EECS 16B

Designing Information Devices and Systems II

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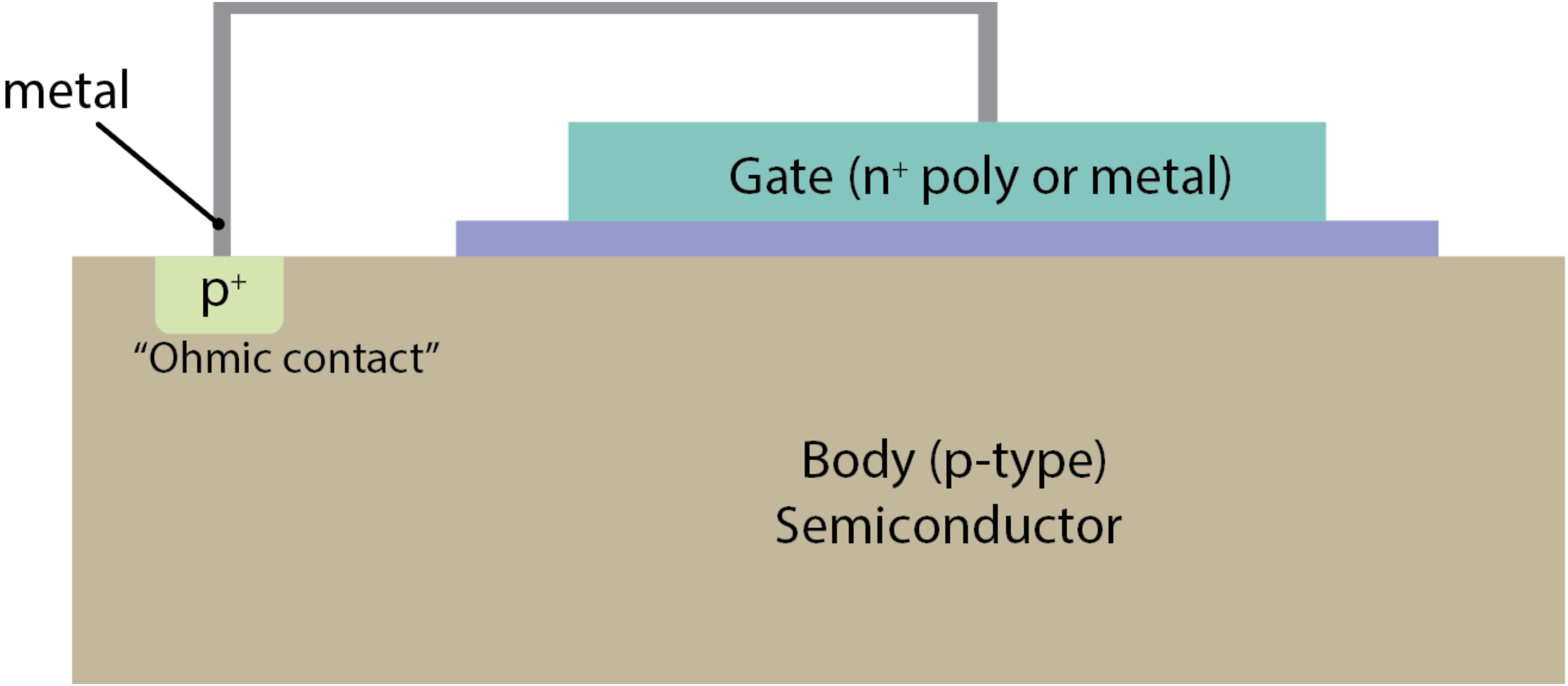
Module 3: CMOS Models and Digital Logic Gates and Applications

EECS 16B

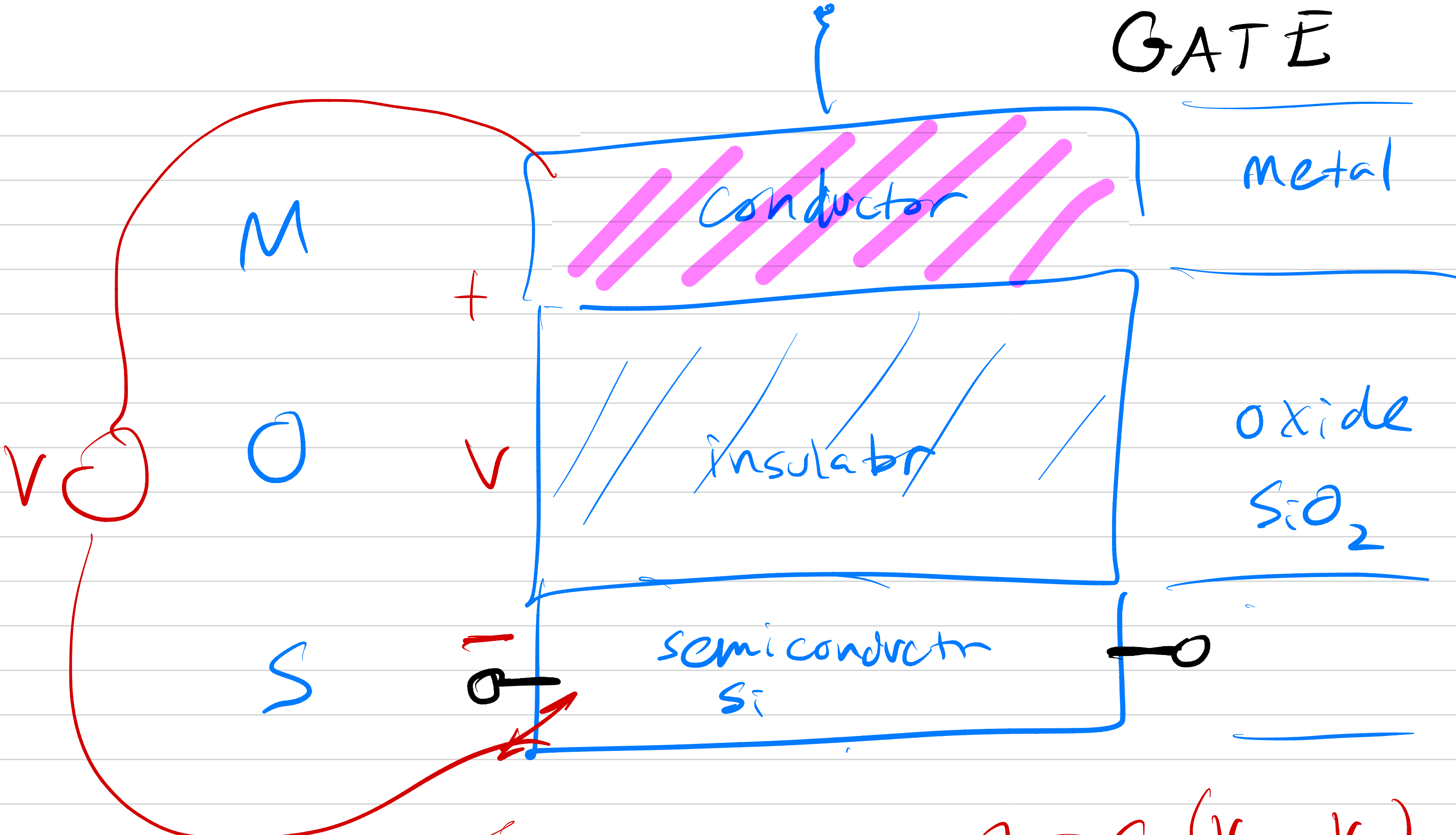
Outline

- Introduction to Transistors
- Simple Transistor Models
- Logic Gates
- Maximum Clock Rates : RC Circuit
- Op-amp settling behavior
- Applications:
  - Analog-to-Digital Conversion (ADC)
  - Digital-to-Analaog Conversion (DAC)
  - Maximum conversion times : RC Circuits !

MOS Capacitor

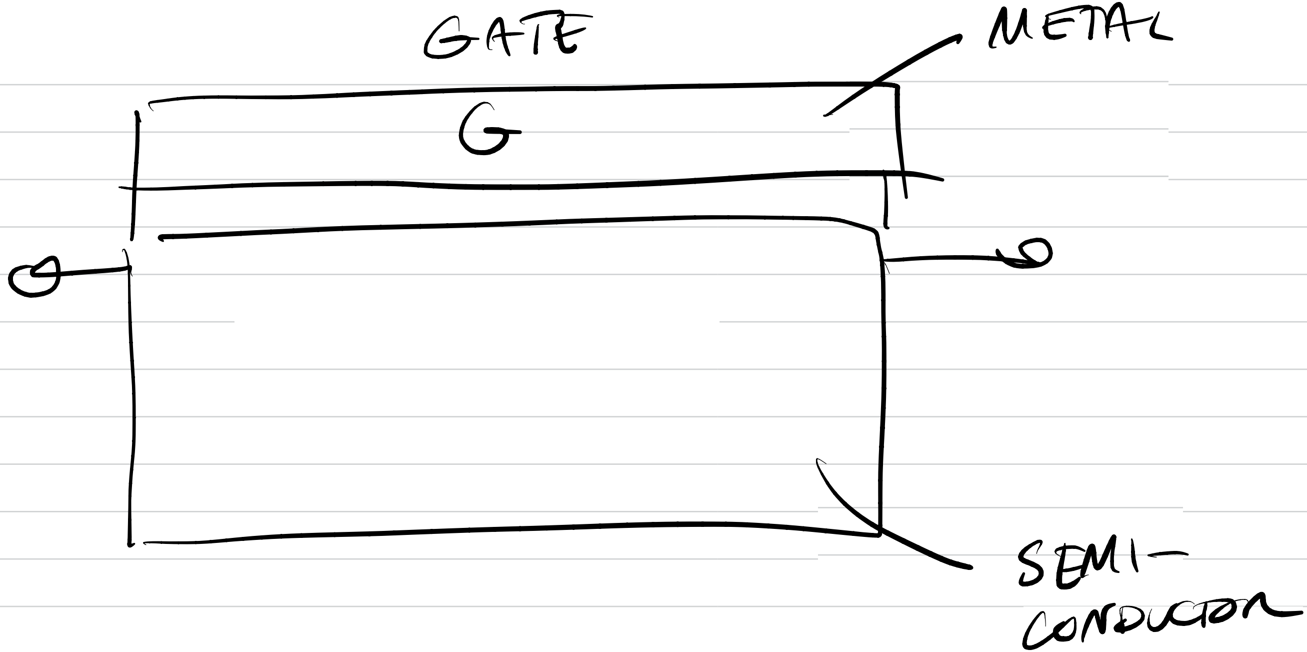


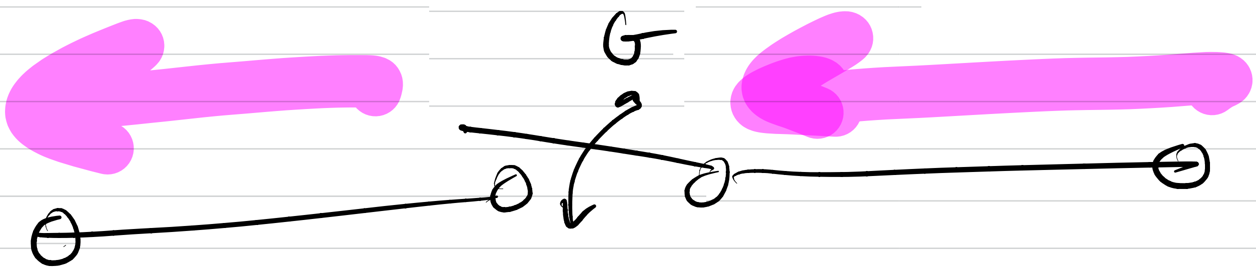
GATE

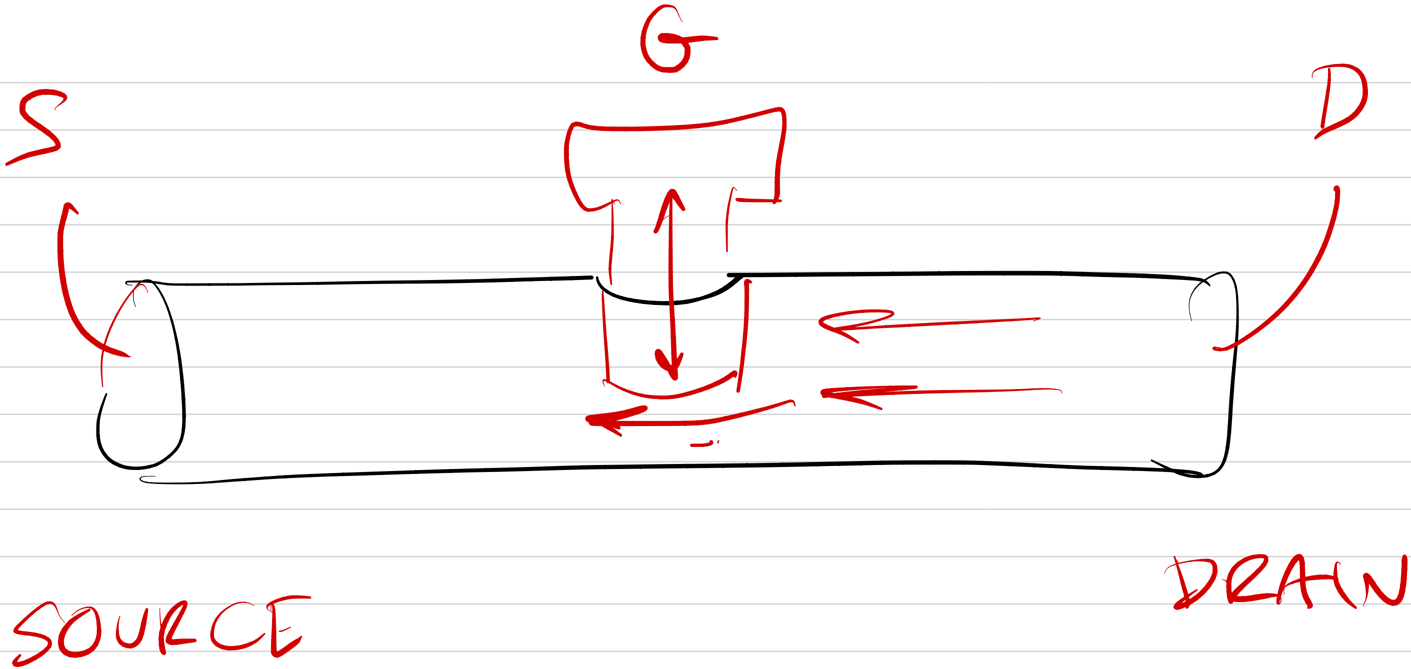


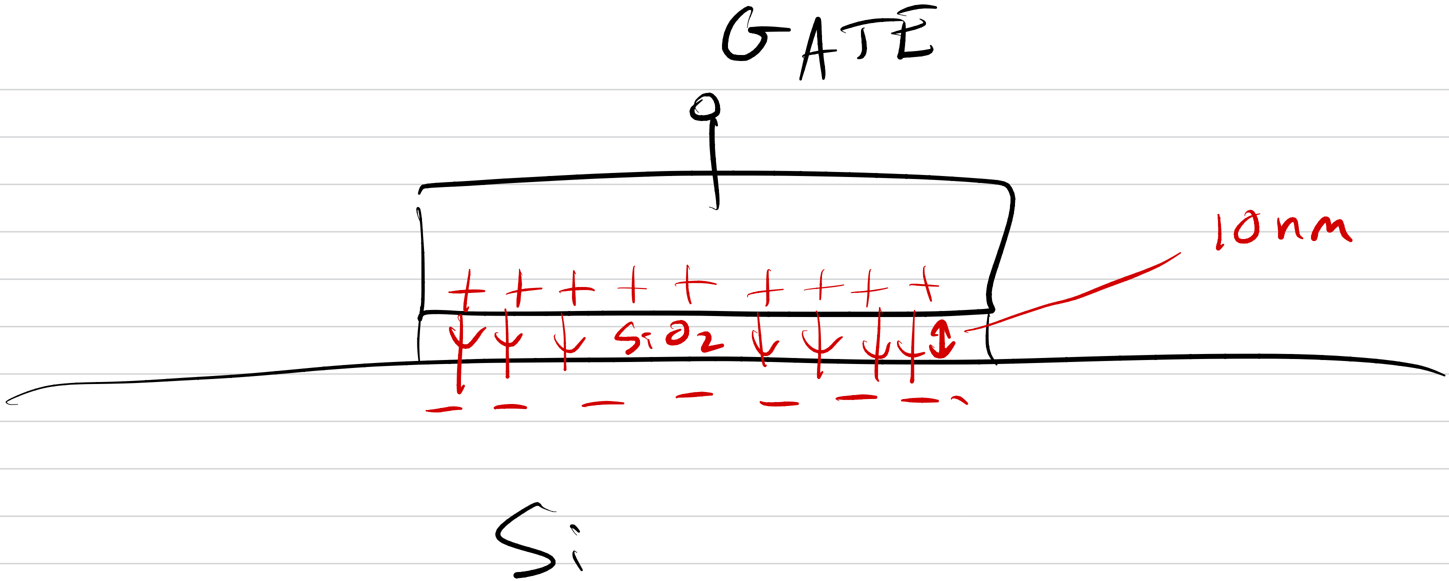
~~$Q = CV$~~

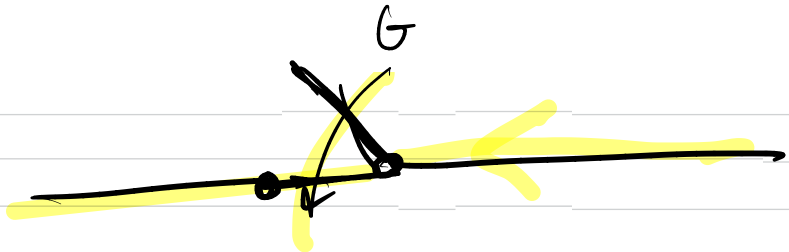
$Q = C(V - V_T)$ $\quad V > V_T$

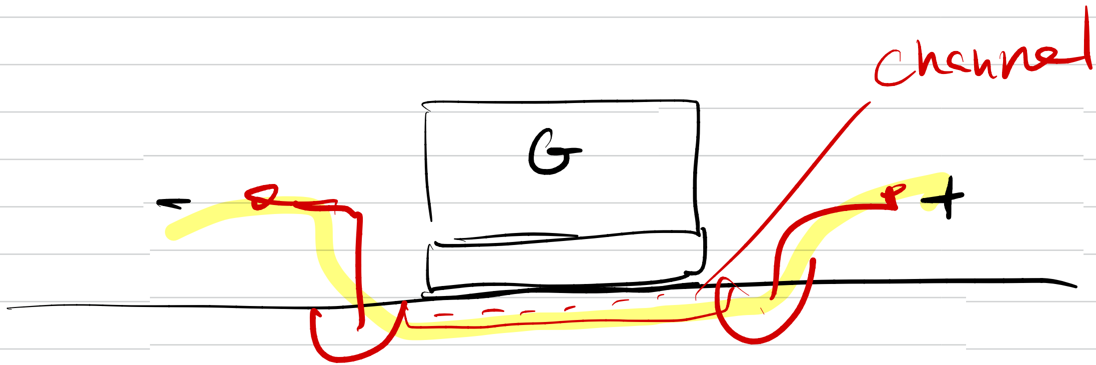

GATE
METAL
G
SEMI-
CONDUCTOR


G

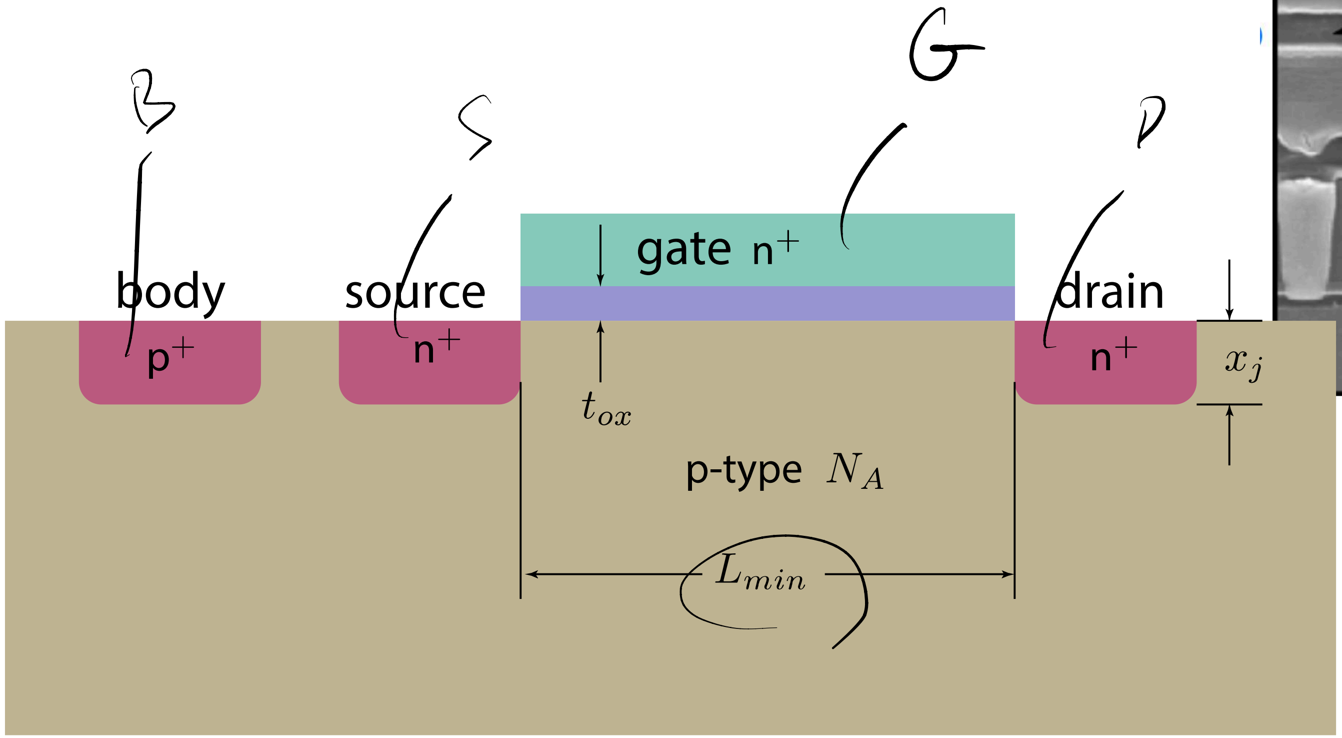

G
S
D
SOURCE
DRAIN

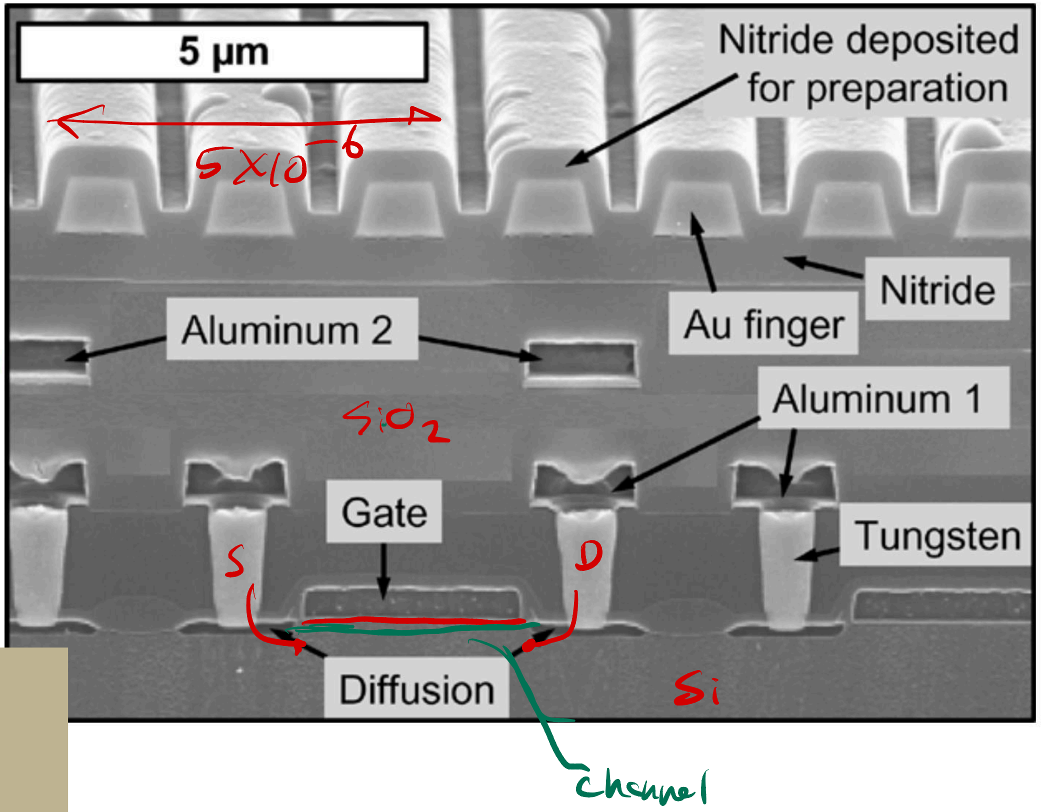

GATE
10nm
SiO_2
Si

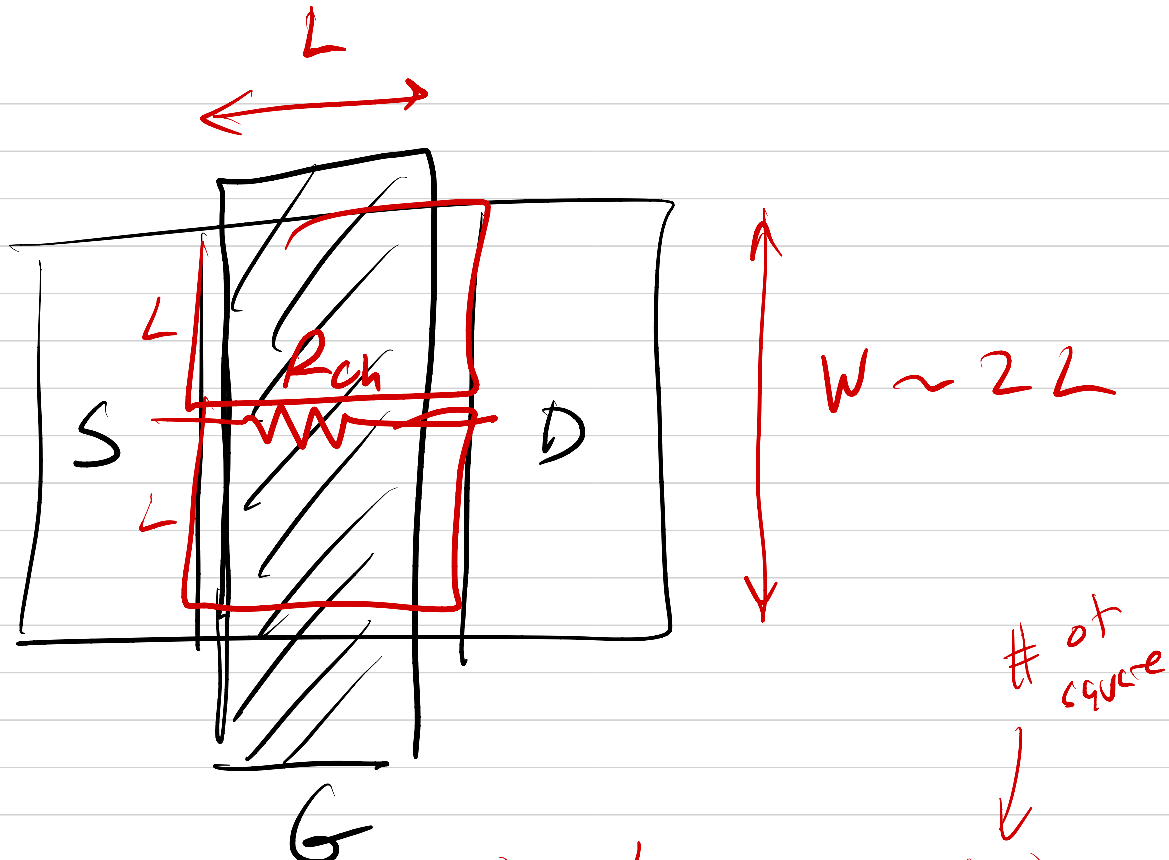

G


channel
G
-
+

Preview: Transistor

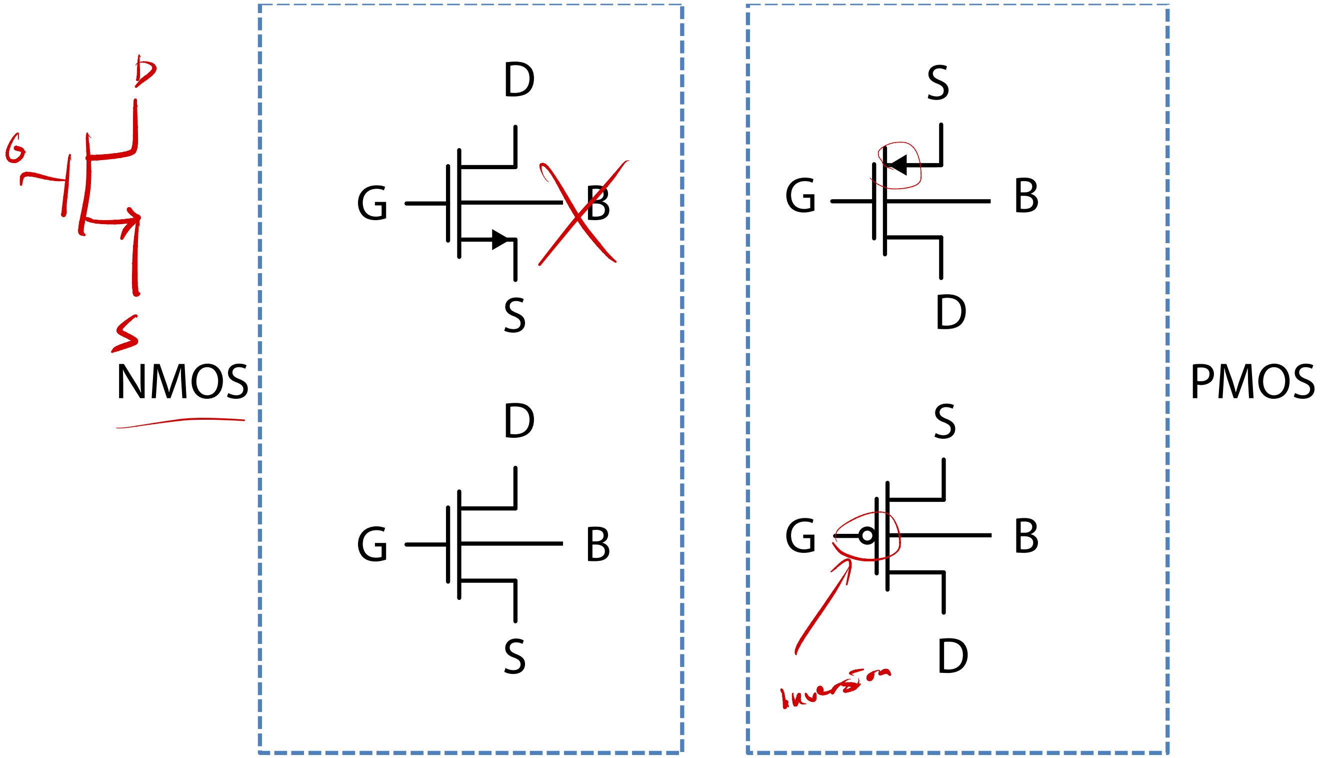






$$R_{ch} = \rho \frac{L}{W \cdot t} = \left(\frac{\rho}{t}\right) \frac{L}{W} = R_{\square} \left(\frac{L}{W}\right)$$

MOS Transistor Schematic



Toy Physical Model of Transistor

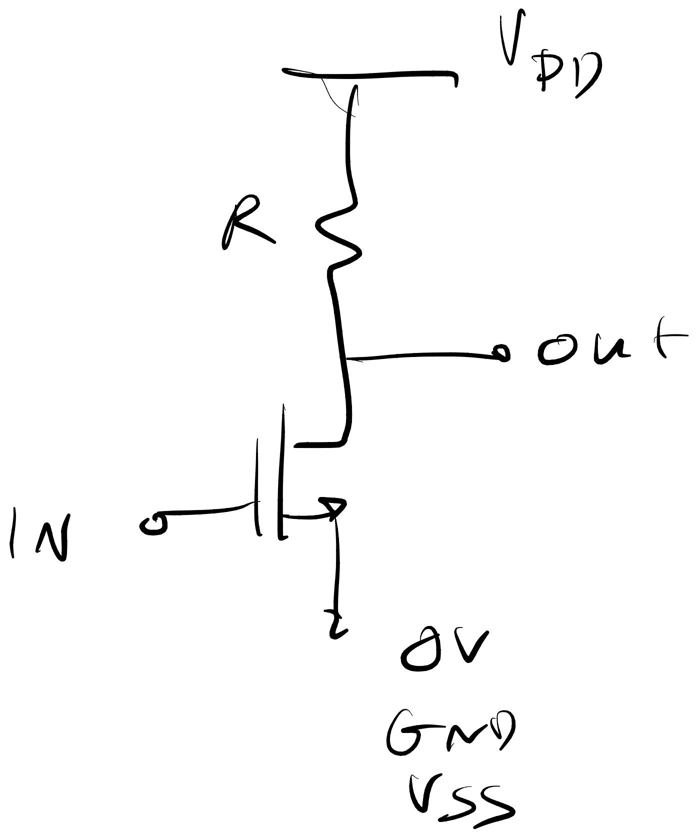
- If we charge up the MOS capacitor, we create a channel that allows current to flow from the source to drain (electron flow)
- If the voltage at the gate is not sufficient to pass a threshold, the path is too resistive and we model it as an open circuit.

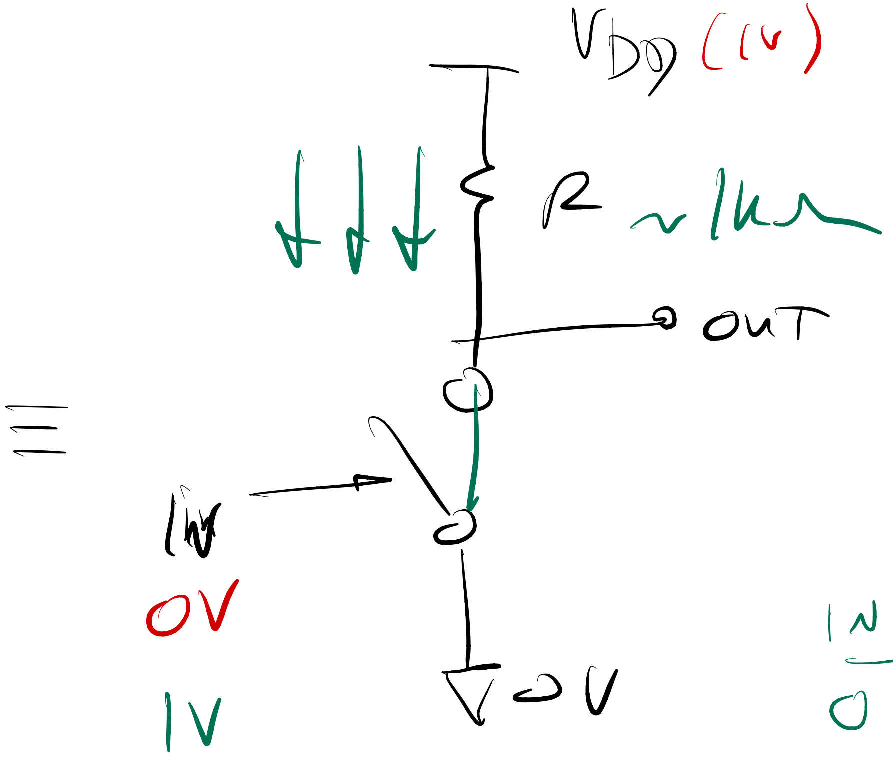
Transistors Have Polarity

- You can build two kinds of transistors, ones that use electron flow to establish current and another that uses “holes” (positive charges with about twice the mass of electrons).
- Holes are legitimate quasi-particles that represent electrons moving among the various bonding states (valence band) in a crystal

Complementary is a compliment !

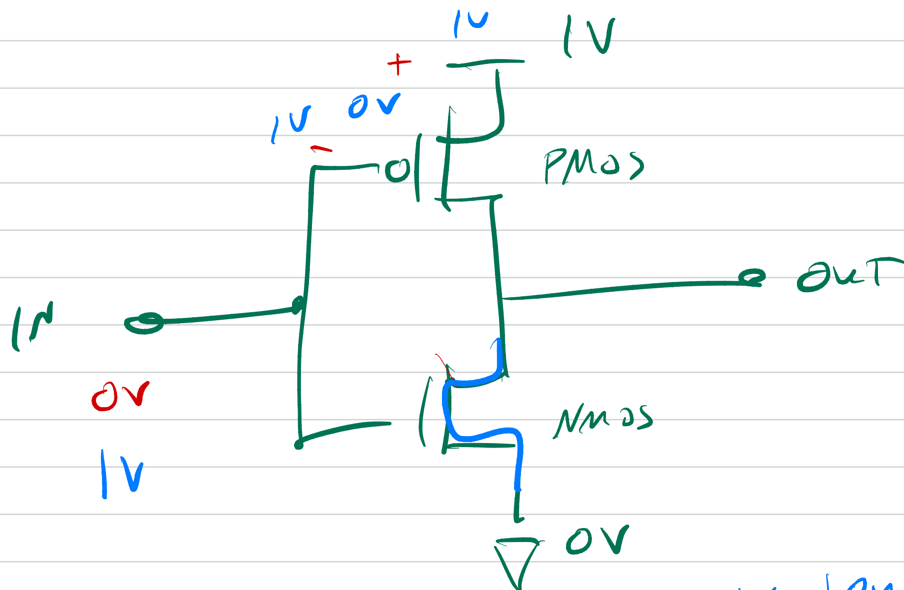
- NMOS + R versus CMOS power consumption

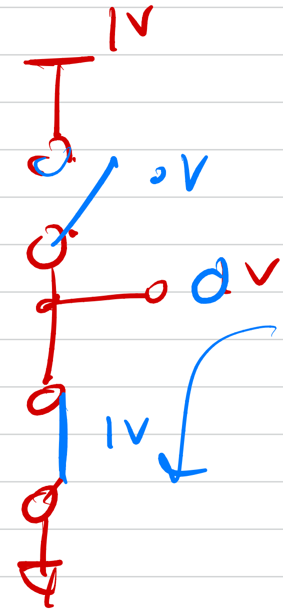


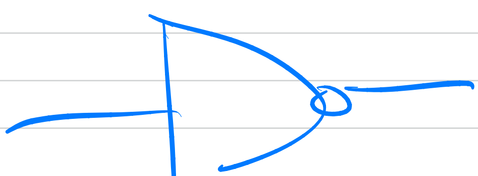


IN	OUT
0	1
1	0

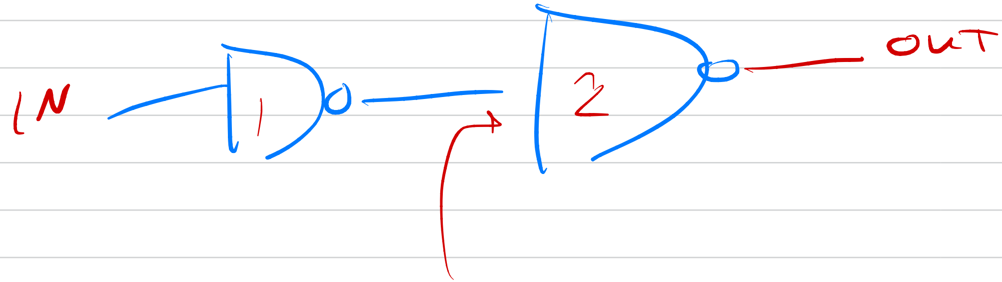
NMOS + PMOS = CMOS



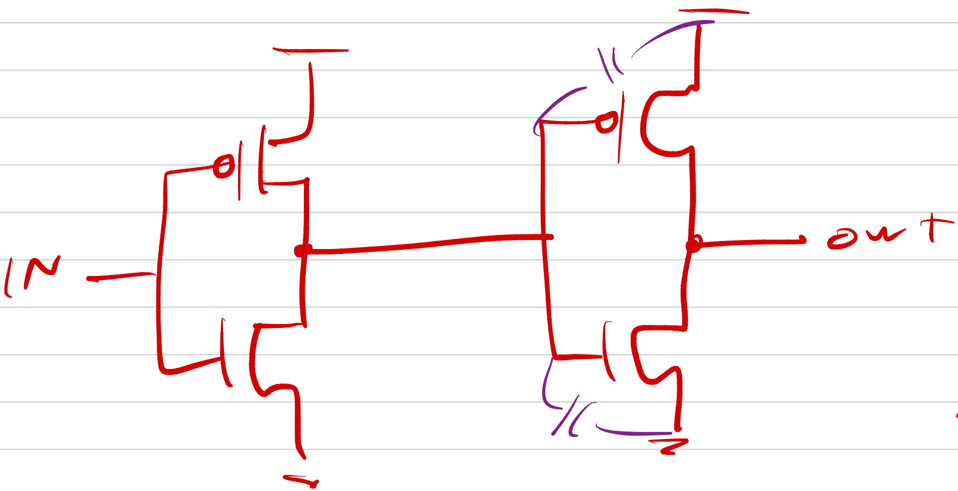


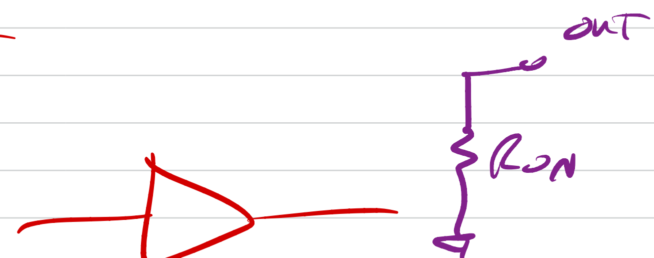


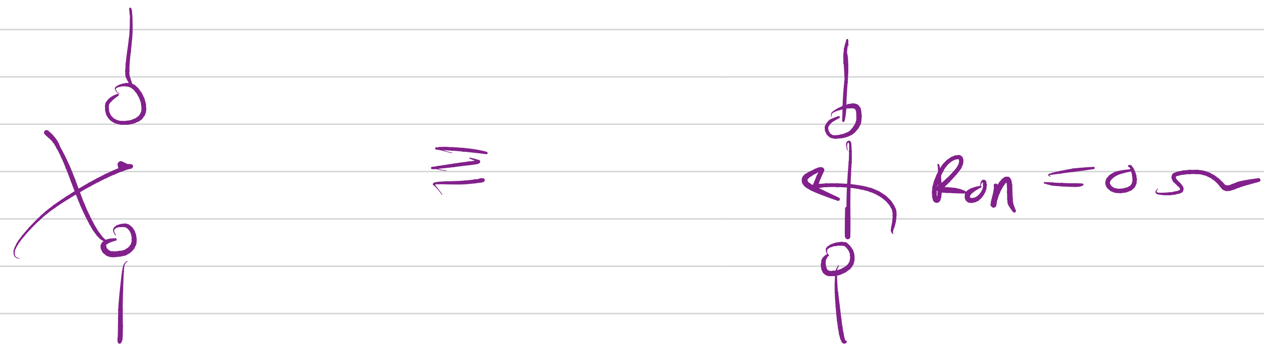
IN	out
0	1
1	0

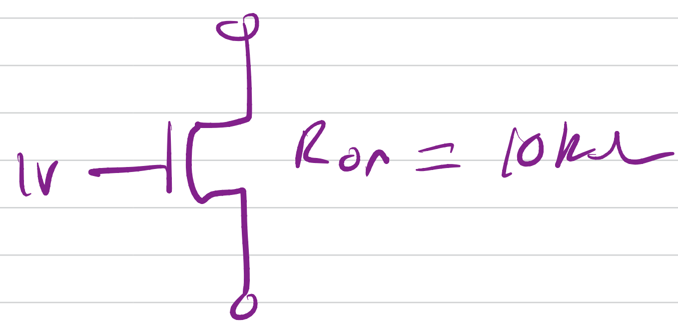


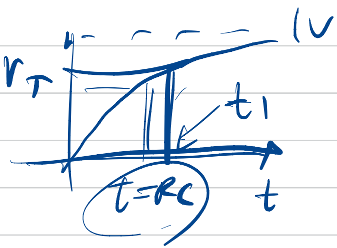
IN	OUT
0	0
1	1

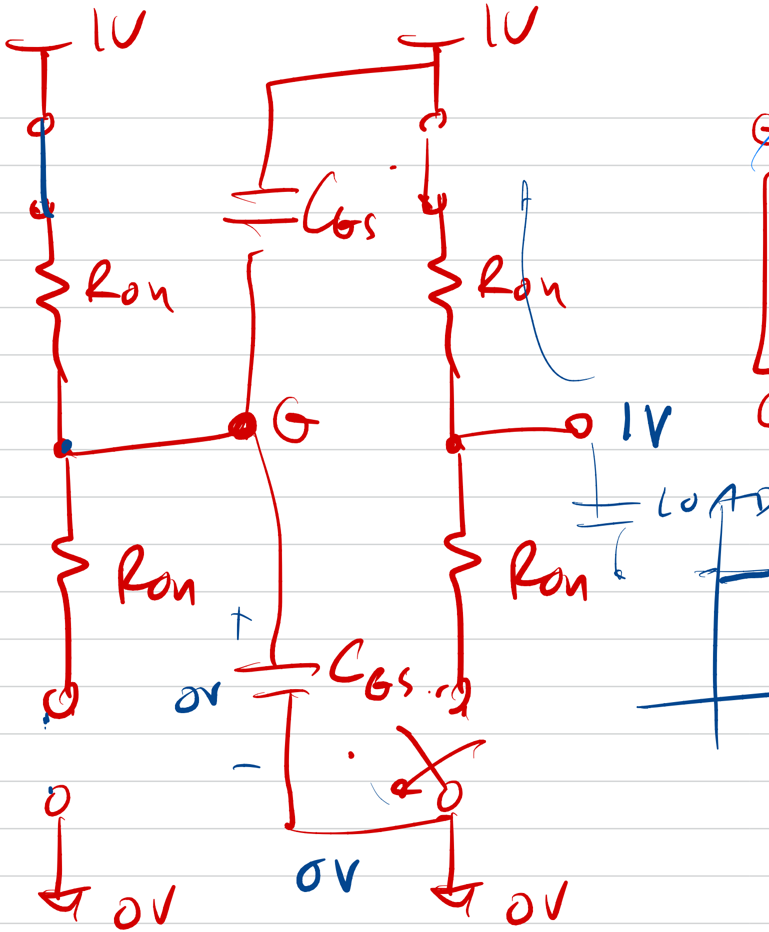


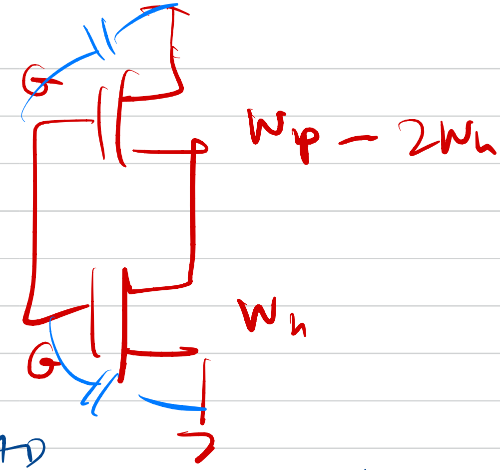


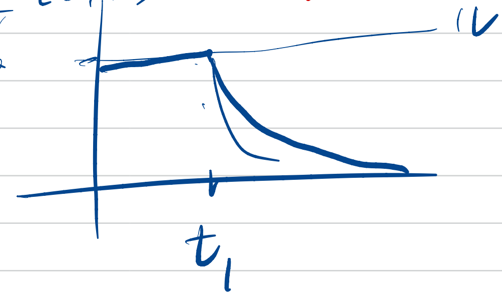

≡
Ron = 0Ω


1V
Ron = 10kΩ

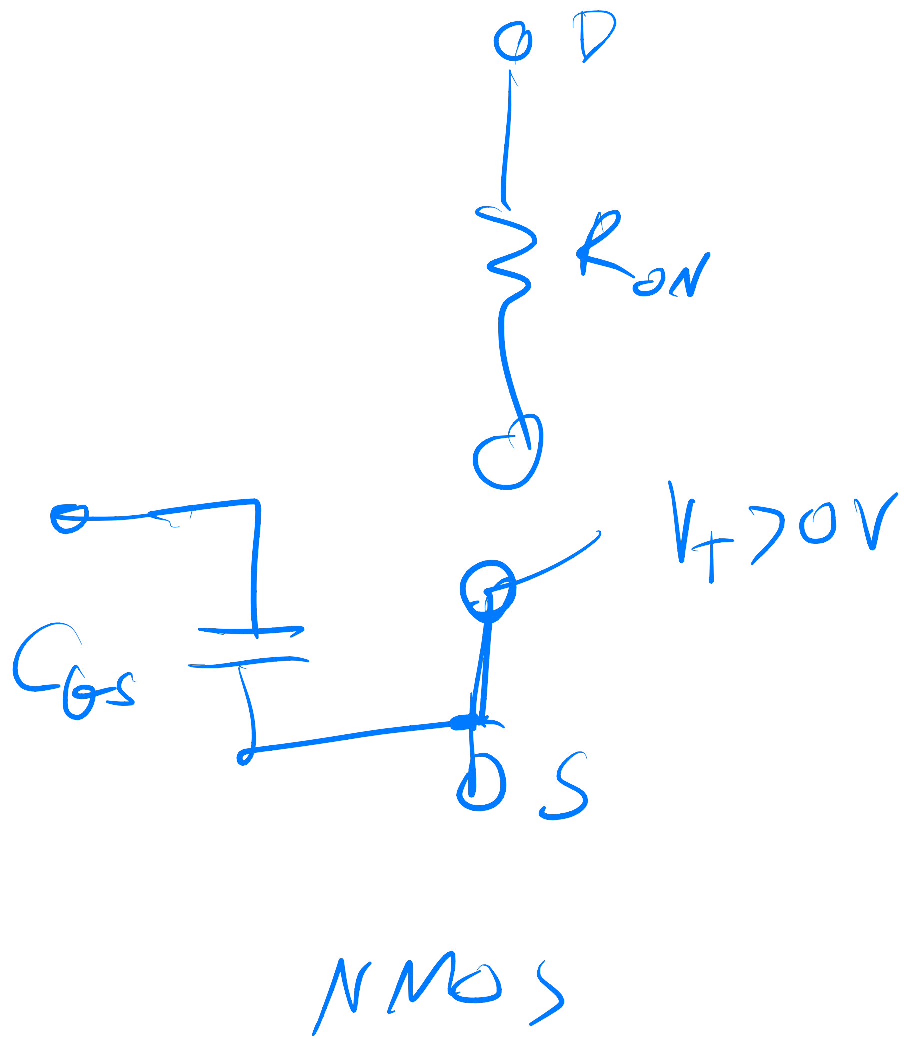

1V
t1
t=RC
t

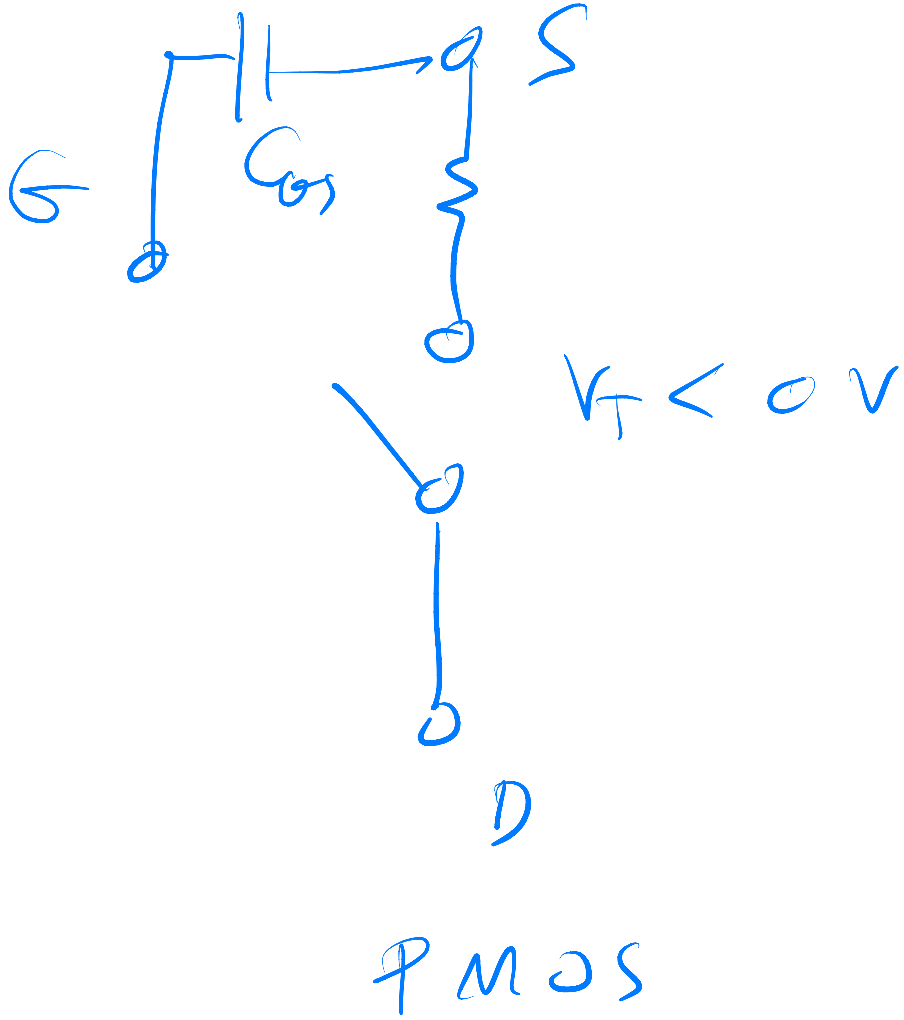

1V
1V
Ron
Ron
CGS
G
1V
Ron
Ron
CGS
0V
0V
0V
0V
LOAD

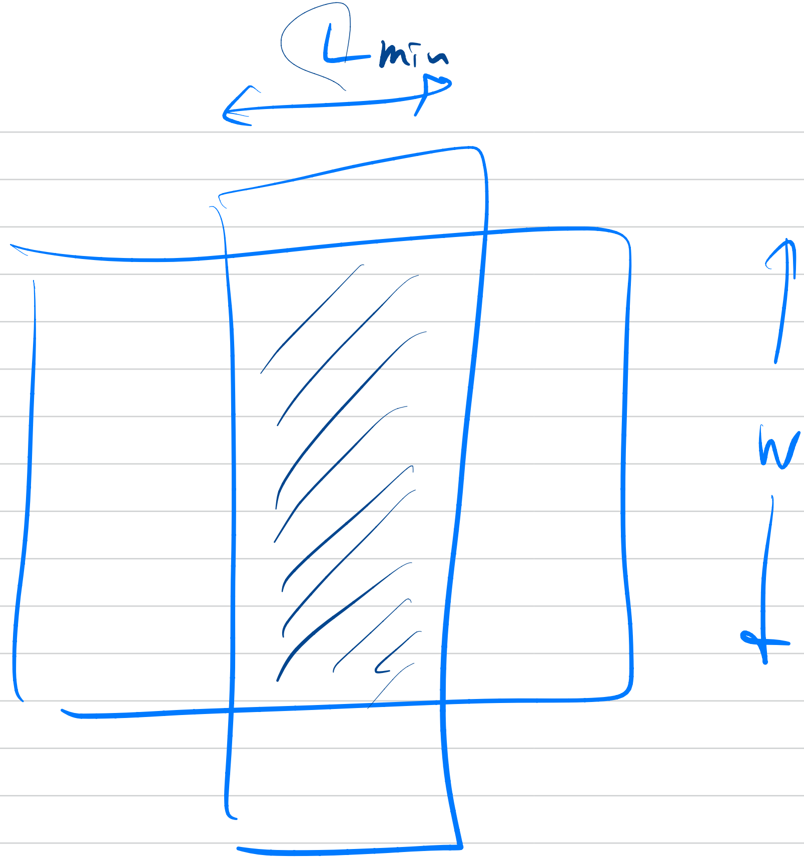

G
Wp - 2Wn
Wn
G


1V
t1

Transistor As Switch



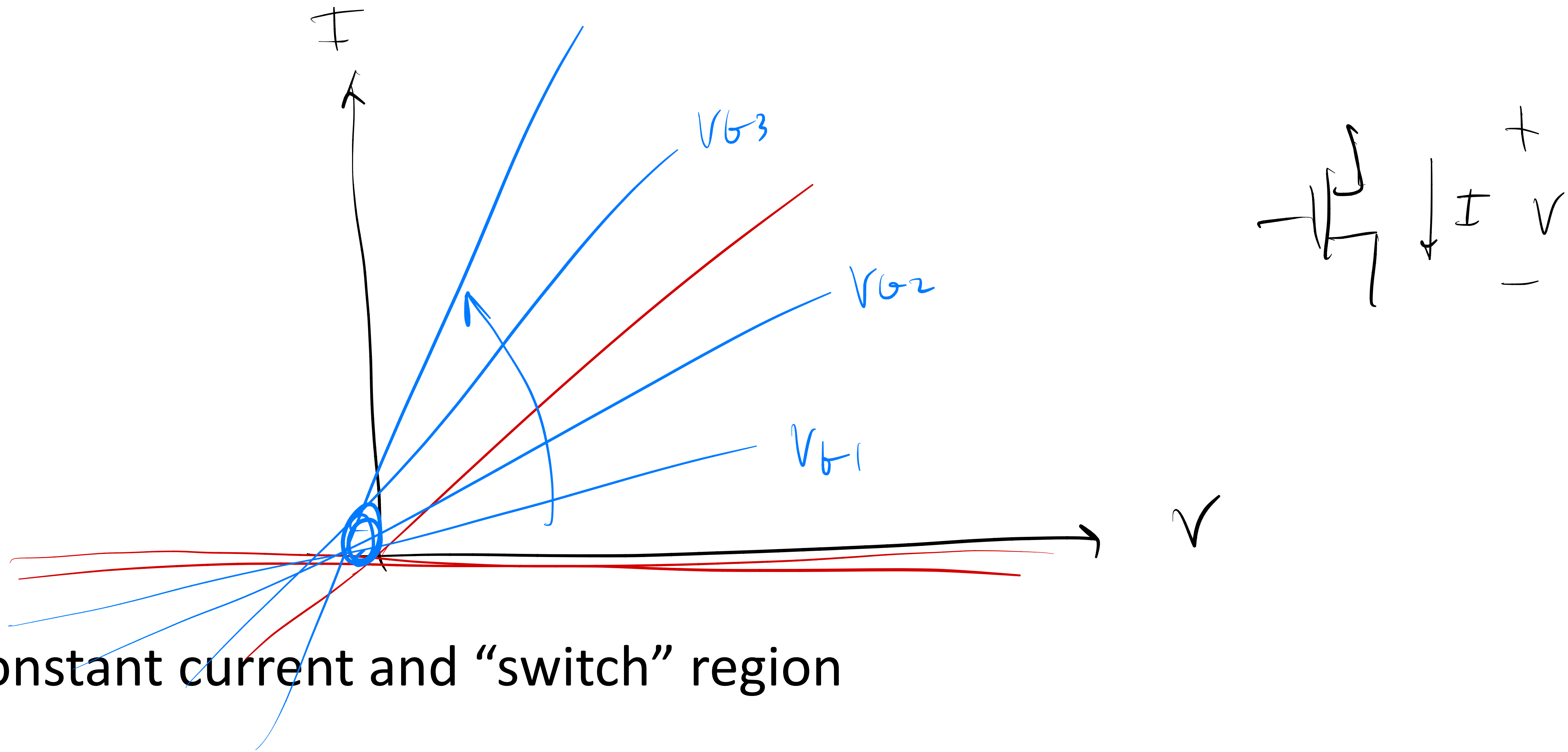




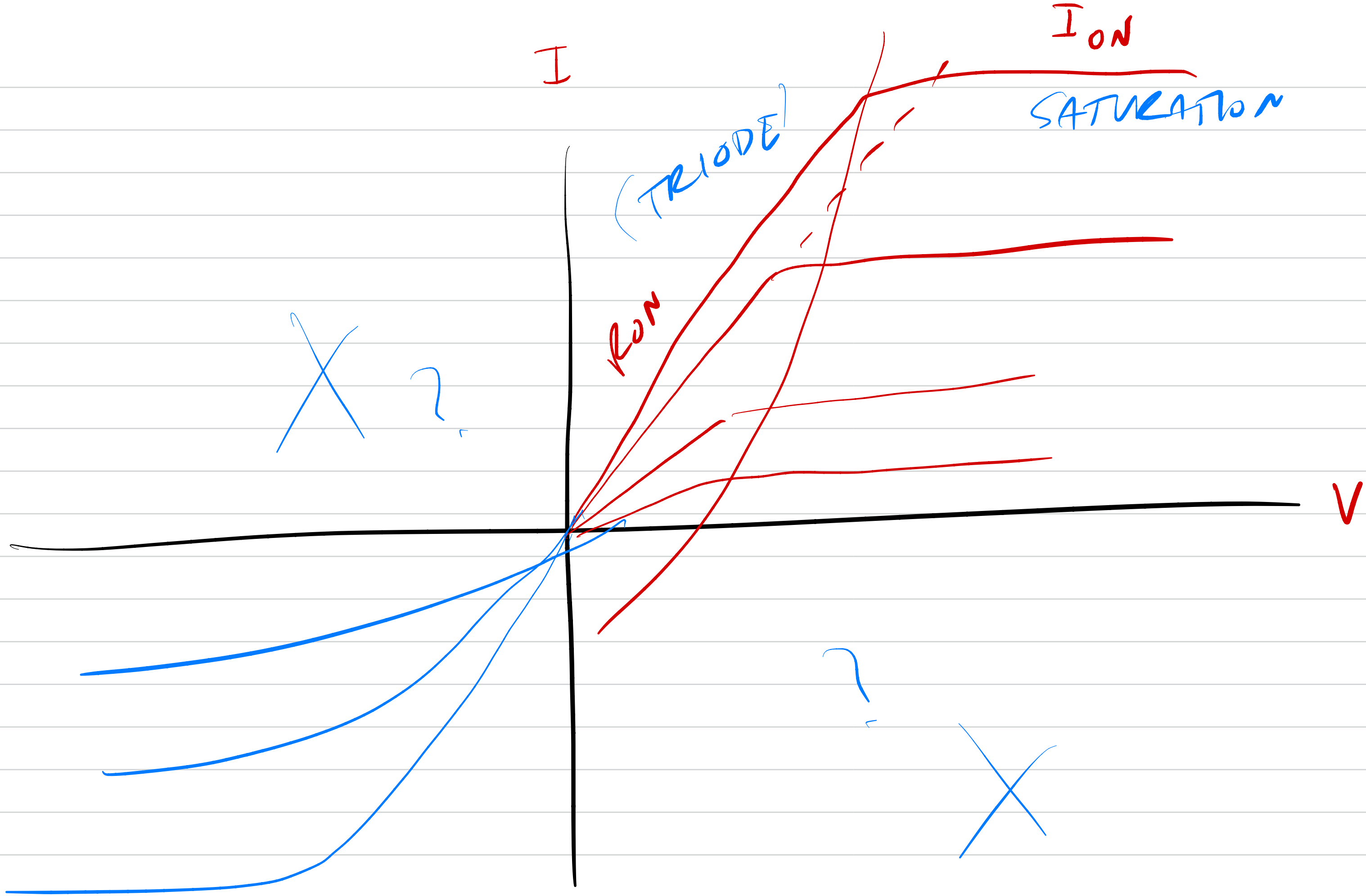
$$\tau = RC \propto \frac{L}{W} \cdot (W \times L)$$

$\uparrow$

Transistor I-V Curve



- Constant current and “switch” region


I
Ion
SATURATION
(TRIODE)
Ron
V
?
?

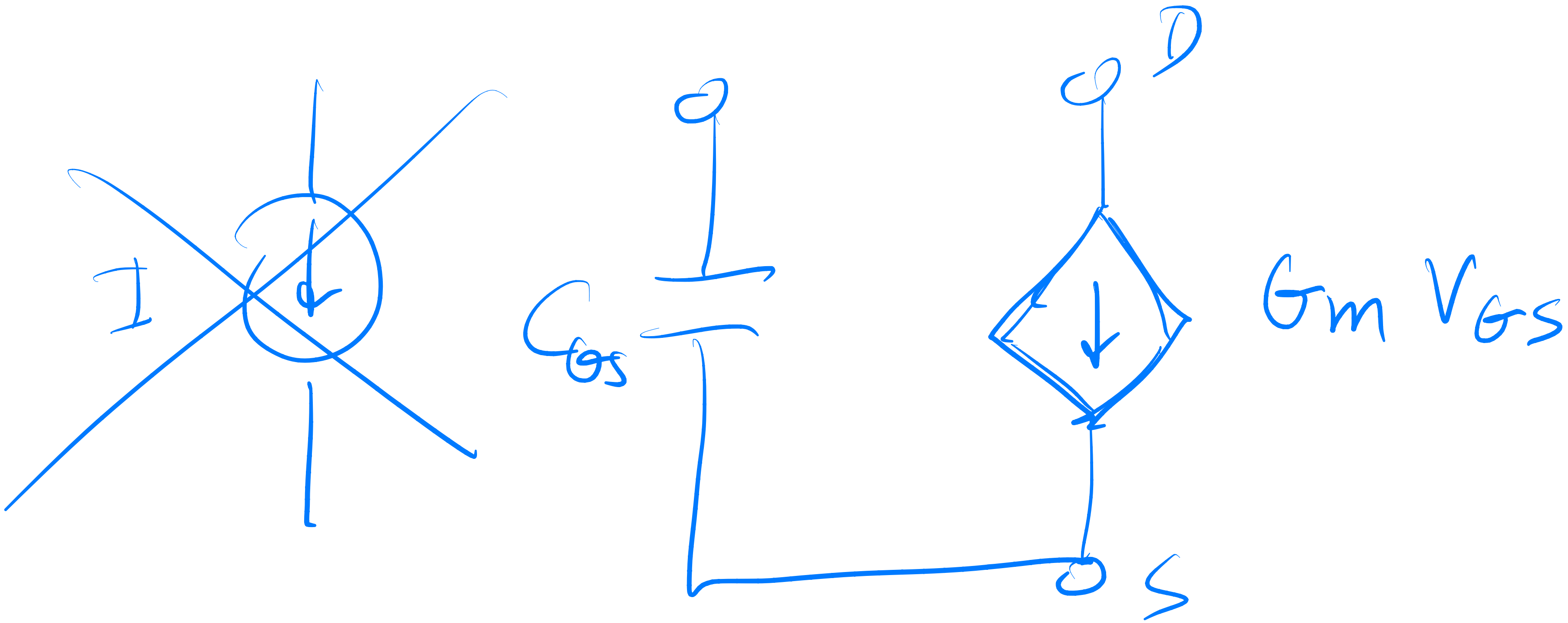
Switch On-Resistance

Switch Gate Capacitance

Switch Off Capacitance

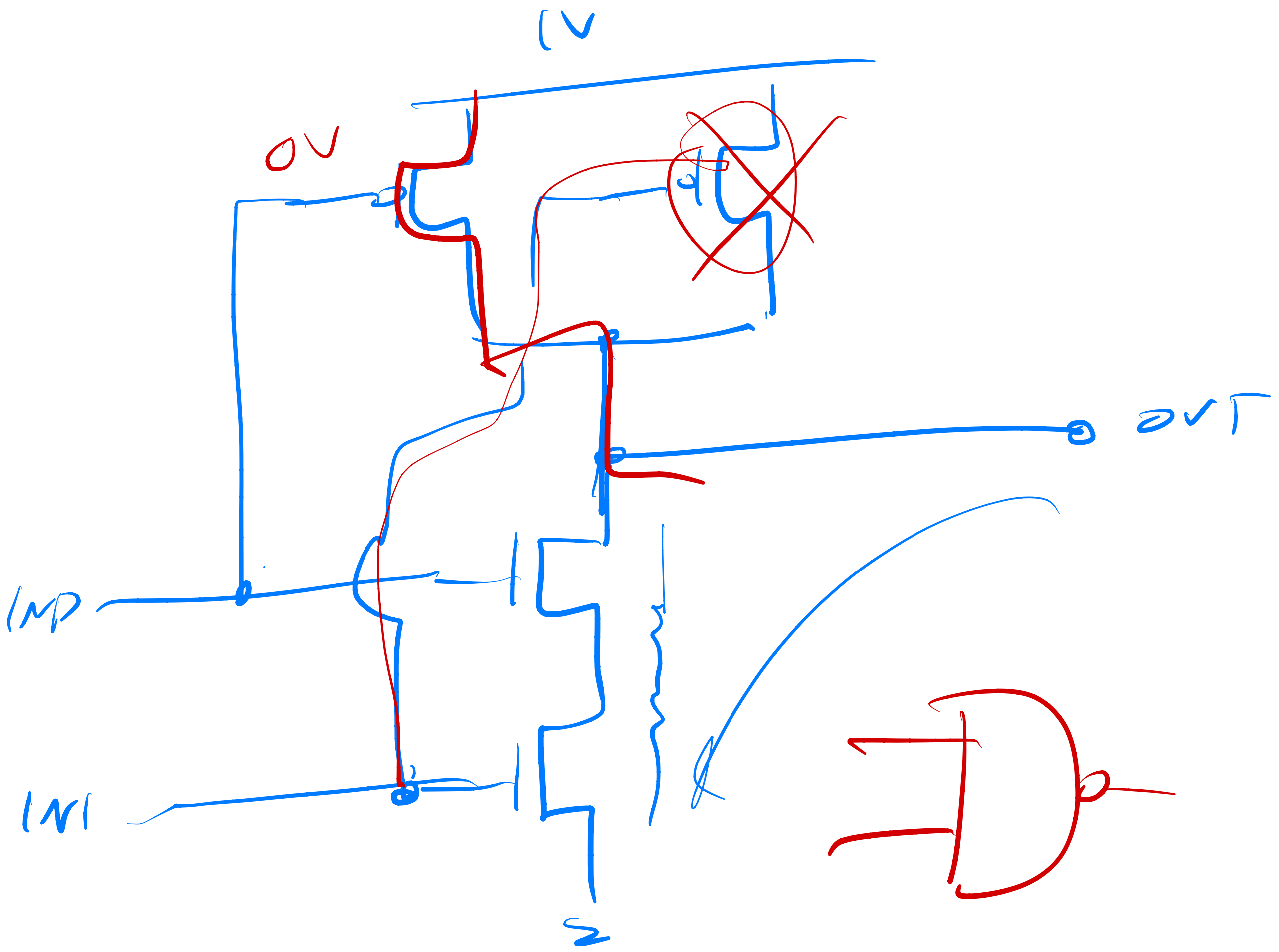
Transistor as a Transconductor

- The channel conductivity is modulated by the gate voltage.
- What's a circuit element that has this property?



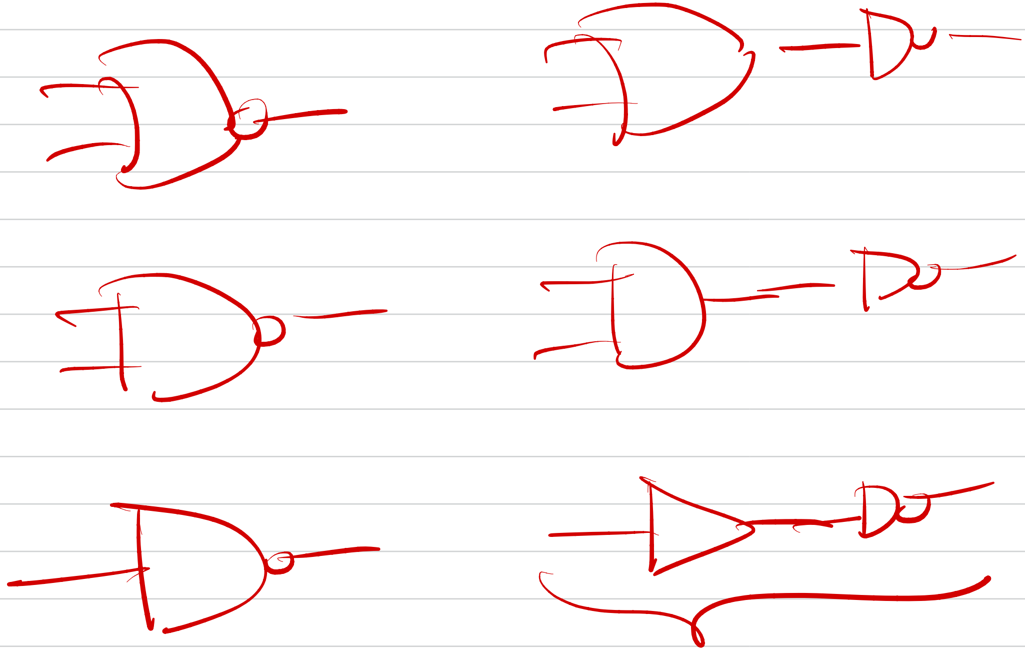
CMOS Inverter

Logic Gates

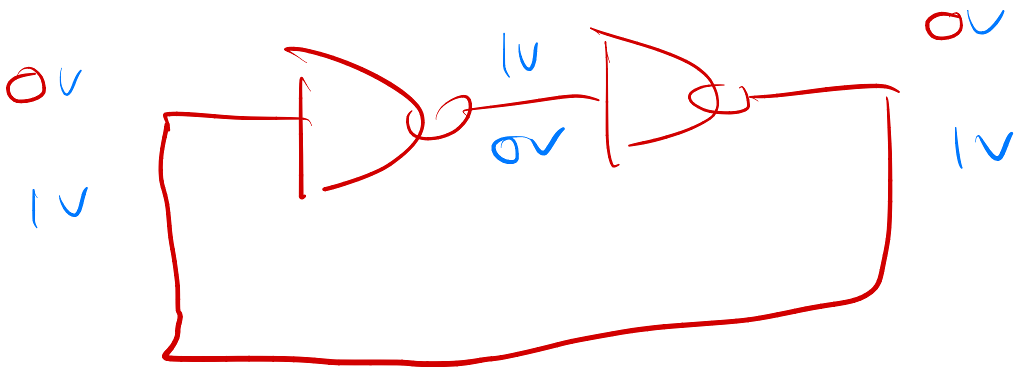


IN1	IN2	OUT
0	0	1
0	1	1
1	0	1
1	1	0

NAND GATE



Static RAM (SRAM)



BISTABLE

Ring Oscillator

Differential Equations for Inverter

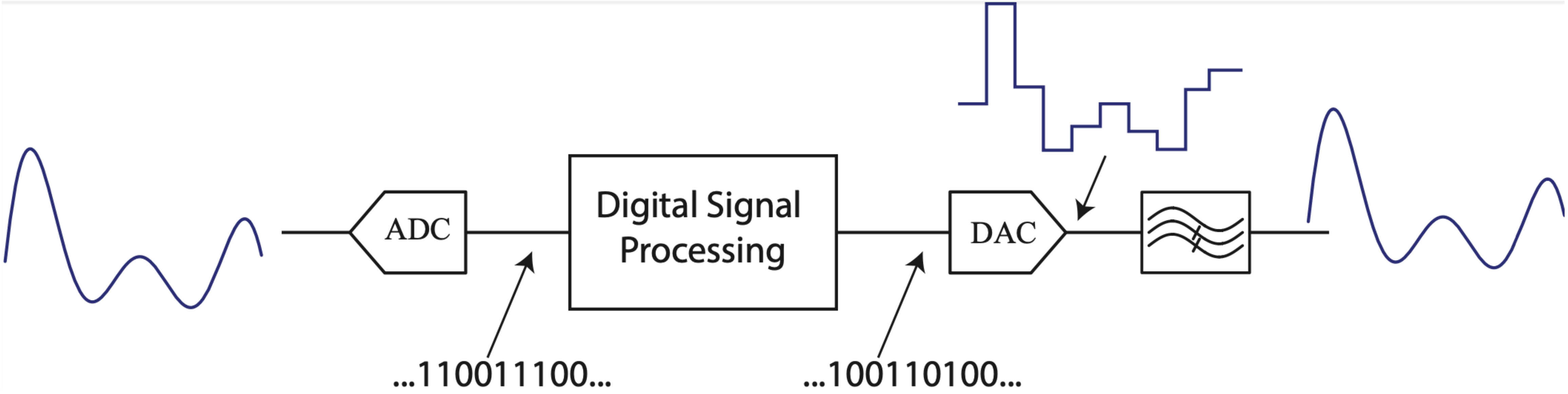
I-V Curve Again

Op-Amp Model with RC

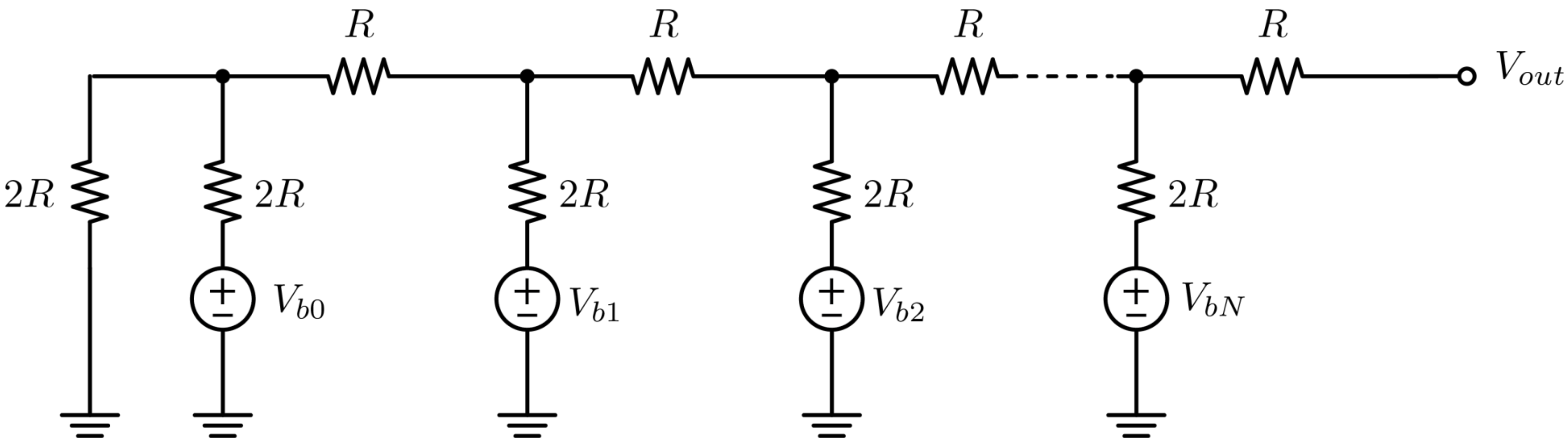
Amplifier Settling Time

Applications

ADCs and DACs



R-2R Ladder Digital-to-Analog Converter

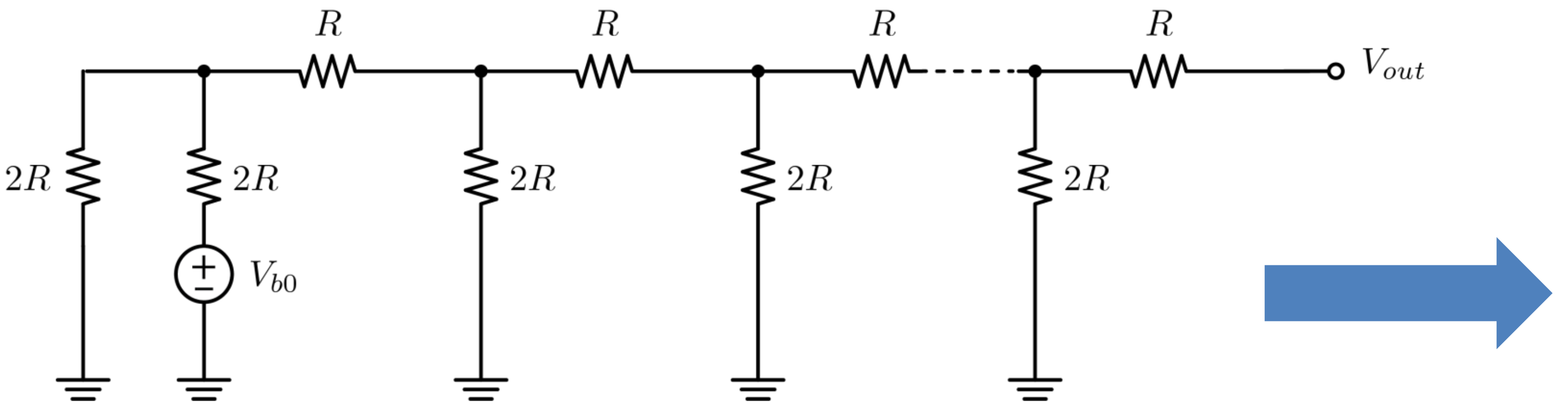


How to set all these "digital" voltages?

Remember Superposition and Equivalence?

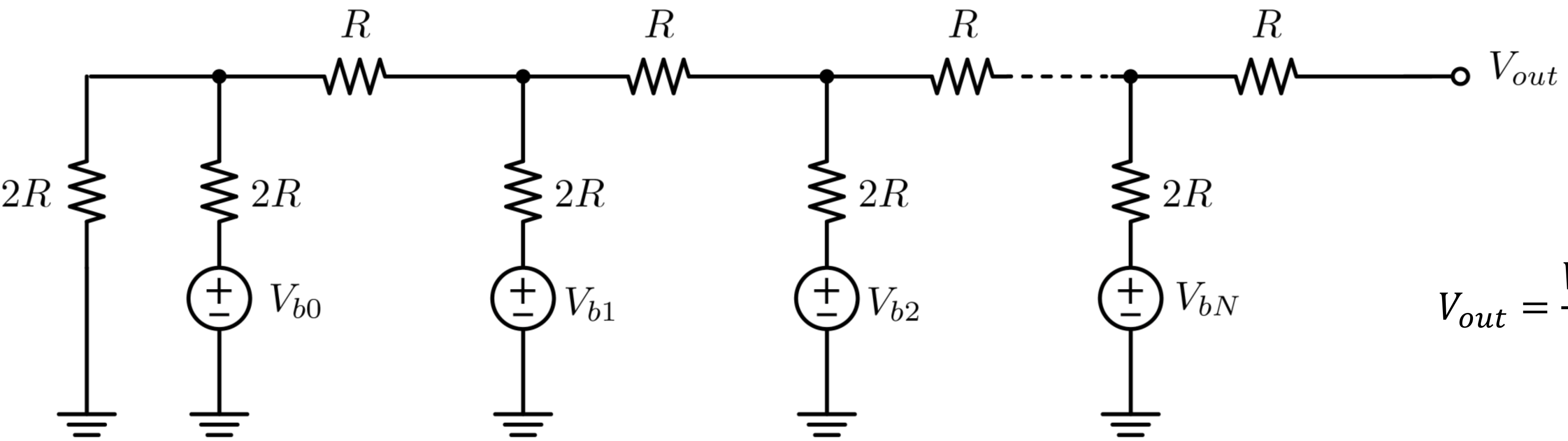
R-2R Ladder Digital-to-Analog Converter

Use superposition: Start with first voltage source:



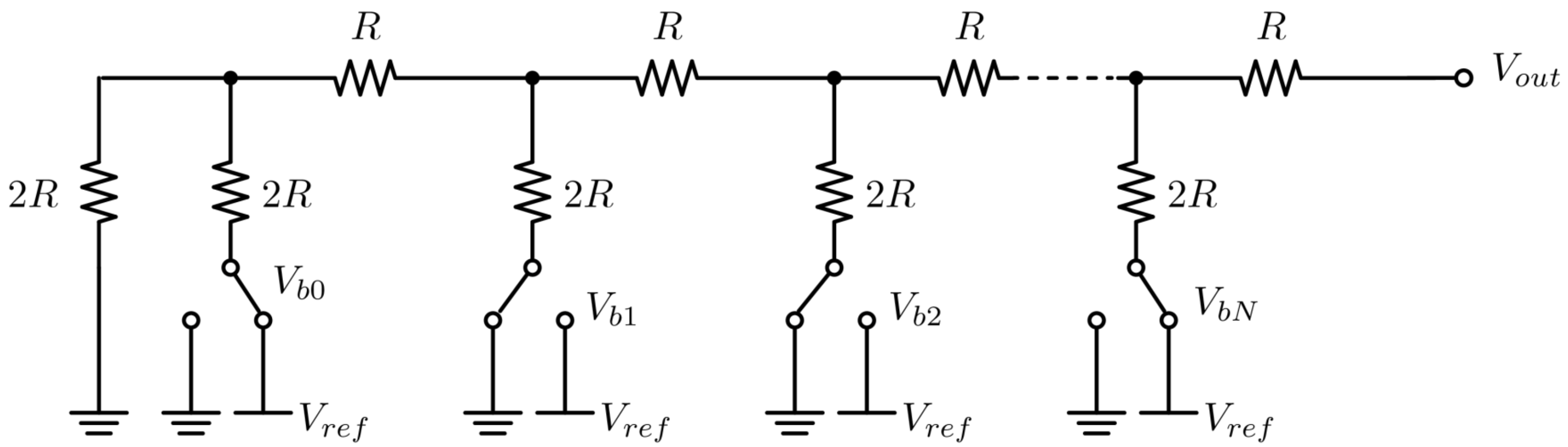
R-2R Ladder Digital-to-Analog Converter

Adding all contributions from the sources



$$V_{out} = \frac{V_{b0}}{2^N} + \frac{V_{b1}}{2^{N-1}} + \cdots + \frac{V_{bN}}{2}$$

Switches

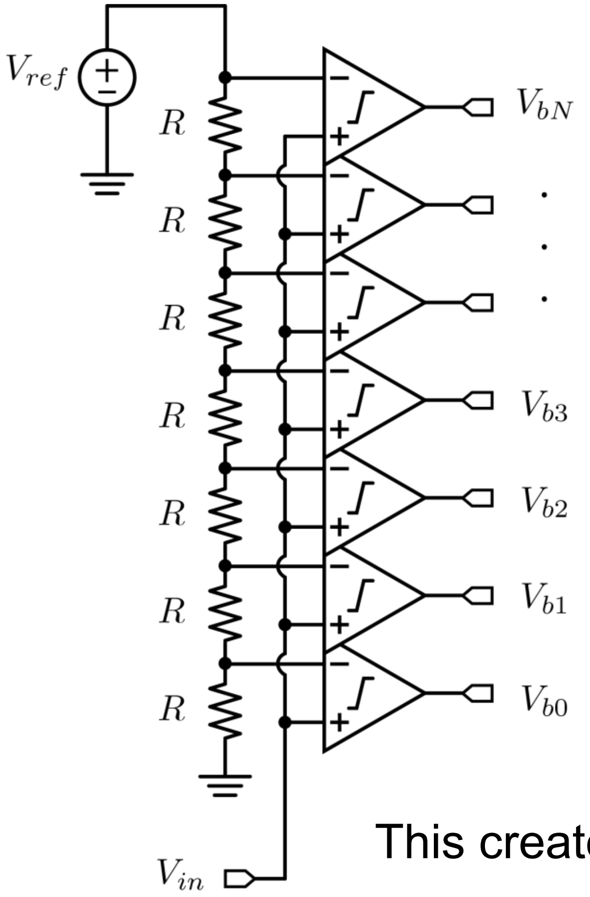


CMOS Gates

How fast can we "convert"?

- If there were no capacitors, we could do it instantly !

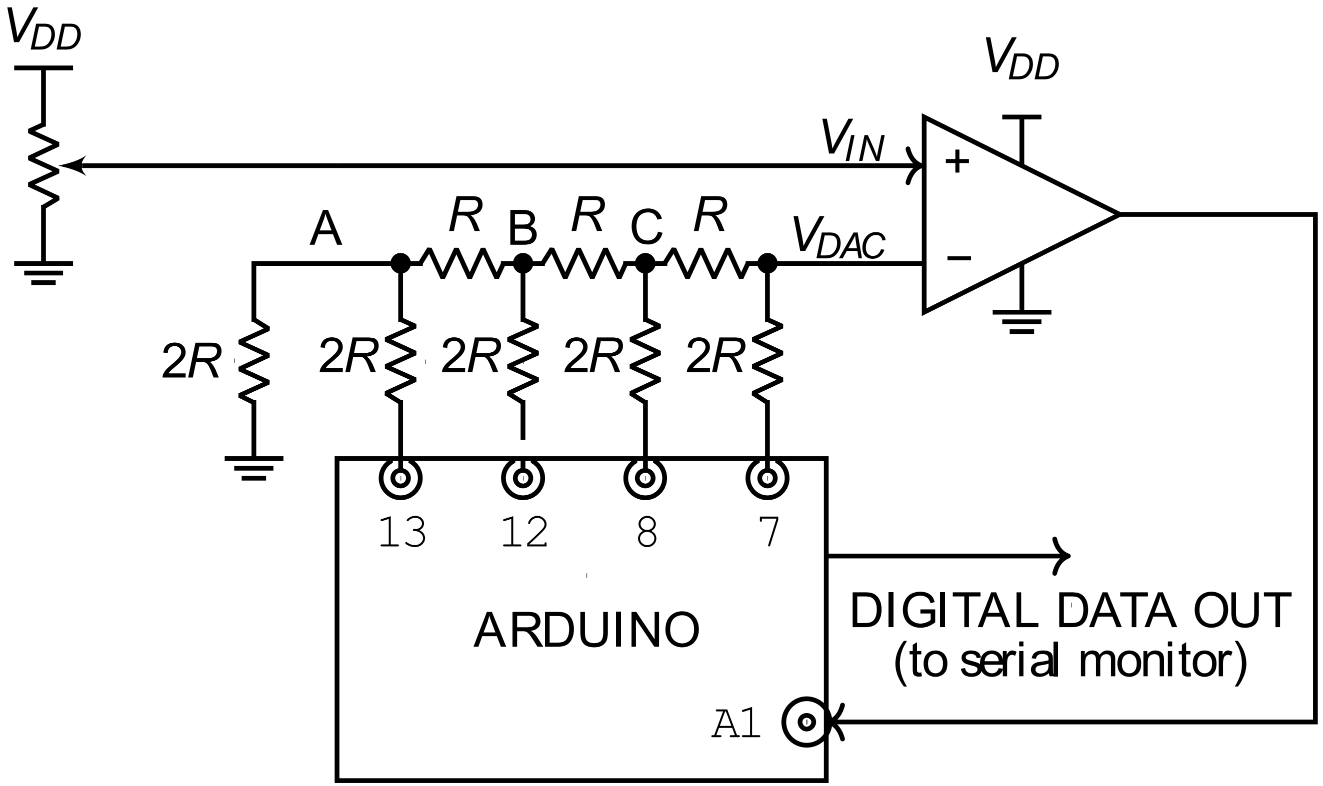
Analog to Digital Conversion



- Very fast massively parallel architecture
- Requires 2^N comparators (specialized op-amps)
- Op-amps have input capacitance
- Power consumption is high for fast operation

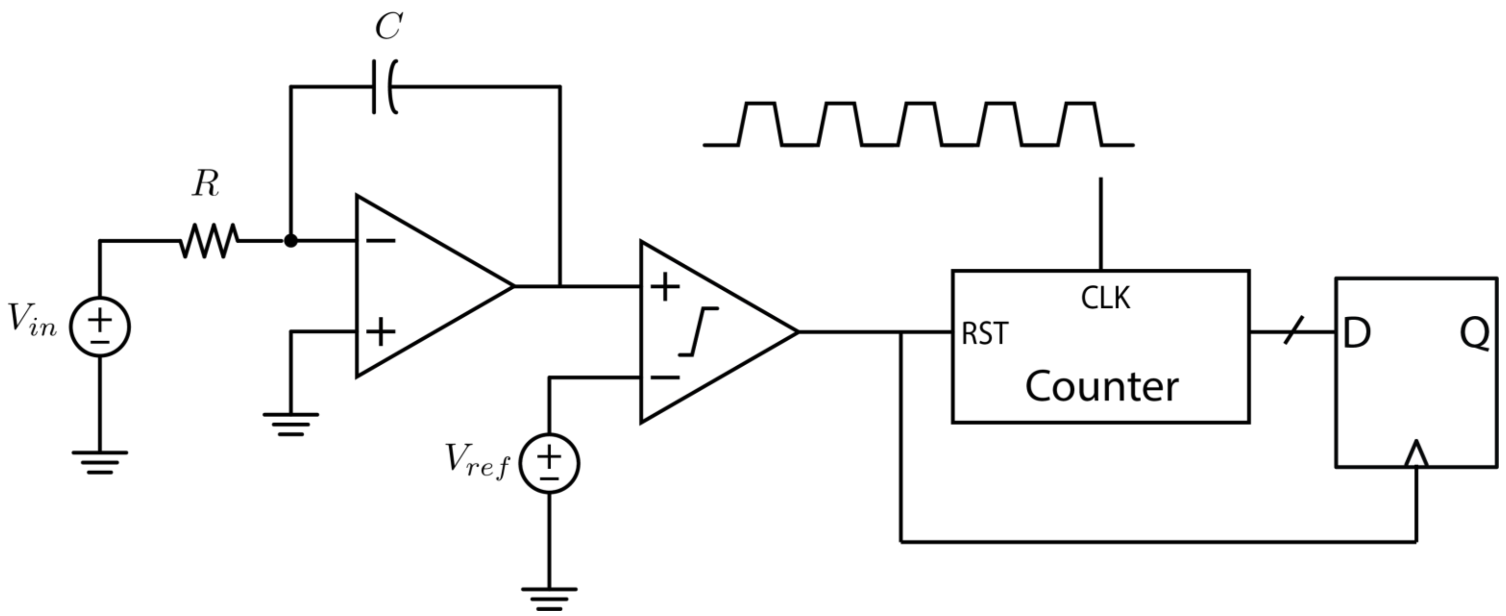
This creates a “Thermometer” digital code. Need to convert to binary for most applications:

Lab 2: SAR (Successive Approximation Resistor) ADC



- Use a DAC to guess signal and find best digital representation
- Can do this in log(N) steps ("guessing game")

RC Integrator Idea



- RC + op-amp creates a ramp with slope proportional to input
- Count how long it takes to reach a reference value
- Counter is digital representation