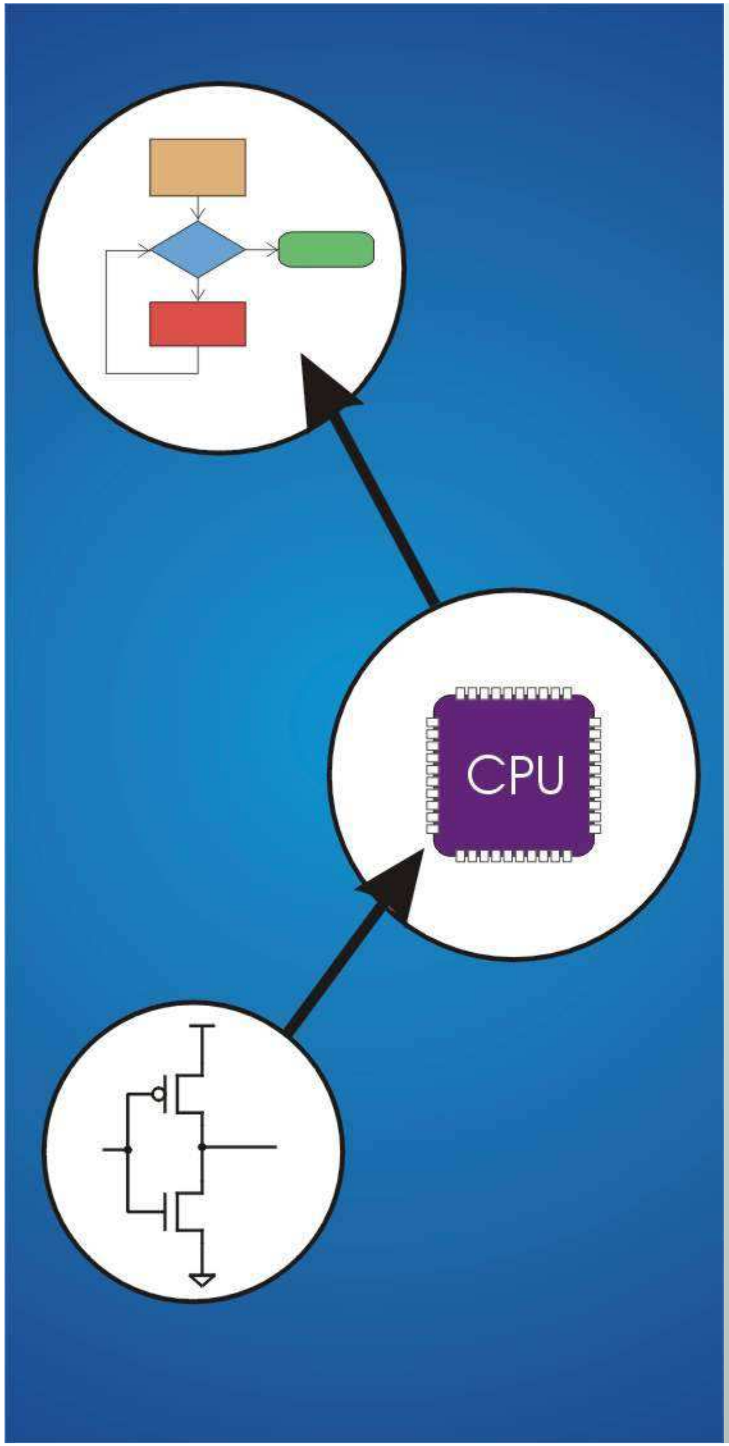
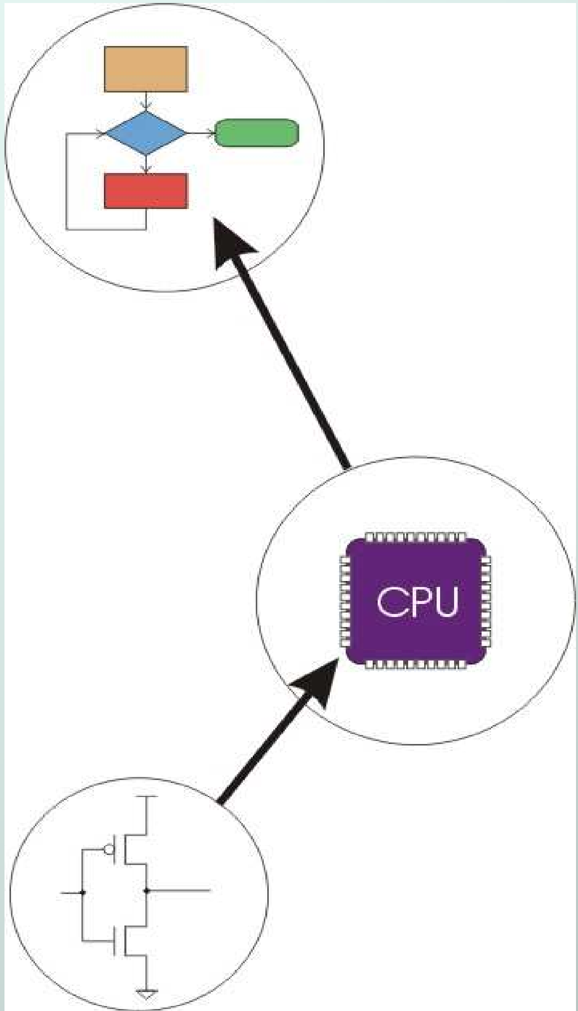


Chapter 3
Digital Logic Structures

Original slides from Gregory Byrd, North Carolina State University

Modified by C. Wilcox, Y. Malaiya
Colorado State University

Computing Layers



Problems

Algorithms

Language

Instruction Set Architecture

Microarchitecture

Circuits

Devices ←

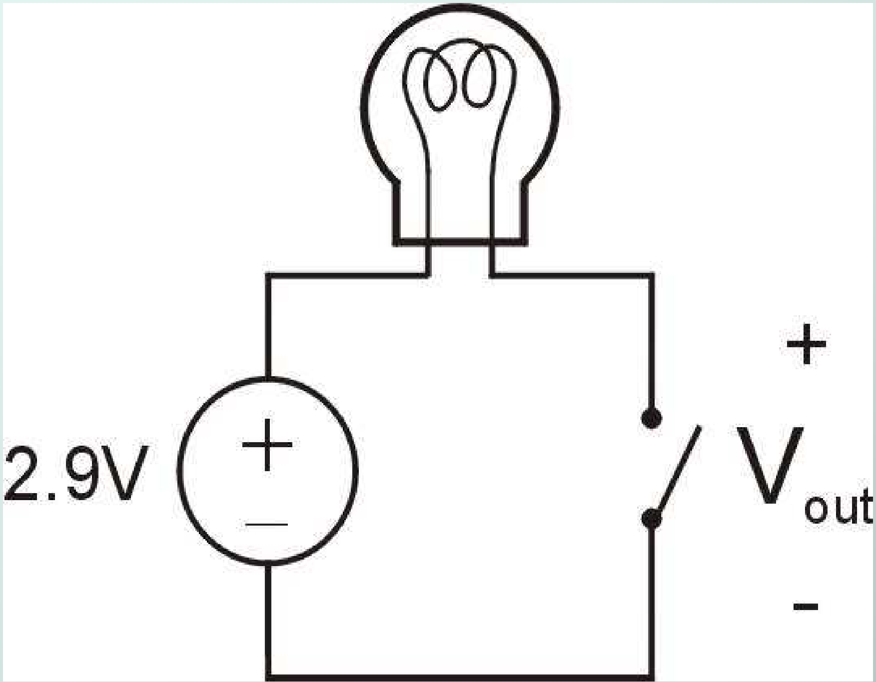
Transistor: Building Block of Computers

- Microprocessors contain millions of transistors
  - **Intel Pentium 4 (2000):** 48 million
  - **Intel Ivy Bridge-HE-4 (2011):** 1.4 Billion

Logically, each transistor acts as a switch

- Combined to implement logic functions (gates)
  - AND, OR, NOT
- Combined to build higher-level structures
  - Adder, multiplexer, decoder, register, …
- Combined to build processor
  - LC-3

Simple Switch Circuit

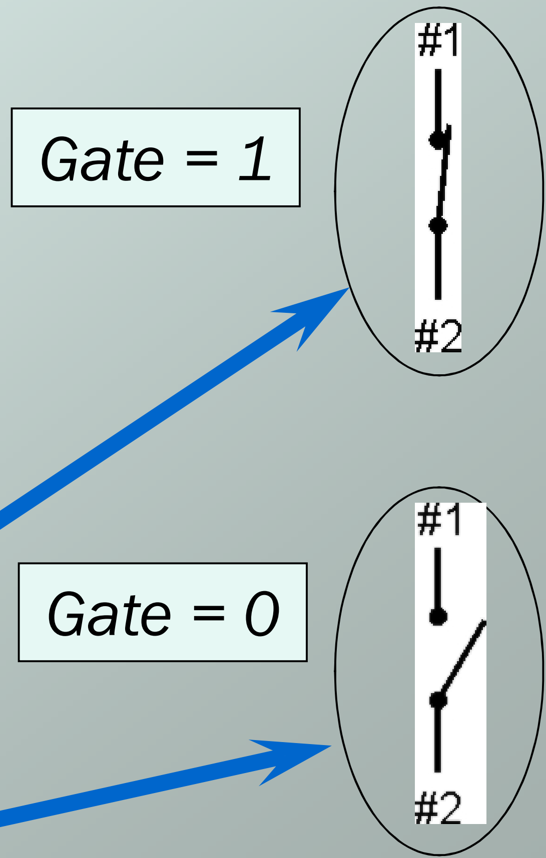


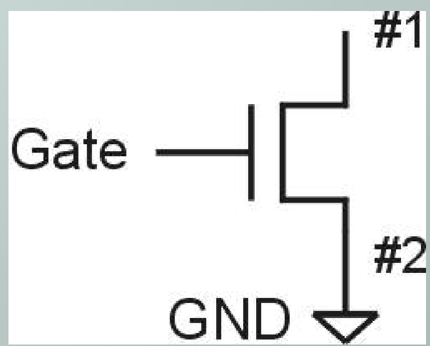
- Switch open:
  - Open circuit, no current
  - Light is off
- Switch closed:
  - Short circuit across switch, current flows
  - Light is on

Switch-based circuits can easily represent two states: on/off, open/closed, voltage/no voltage.

n-type MOS Transistor

- MOS = Metal Oxide Semiconductor
  - two types: n-type and p-type
- n-type
  - when Gate has positive voltage, short circuit between #1 and #2 (switch closed)
  - when Gate has zero voltage, open circuit between #1 and #2 (switch open)

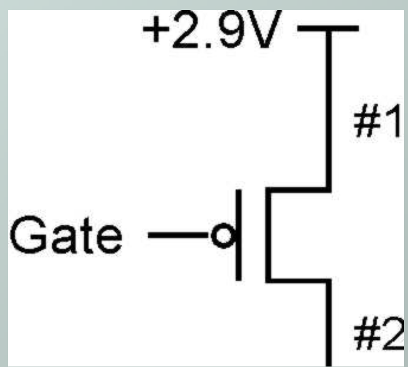


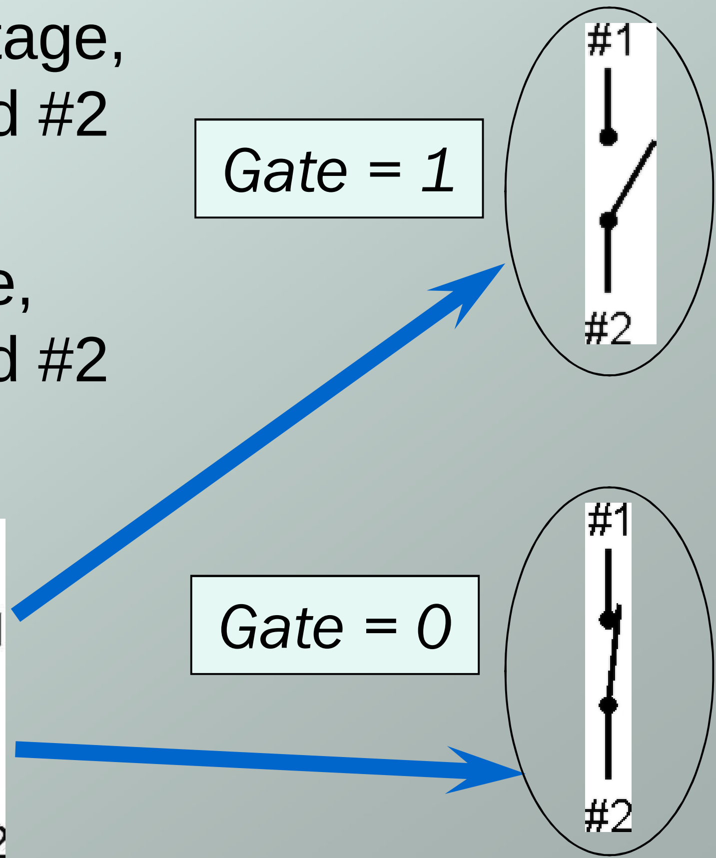


Terminal #2 must be connected to GND (0V).

p-type MOS Transistor

- p-type is *complementary* to n-type
  - when Gate has positive voltage, open circuit between #1 and #2 (switch open)
  - when Gate has zero voltage, short circuit between #1 and #2 (switch closed)





Terminal #1 must be connected to +2.9V.

Logic Gates

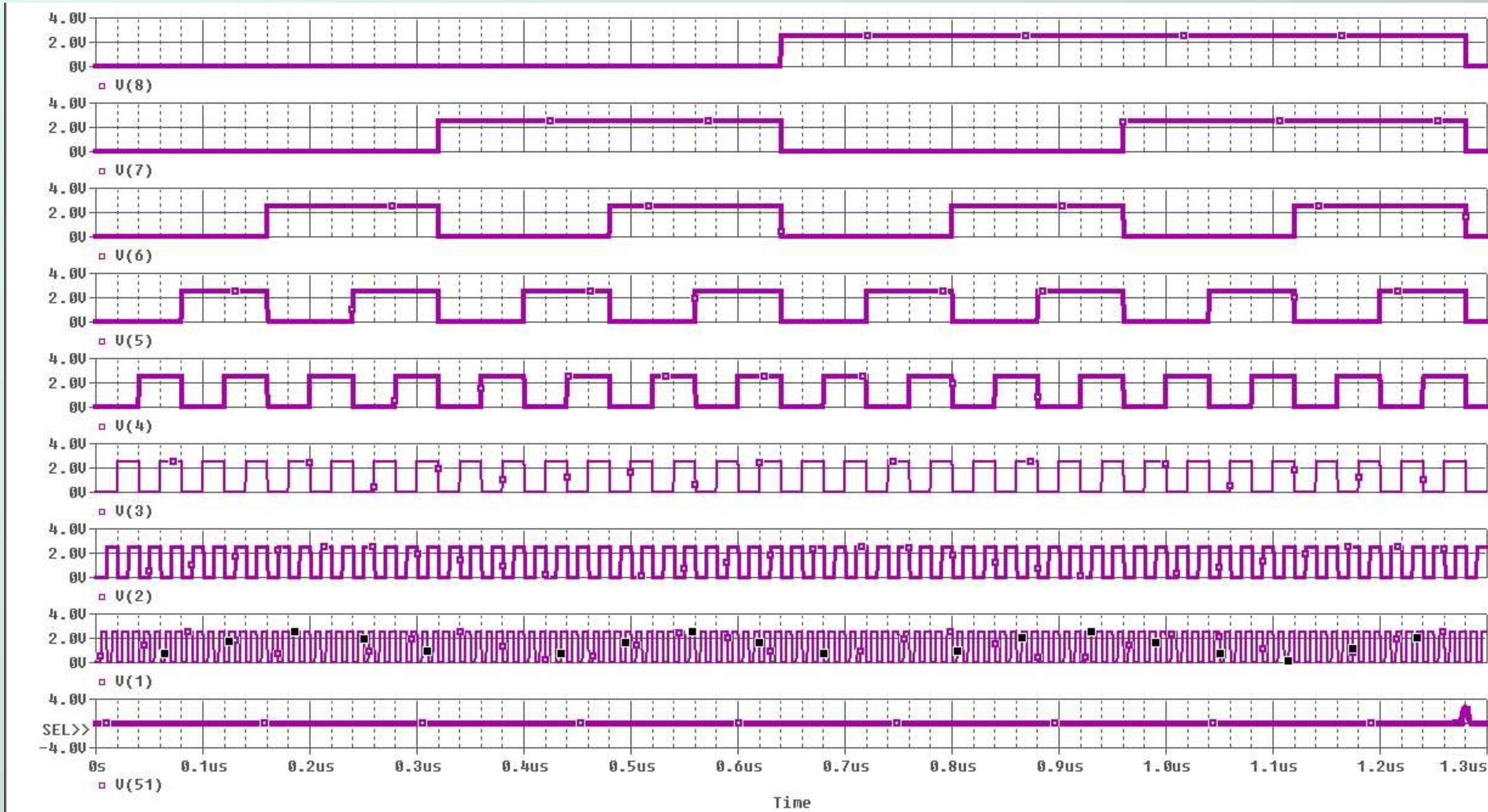
- Use switch behavior of MOS transistors to implement logical functions: AND, OR, NOT.
- Digital symbols:
  - recall that we assign a range of analog voltages to each digital (logic) symbol

  - assignment of voltage ranges depends on electrical properties of transistors being used
    - typical values for "1": +5V, +3.3V, +2.9V
    - from now on we'll use +2.9V

CMOS Circuit

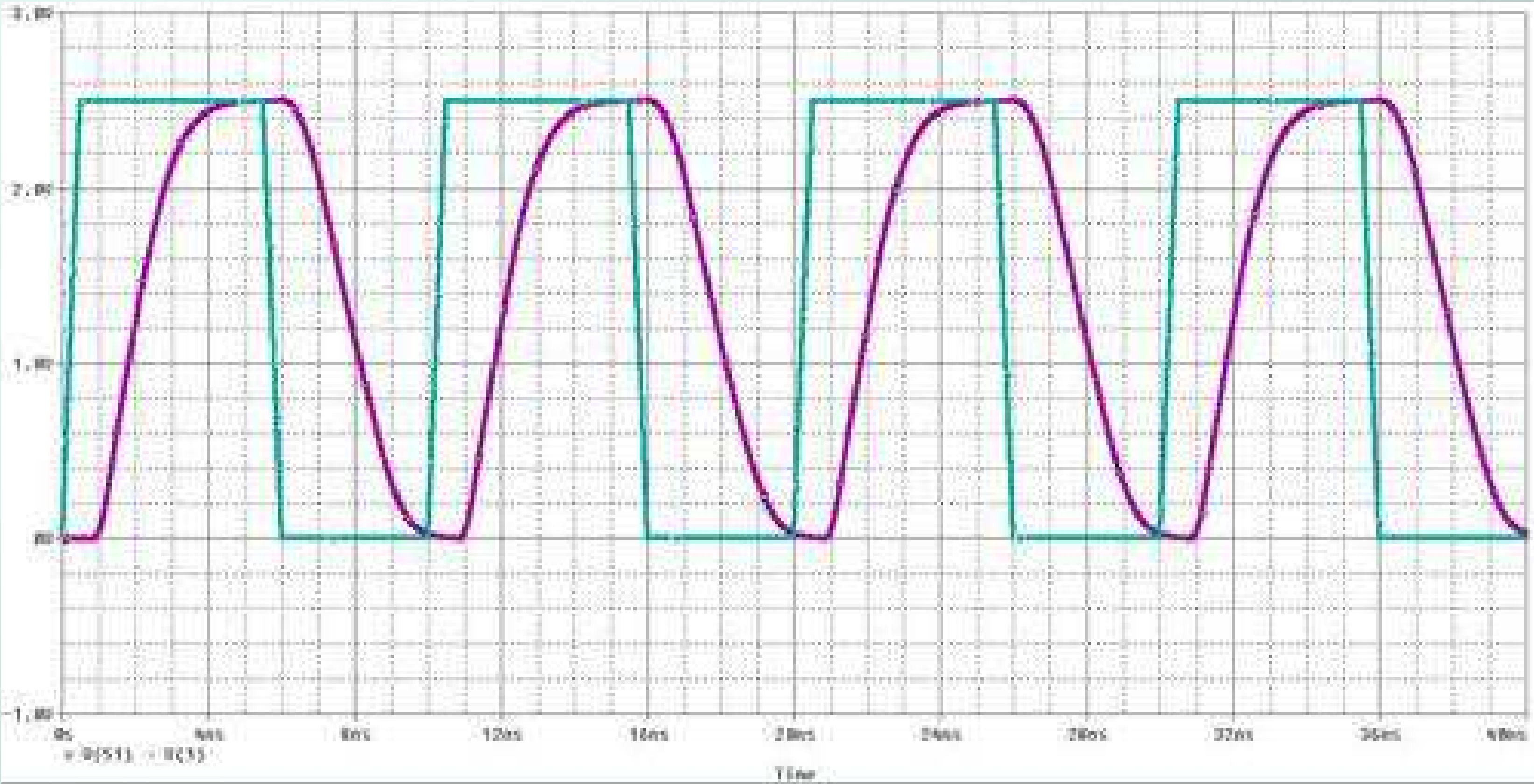
- Complementary MOS
- Uses both n-type and p-type MOS transistors
  - p-type
    - Attached to + voltage
    - Pulls output voltage UP when input is zero
  - n-type
    - Attached to GND
    - Pulls output voltage DOWN when input is one
- **For all inputs, make sure that output is either connected to GND or to +, but not both!**

Transistor Output (Ideal)



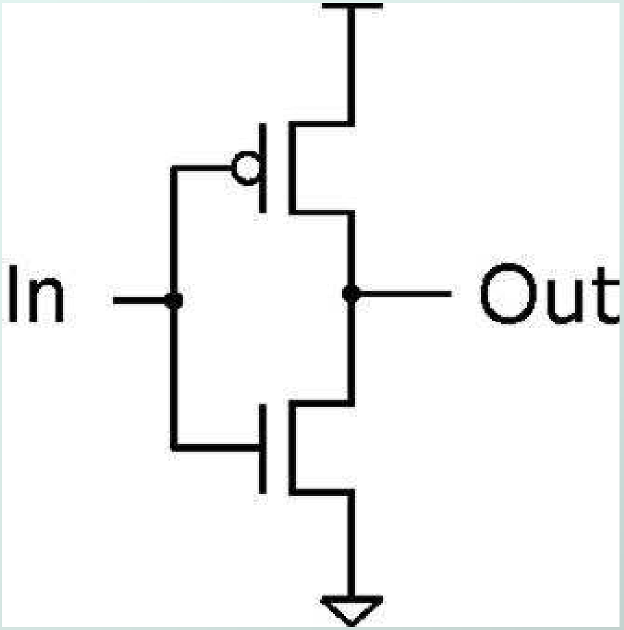
Logic analyzer view of waveforms

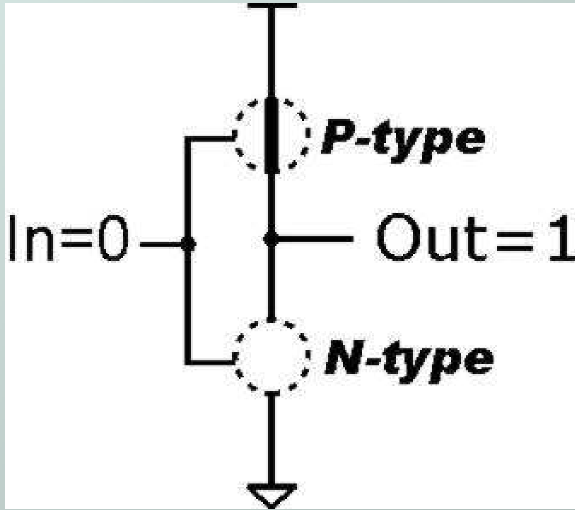
Transistor Output (Actual)

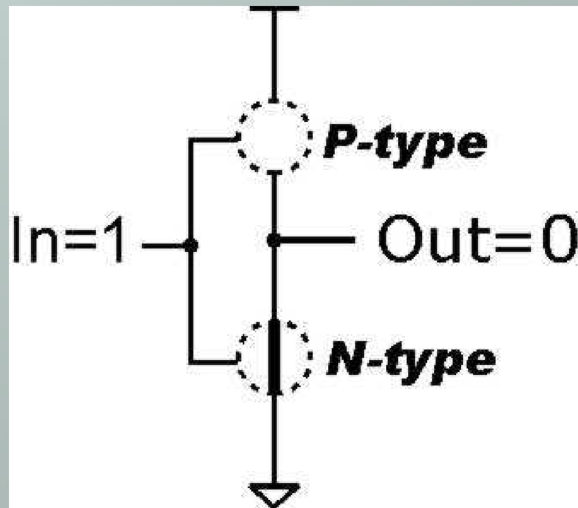


Actual waveform is not ideal!

Inverter (NOT Gate)





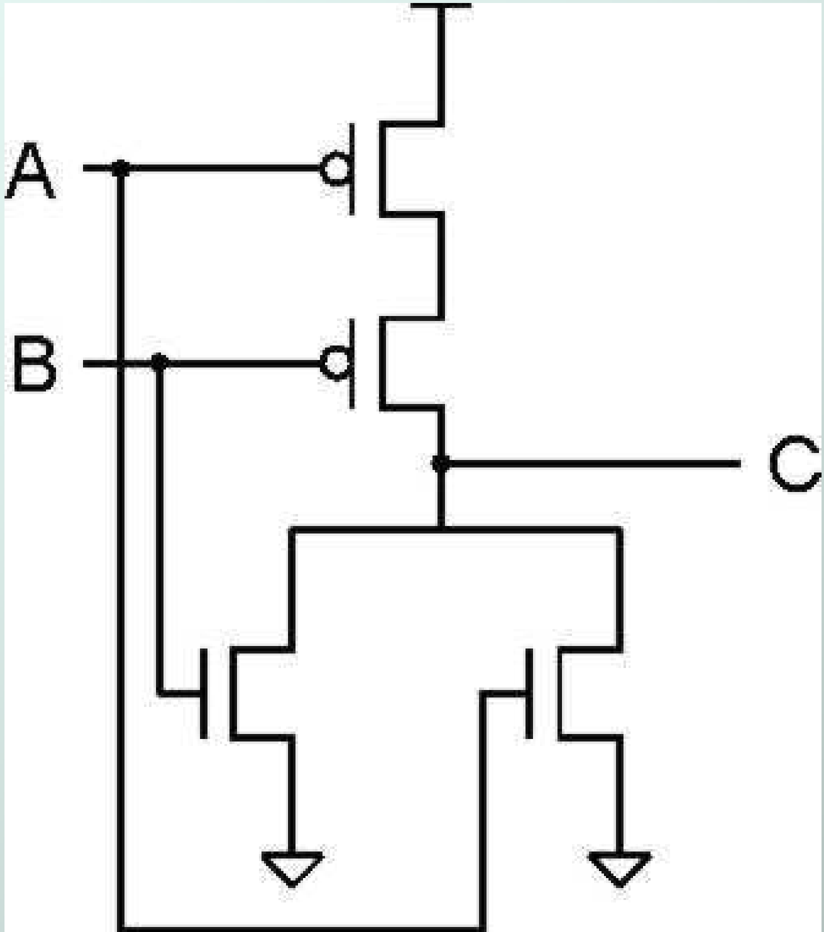


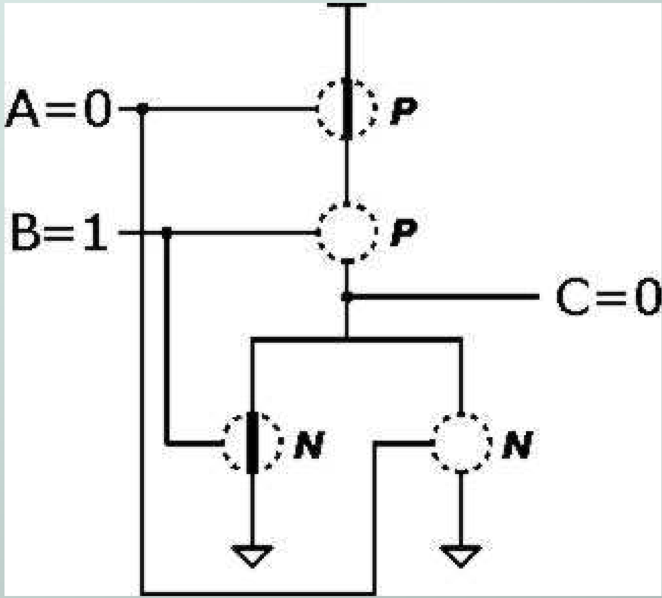
In	Out
0 V	2.9 V
2.9 V	0 V

In	Out
0	1
1	0

Truth table

NOR Gate



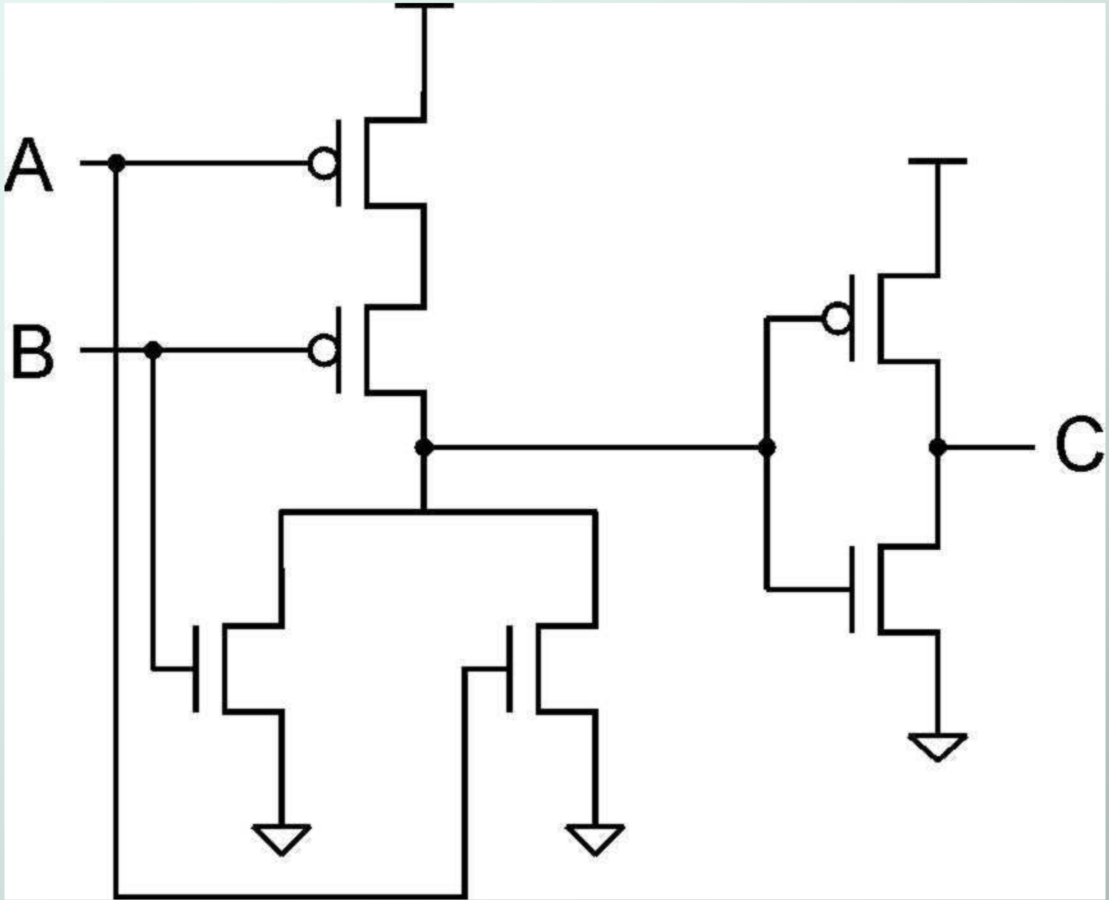


A	B	C
0	0	1
0	1	0
1	0	0
1	1	0

Truth table

Note: Serial structure on top, parallel on bottom.

OR Gate

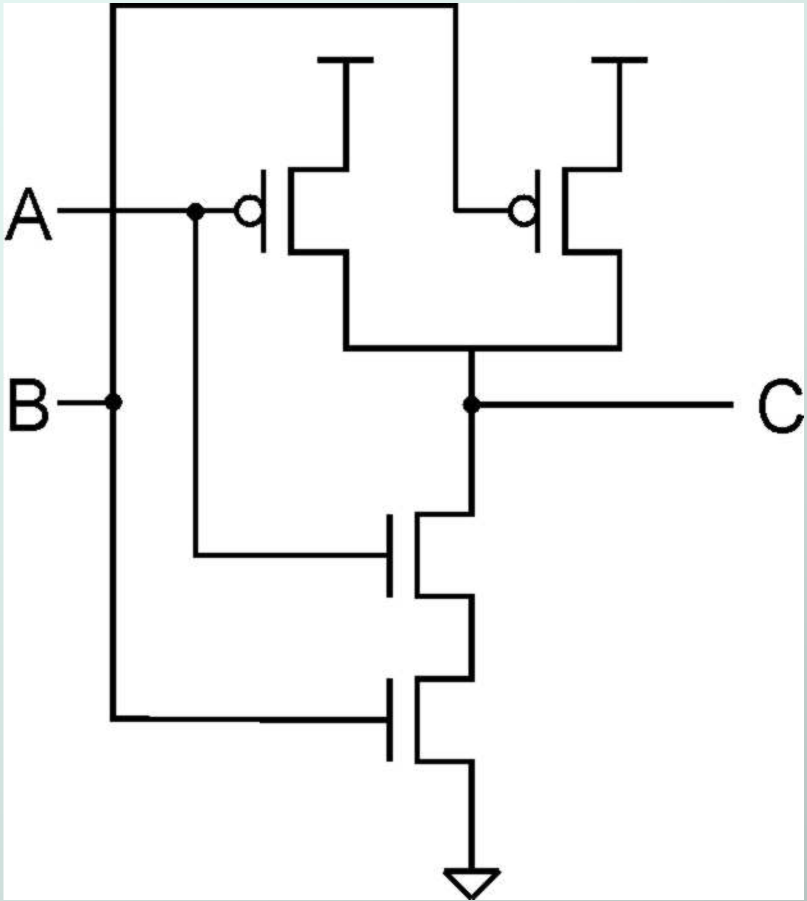


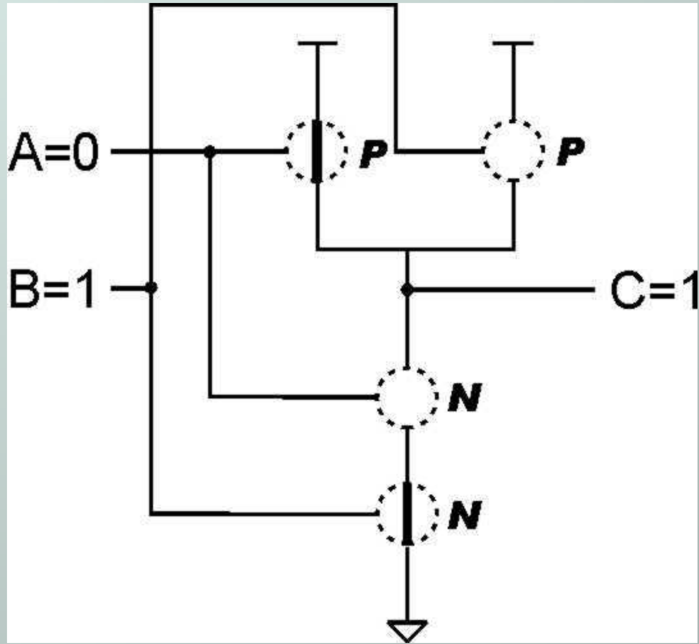
A	B	C
0	0	0
0	1	1
1	0	1
1	1	1

Truth table

Add inverter to NOR.

NAND Gate (AND-NOT)



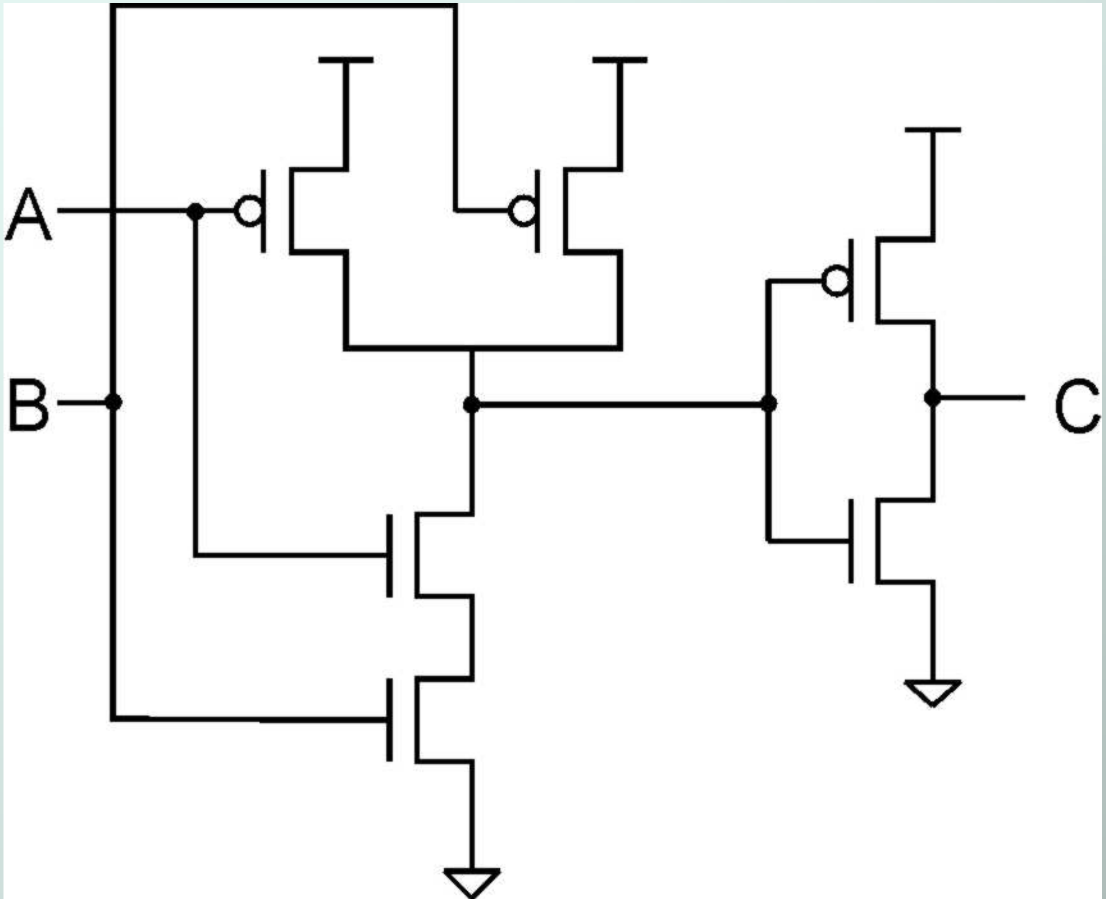


Truth table

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

Note: Parallel structure on top, serial on bottom.

AND Gate

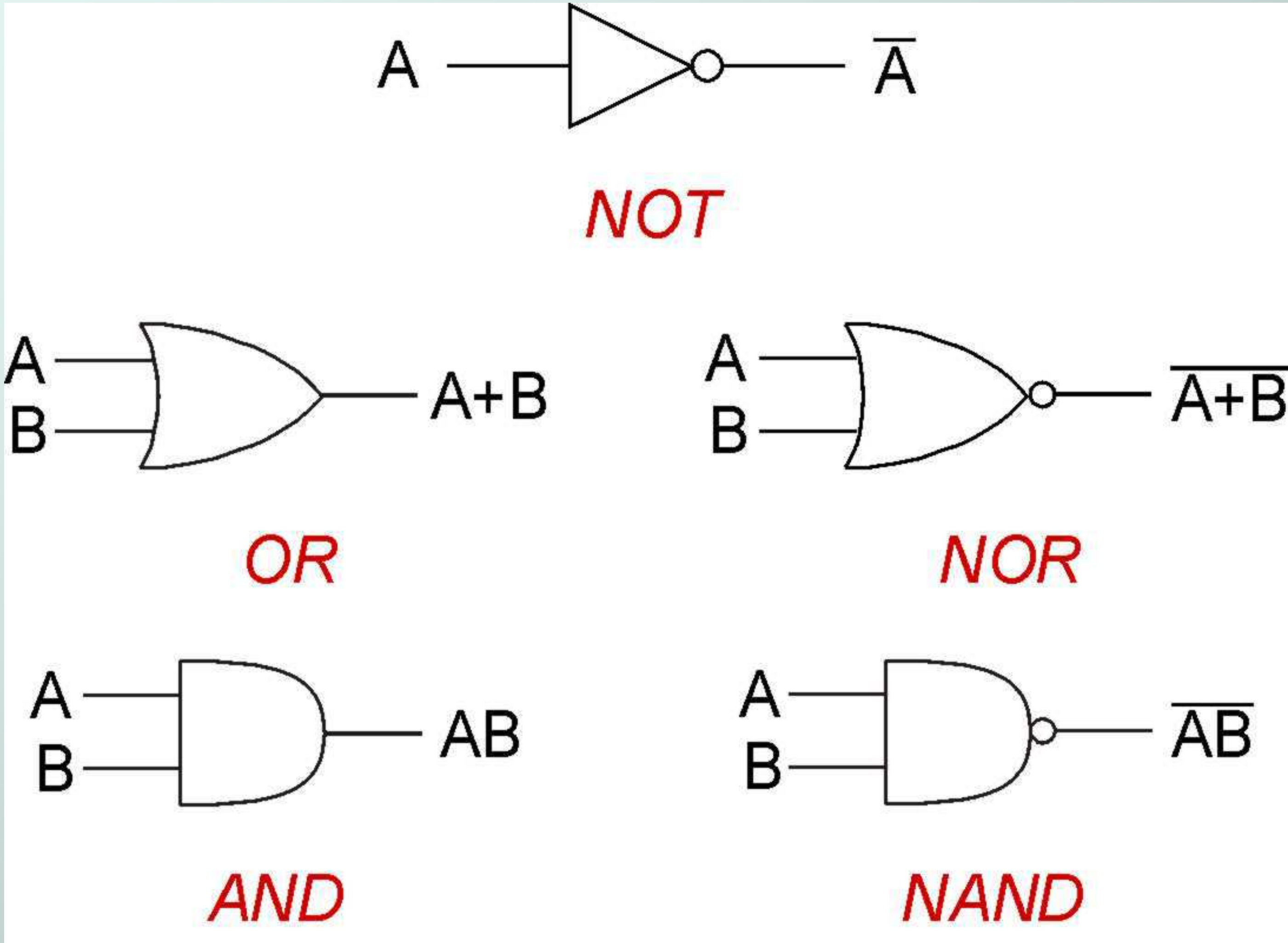


A	B	C
0	0	0
0	1	0
1	0	0
1	1	1

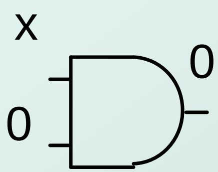
Truth table

Add inverter to NAND.

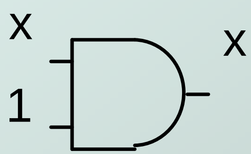
Basic Logic Gates



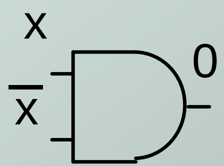
Boolean Algebra



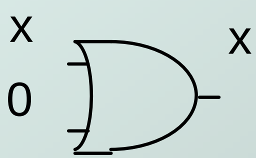
x.0 = 0



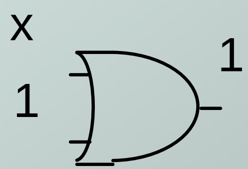
x.1 = x



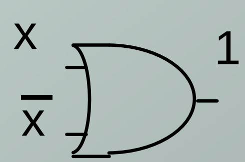
$x.\bar{x} = 0$



X+0 = x



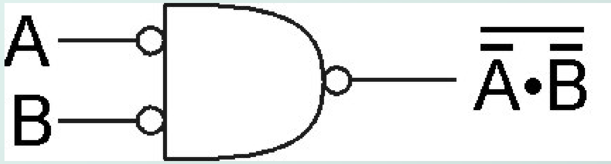
x+1 = 1



$x+\bar{x} = 1$

DeMorgan's Law

- Converting AND to OR (with some help from NOT)
- Consider the following gate:



A B	$\bar{A}$	$\bar{B}$	$\bar{A} \cdot \bar{B}$	$\overline{\bar{A} \cdot \bar{B}}$
0 0	1	1	1	0
0 1	1	0	0	1
1 0	0	1	0	1
1 1	0	0	0	1

To convert AND to OR (or vice versa), invert inputs and output.

Same as A OR B!

More than 2 Inputs?

- AND/OR can take any number of inputs.
  - AND = 1 if all inputs are 1.
  - OR = 1 if any input is 1.
  - Similar for NAND/NOR.
- Can implement with multiple two-input gates, or with single CMOS circuit.

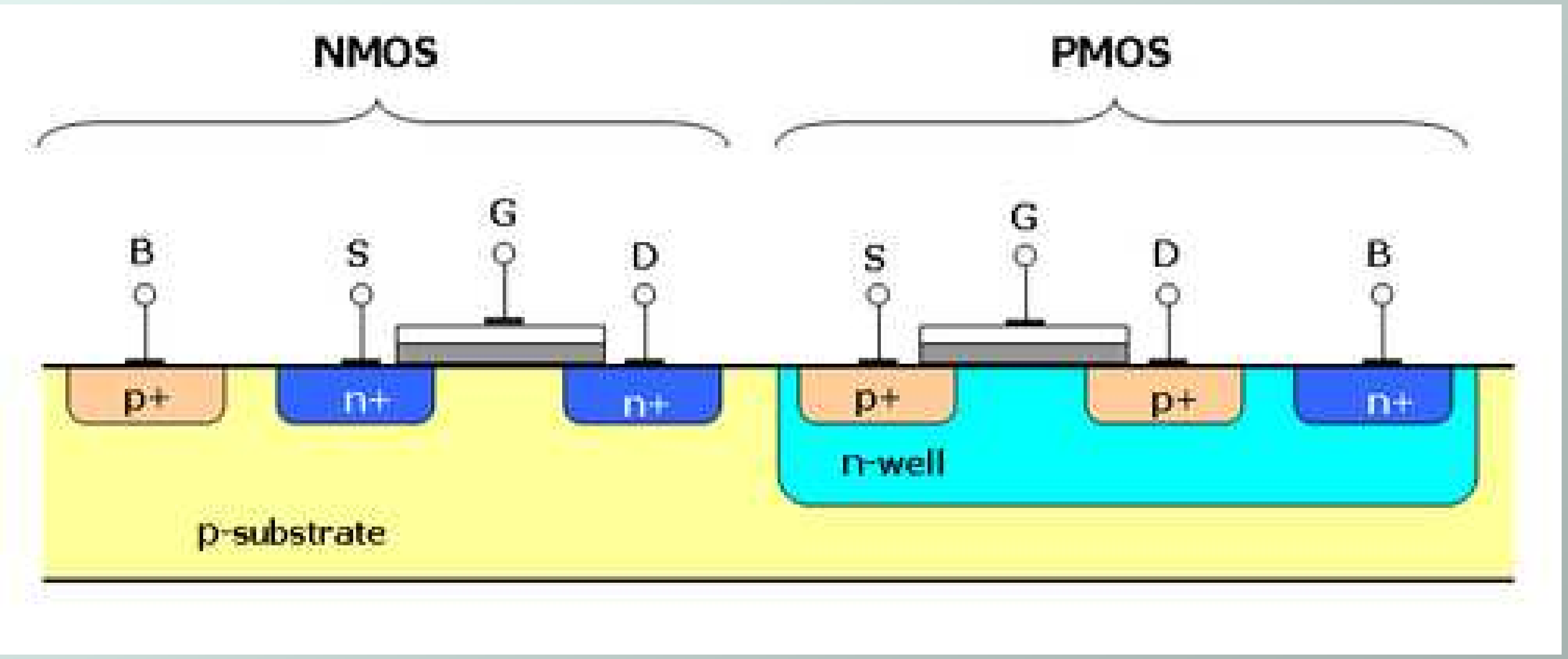
Summary

- MOS transistors are used as switches to implement logic functions.
  - n-type: connect to GND, turn on (1) to pull down to 0
  - p-type: connect to +2.9V, turn on (0) to pull up to 1
- Basic gates: NOT, NOR, NAND
  - Logic functions are usually expressed with AND, OR, and NOT
- DeMorgan's Law: handles inversion
  - Convert AND to OR (and vice versa) by inverting inputs and output

Building Functions from Logic Gates

- ***Combinational Logic Circuit***
  - output depends only on the current inputs
  - stateless
- ***Sequential Logic Circuit***
  - output depends on the sequence of inputs (past and present)
  - stores information (state) from past inputs
- We'll first look at some useful combinational circuits, then show how to use sequential circuits to store information.

Physical Transistor



http://en.wikipedia.org/wiki/CMOS