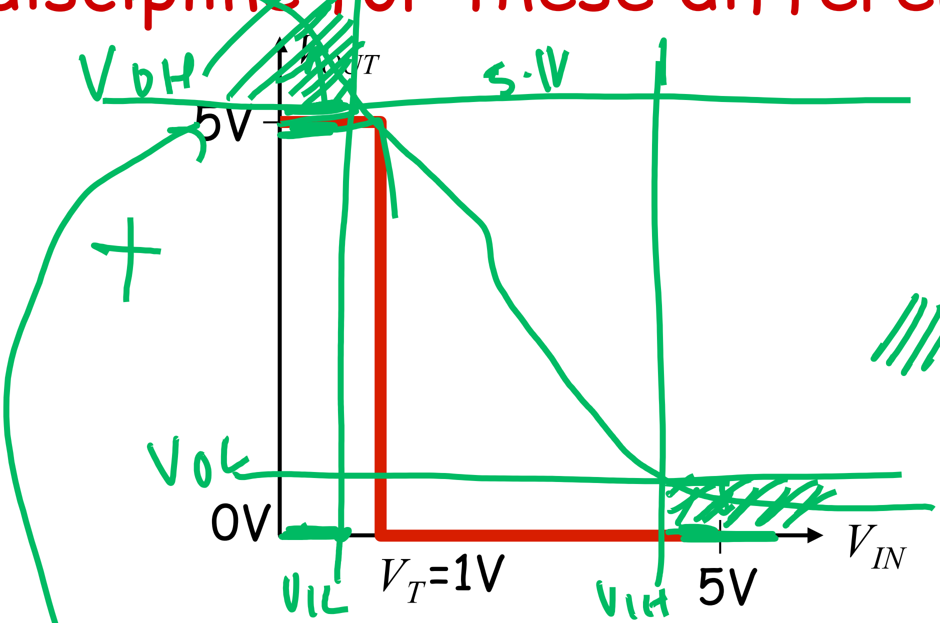
V_{OH} = 4.5V V_{IH} = 4.1V





Does our inverter satisfy the static discipline for these different thresholds?





//// valid regions

V_{OL} = 0.2V V_{IL} = 0.5V

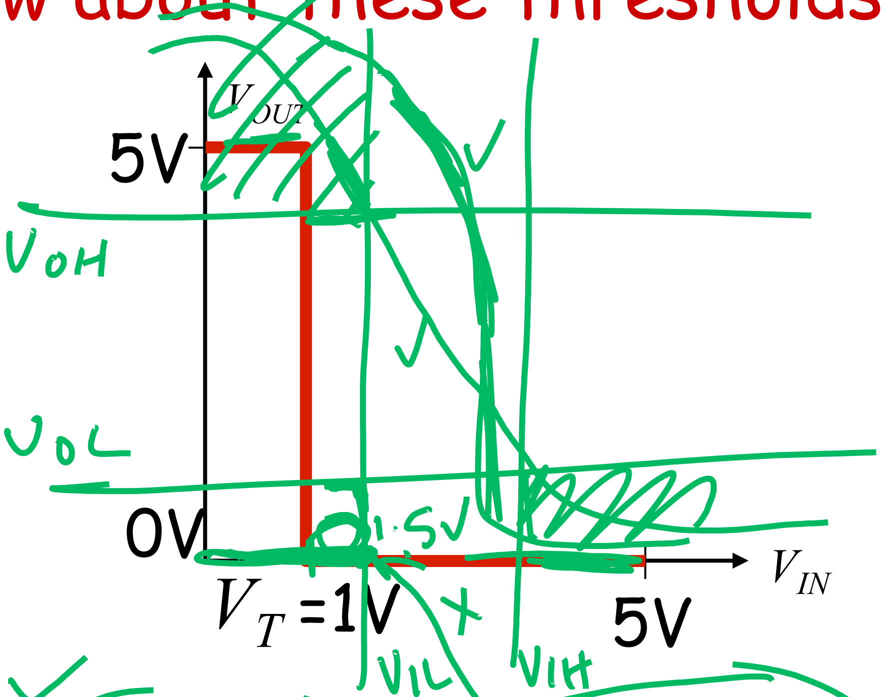
V_{OH} = 5.1V V_{IH} = 4.5V

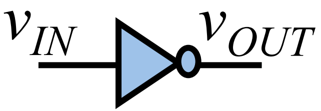
NO

V_{OL} = 0.2V V_{IL} = 0.5V

V_{OH} = 5.1V V_{IH} = 4.5V

How about these thresholds?





V_{OL} = 0.5V $\quad$ V_{IL} = 1.5V

V_{OH} = 4.5V $\quad$ V_{IH} = 3.5V

V_{OL} = 0.5V

V_{OH} = 4.5V

V_{IL} = 1.5V

V_{IH} = 3.5V

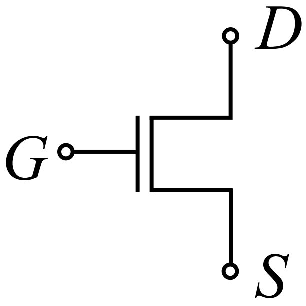
V_{IL} — V_{IH}

?

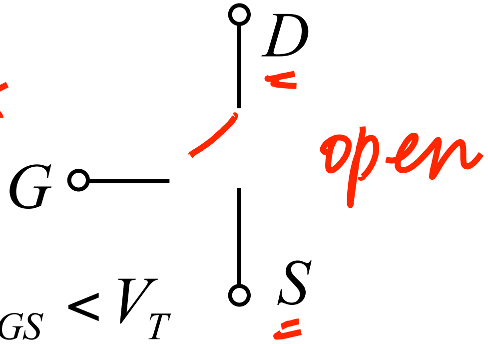
NO!

Switch Resistor (SR) Model of MOSFET

…a more accurate MOSFET model

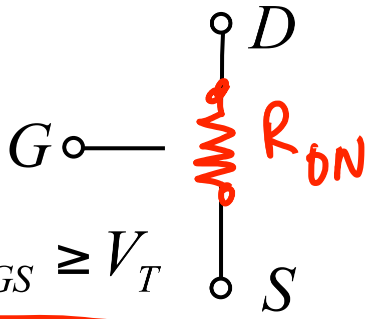


OFF



$v_{GS} < V_T$

ON state



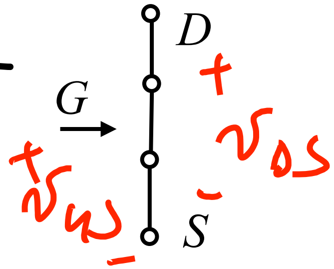
$v_{GS} \geq V_T$

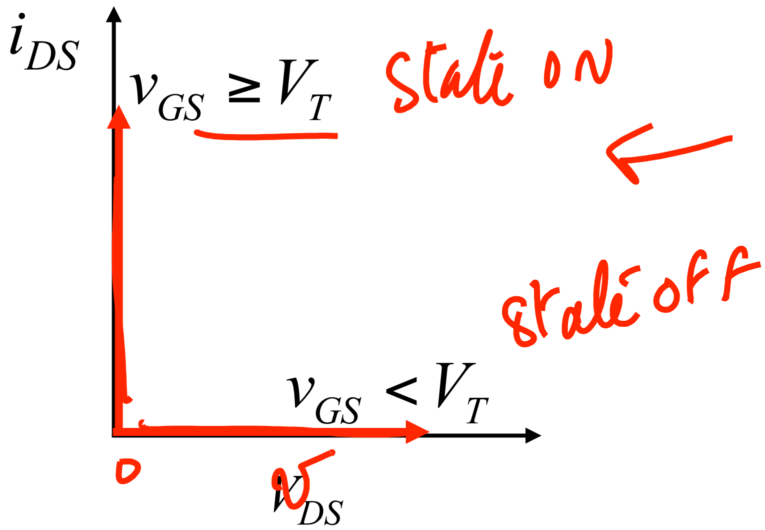
e.g. $R_{ON} = 5k\Omega$

SR Model of MOSFET

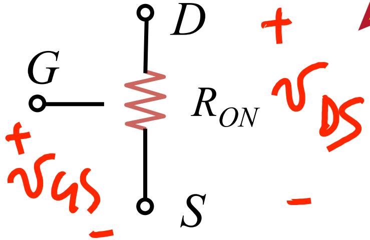
Demo

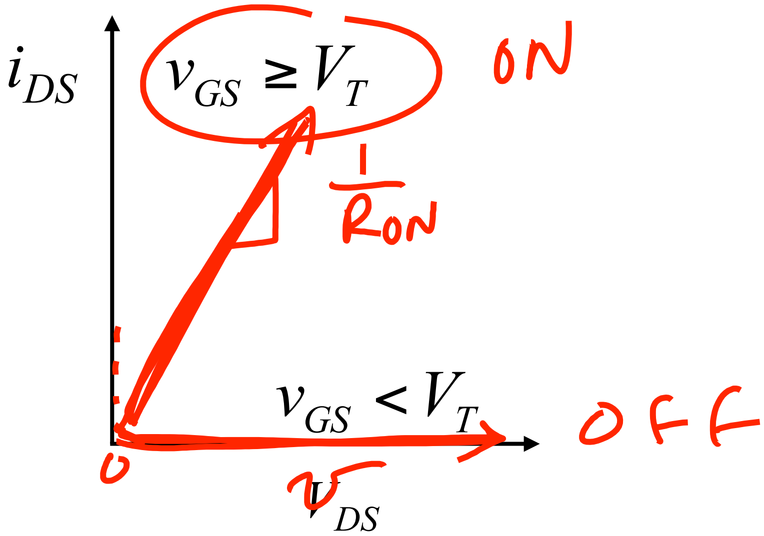
MOSFET
S model



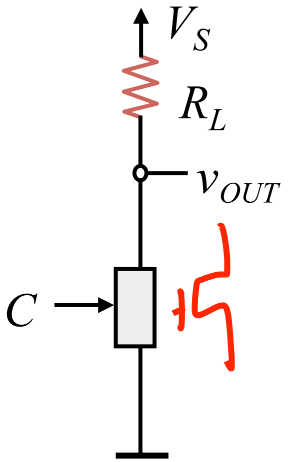


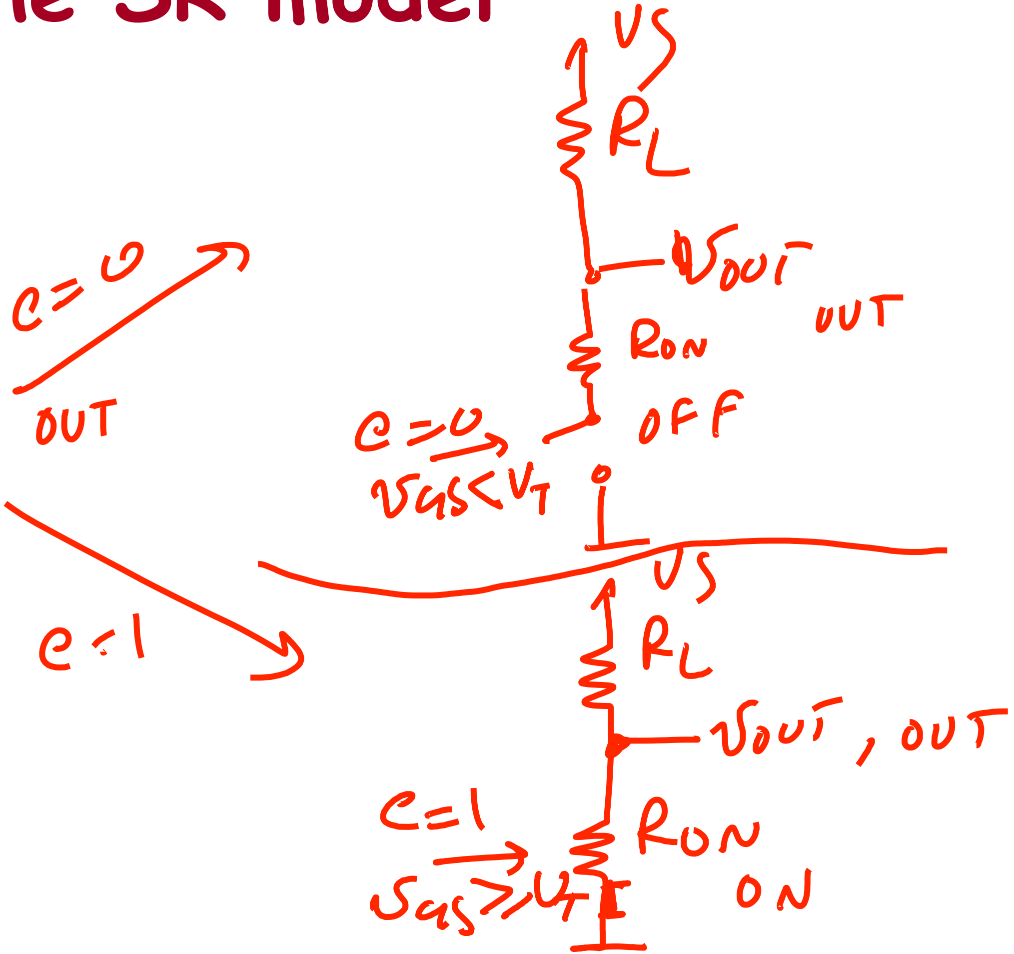
MOSFET
SR model





Using the SR model





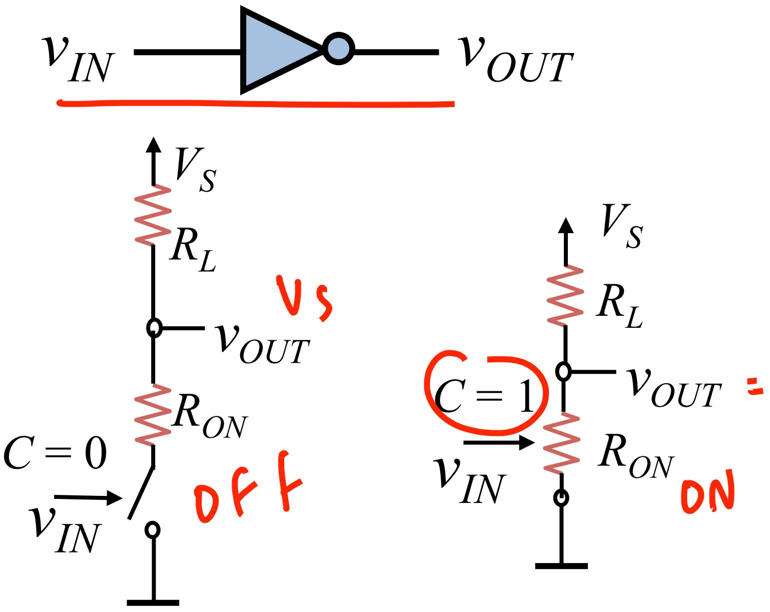
C	OUT
0	1
1	0

choose R_L, R_{ON}, V_S

$$V_{OUT} = \frac{V_S R_{ON}}{R_L + R_{ON}} < V_{OL}$$

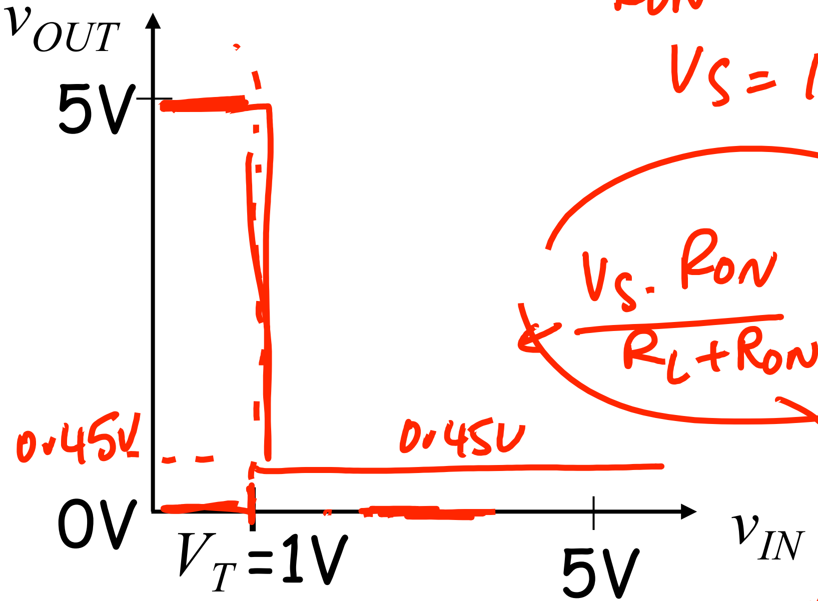
$R_{ON} \ll R_L$

Transfer Function for Inverter using the SR MOSFET Model



C = 0

C = 1



$$\frac{R_L}{R_{ON}} = 10$$

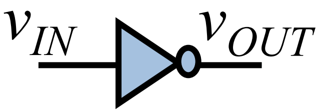
$$V_S = 10$$

$$\frac{V_S \cdot R_{ON}}{R_L + R_{ON}} = 0.45$$

$$\frac{V_S \times 1}{\frac{R_L}{R_{ON}} + 1}$$

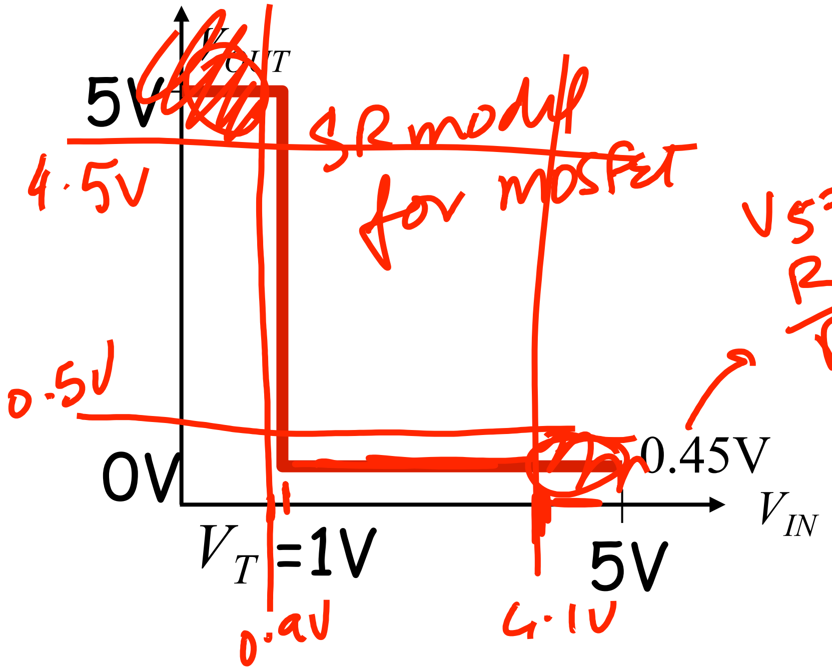
10

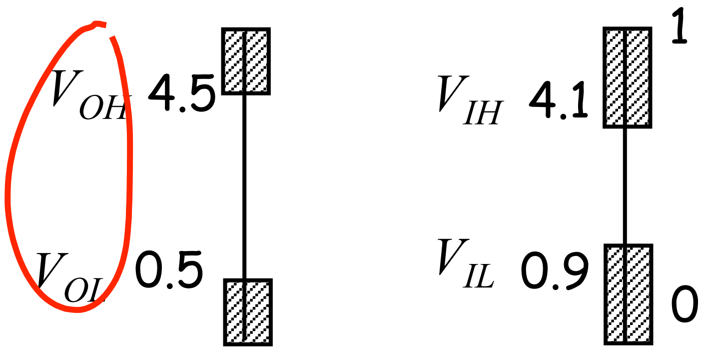
Does our inverter satisfy the voltage thresholds for this static discipline?



V_{OL} = 0.5V V_{IL} = 0.9V

V_{OH} = 4.5V V_{IH} = 4.1V

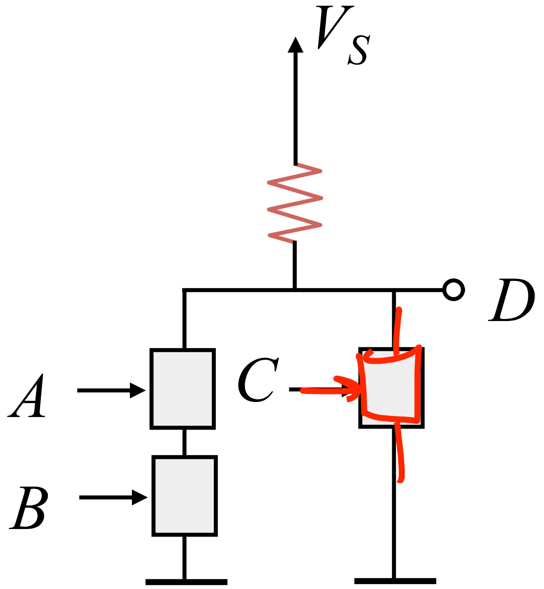


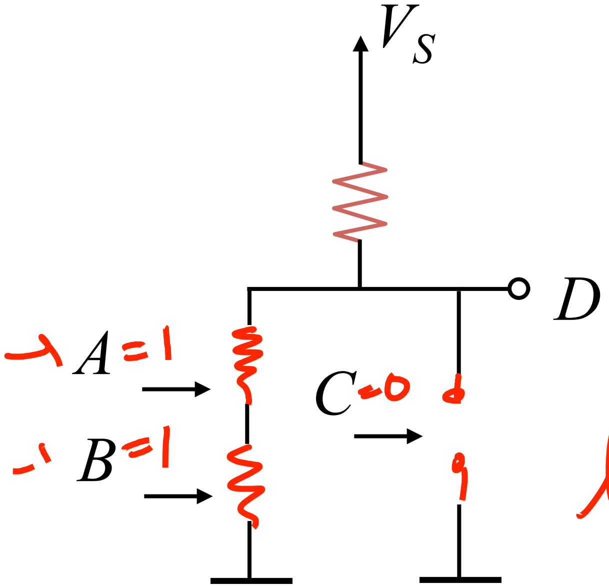


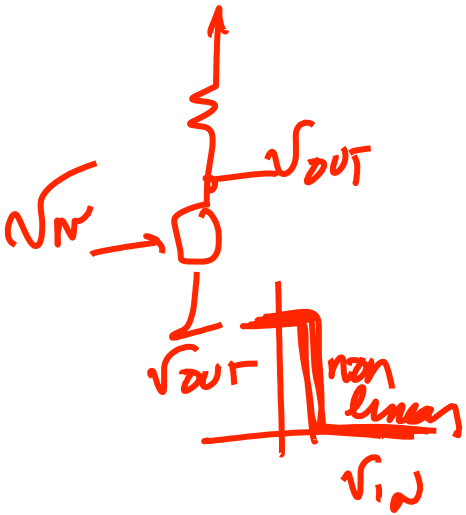
what would happen if you had $\frac{R_L}{R_{ON}} = 5$

So, our inverter satisfies this static discipline

Some Interesting Insights…
Our Digital Subcircuits are Linear

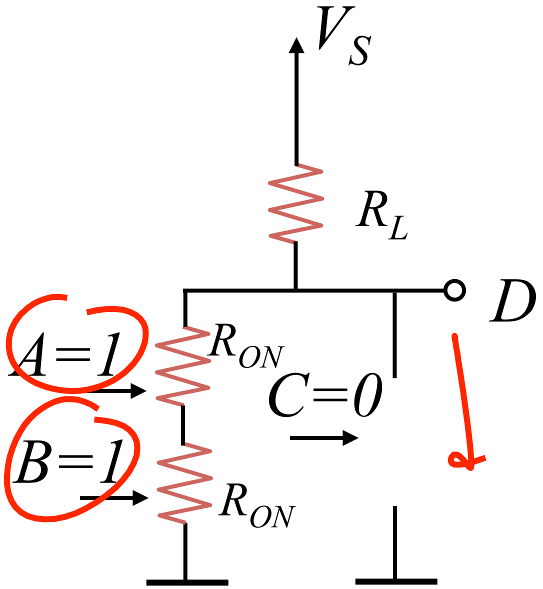


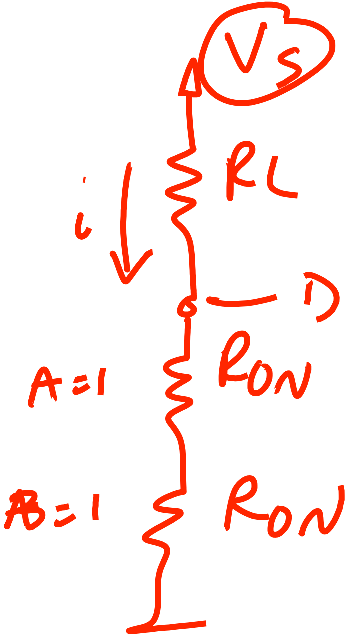




linear subcircuit!

Static Power in Digital Circuits





$V_T = 1V$

$V_S = 5V$

$\frac{1}{7}$

$V_S = 0.7V$

→ 0.3V-0.5V

$$\text{Power} = \frac{V_S^2}{2R_{ON}+R_L} = V_S \cdot i$$

$$\frac{V_S}{2R_{ON}+R_L}$$

6.002x

$V_S = 5V$

$V_T : 1V$

Analog and Digital (or Mixed Signals) are Everywhere