

Logic Design (Part 1)

Transistors & Gates

(Chapter 3)

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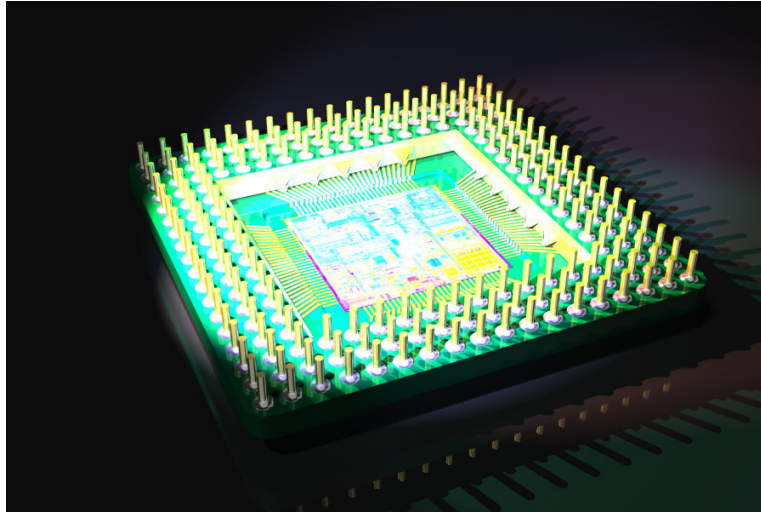
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Recap...where are we:

- Data representation
 - 2C representation of integers
 - Convert decimal to 2C and 2C to decimal
 - 2C rep of decimal N : if positive, same as unsigned
if negative, flip bits and add
- ASCII
- Arithmetic operations
- Boolean logic:
 - Truth tables
 - Logical connectives: AND, OR, NOT, XOR,
 - Derive values of boolean expression by filling truth table
- How is data represented in C
 - Will return to this

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Agenda next 3 weeks: Inside a microprocessor



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Recall: what are Computers meant to do ?

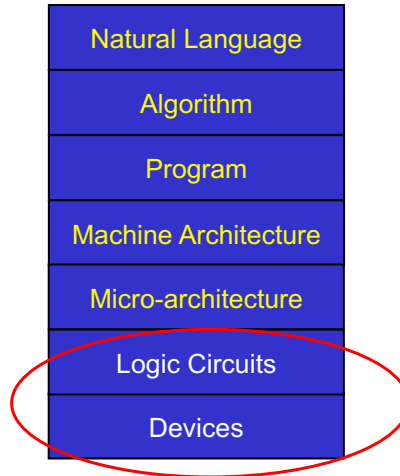
- We will be solving problems that are describable in English (or Greek or French or Hindi or Chinese or ...) and *using a box filled with electrons* and magnetism to accomplish the task.
 - This is accomplished using a system of well defined (sometimes) transformations that have been developed over the last 50+ years.
- At the lowest level, computers use 0's and 1's (binary) to represent data
- We first take a quick look at technology that gets electrons to run around

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Problem Transformation- levels of abstraction

**The desired behavior:
the application**

**The building blocks:
electronic devices**



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Recall: Why use Binary and How to represent data in a computer?

- At the lowest level, a computer has electronic “plumbing”
 - Operates by controlling the flow of electrons
 - Electrons flowing on the wire when voltage exists
- Easy to recognize two conditions:
 1. presence of a voltage – call this state “1”
 2. absence of a voltage – call this state “0”

More complex to base state on value of voltage, but can be done
- Think of the two states 0,1 as states of a switch
 - Change from 0 to 1 means throwing switch to turn on the light
 - Presence of voltage on the wire means value of bit = 1 else 0

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Physics review from Labs

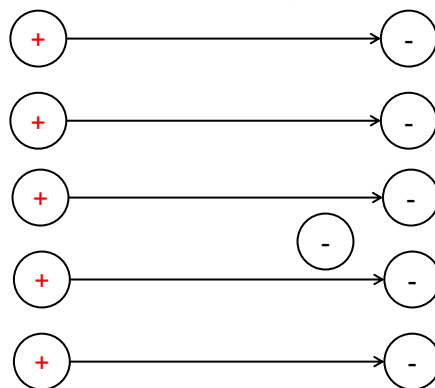
- Electricity corresponds to the flow of negatively charged particles called electrons.
 - Particles of opposite sign, (+ve and -ve), attract each other
 - Particles of the same sign repel each other.
- A **voltage** difference between 2 points captures the amount of work it would take to move charge from one point to another
- analogous to an elevation difference in a waterfall
- Current** is the flow of electrons
- Ohm's Law $V = IR$**



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Voltage/Current and Electric Field

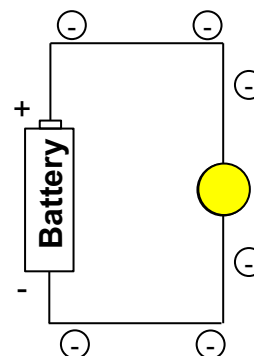
E-field produces "potential difference"
Aka: motivation for charge to flow



← Direction of charge carrier (e-)

→ Direction of current

Battery provide voltage
Aka: potential difference



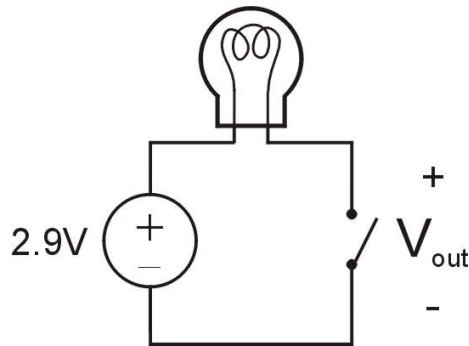
← Direction of current

Ohm's Law: $V = IR$

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Simple Switch Circuit

The light bulb has a resistance value



Switch open:

- No current through circuit
 - Resistance=infinity
- Light is **off**
- V_{out} is **+2.9V**

Switch closed:

- Short circuit across switch
- Current flows
- Light is **on**
- V_{out} is **0V**

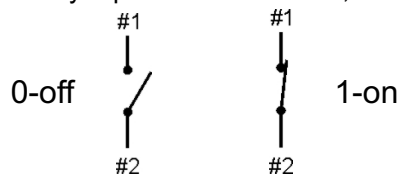
Key Takeaway:

Switch-based circuits can easily represent two states: on/off, open/closed, voltage/no voltage, 0/1!!

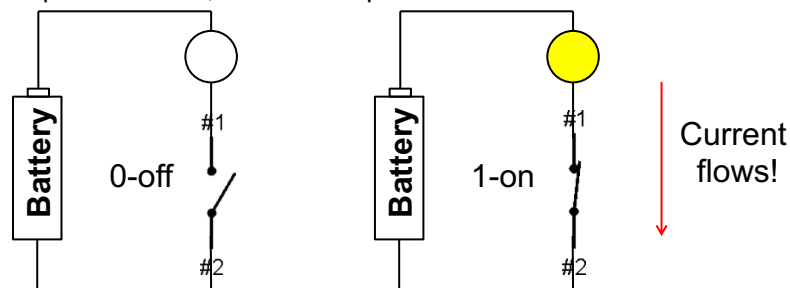
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Switches to logic

- A switch inherently represents two states, on/off



- When put in a circuit, can start/stop current flow

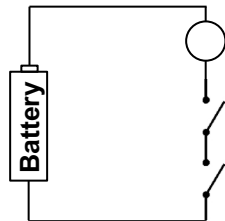


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Switches to logic

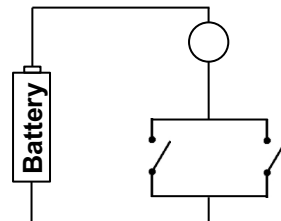
- Putting multiple switches together, and we get basic logic structures

*Switches
are in
series (AND)*



Both switches
must be "on" for
bulb to light up
(AND)

*Switches
are in
Parallel (OR)*

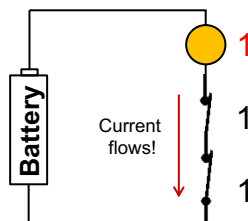


Only 1 switch
Must be "on" for
Bulb to light up
(OR)

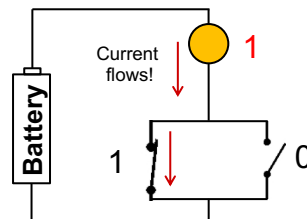
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Switches to logic

- Putting multiple switches together, and we get basic logic structures



Both switches
must be "on" for
bulb to light up
(AND)



Only 1 switch
Must be "on" for
Bulb to light up
(OR)

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Digital Circuits: It's all about switching...

- Tubes
- Transistors
- CMOS FET

Computers use transistors as switches to manipulate bits

Before transistors: tubes, electro-mechanical relays (pre 1950s)

Mechanical adders (punch cards, gears) as far back as mid-1600s

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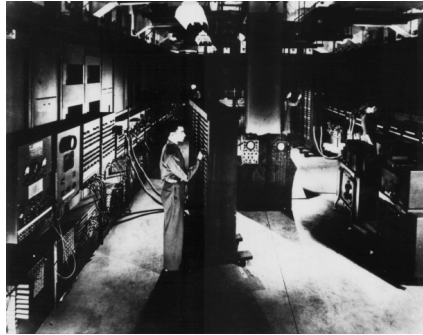
Vacuum Tubes

- Also known as valves because they control the flow of electrons
 - Flow from Cathode to Anode
- First computer built using vacuum tubes

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Historical Perspective

- ENIAC built in World War II the first general purpose computer
 - Used for computing artillery firing tables
 - 80 feet long by 8.5 feet high and several feet wide
 - Each of the twenty 10 digit registers was 2 feet long
 - Used 19,000 vacuum tubes
 - Performed 1900 additions per second



Historical Fact: Who are the “top secret rosies”?

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Transistors: Building block of computers

- Also viewed in digital circuits as a “switch”
 - Transistors used in analog circuits: Stereos, Image proc., etc.
- Brought about a big change
 - Size, Speed, Precision
 - Moore’s law: they get smaller and faster
 - Can put more and more onto a single chip
- Microprocessors contain millions of transistors
 - Intel 80286 (1982): 200,000
 - Intel i860 (1989): 1 million
 - Intel Pentium 4 (2000): 48 million
 - Intel Core Duo 2 (2006): 291 million
 - Intel 8-core Xeon Nehalem-EX (2010): 2.3 billion
 - Intel Core 9 (2019): >5 billion
 - GPUs: nVIDIA GA100 (2020): 54 billion
 - Some flash memory chips contain over trillion

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Basics of Digital Circuit Design

- How to build a switch ?
 - Transistors
- How to build basic logic functions – gates using transistors ?
 - Build simple gates (AND, NOT, OR, ...) using transistors
- How to build more complex combinational logic using gates
 - Build Adders, multiplexer, decoder, storage devices using simple gates (AND, NOT, OR..)
- Build a whole computer using complex logic devices
 - Assemble all the pieces together into an 'orchestra' – this is the CPU !
- Important: power of abstraction (and layers)
 - Once you know how to build a gate using transistors, you don't have to think transistors any more!
 - Once you have a collection of gates on a single chip, you don't have to think about individual gates.
 - etc. etc.

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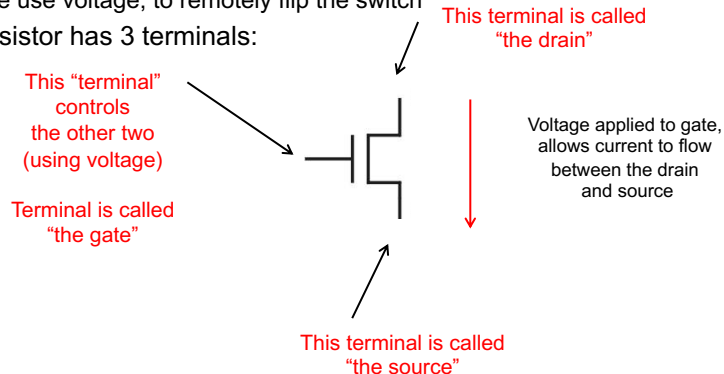
What is a transistor?

- A transistor is an electrical device that allows us to control the flow of current in a circuit
 - A transistor can act like an electronic "switch" in a circuit
 - A transistor can also function as an "amplifier" of voltage or current
- Over the decades, engineers have developed several electronic "switches" in circuits:
 - mechanical relays, vacuum tubes
 - diodes, transistors
 - MEMS devices, photonic, biological
- Switch-like behavior is important, because it can give rise to logic
 - In a CPU, we use transistors as switches, to implement logic gates
- Voltage controlled switch
 - the switch is closed or open depending on input voltage

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Transistor as electronic switch

- In the previous example with switches, someone must manually “flip” the switches to control the “input” to our gates
- In a computer we need to generate signal to flip the switch
 - Transistor offers us this capability
 - We use voltage, to remotely flip the switch
- A transistor has 3 terminals:



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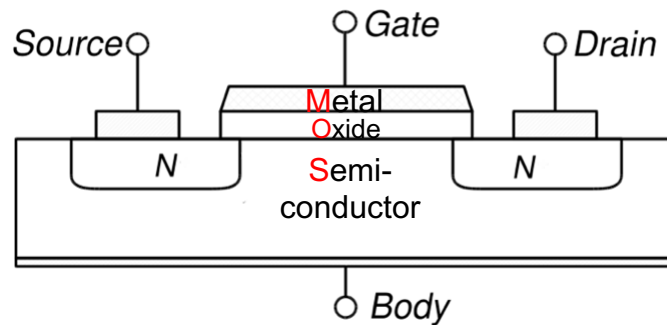
How does a transistor work – Semiconductor basics

- Most materials are either insulators or conductors
 - They don't “change” their properties
- Semiconductors: between insulator and conductor
- Semiconductors: Based on voltage applied to “gate” it is either insulator or a conductor
 - Electric field creates a circuit
 - Changes the device from an insulator to a conductor
- Overview: two types of materials
 - N-type: extra electrons can be used to carry a current
 - P-type: extra 'holes' into which electrons can flow
- how does it work ?? Read notes at end of this lecture

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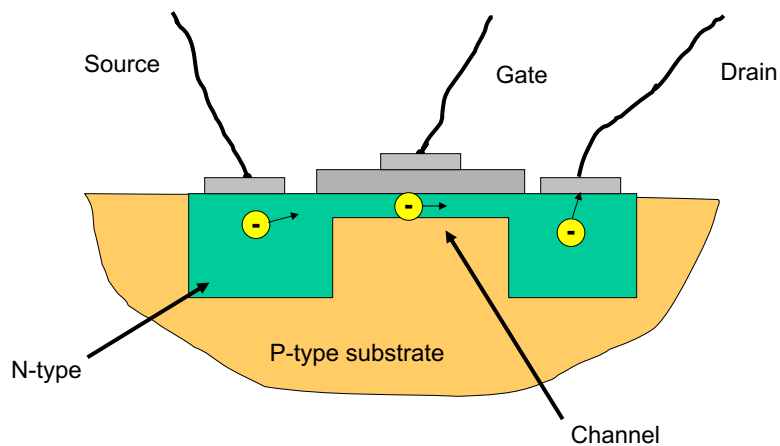
the MOSFET (your 1st Transistor!)

- MOSFET : **M**etal **O**xide **S**emiconductor **F**ield **E**ffect **T**ransistor
- Picture shows a cross section of such a device.
- Notice it has 4 electrical terminals: Source/Drain/Gate/Body



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MOS FET (Metal Oxide SemiConductor)



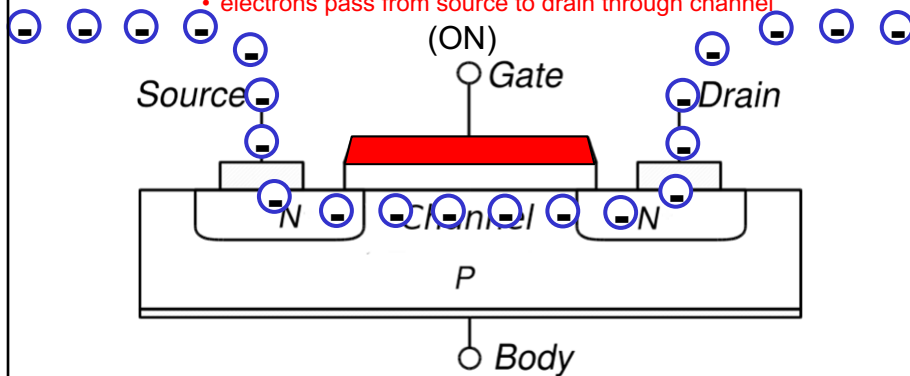
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How we want it to work...

- Goal: Pass current through this device (from drain to source)
 - BUT we want to control that current (using the gate terminal)

– If GATE is ON

- electrons pass from source to drain through channel



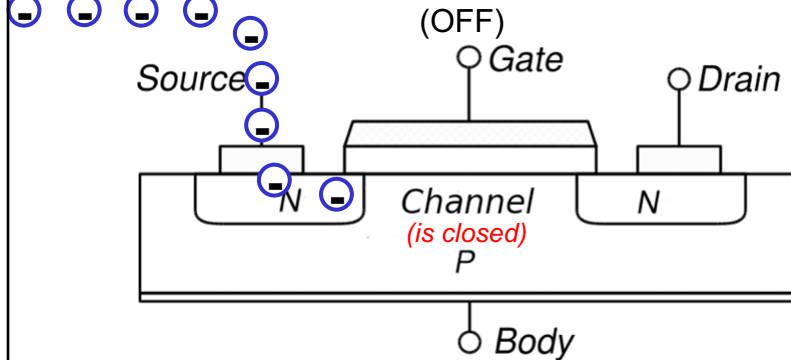
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How we want it to work...

- Goal: Pass current through this device (from drain to source)
 - BUT we want to control that current (using the gate terminal)

– If GATE is OFF

- electrons cannot pass through channel



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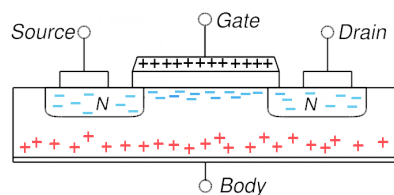
Details....how is this achieved....

- Read details in the notes (and online materials)...

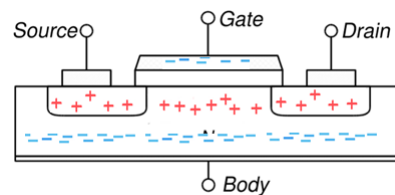
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Two types of MOSFETs: nMOSFET and pMOSFET

- nMOSFET (nMOS): channel carries negative charges (electrons)
 - GATE MUST BE (+) to be ON
- pMOSFET (pMOS): channel carries positive charges (holes)
 - GATE MUST BE (-) to be ON



n-type



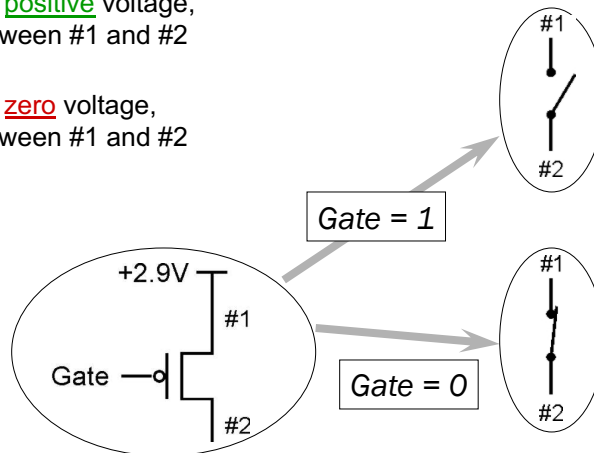
p-type

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Abstraction: Simplified view of p-type MOS Transistor

▪p-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)



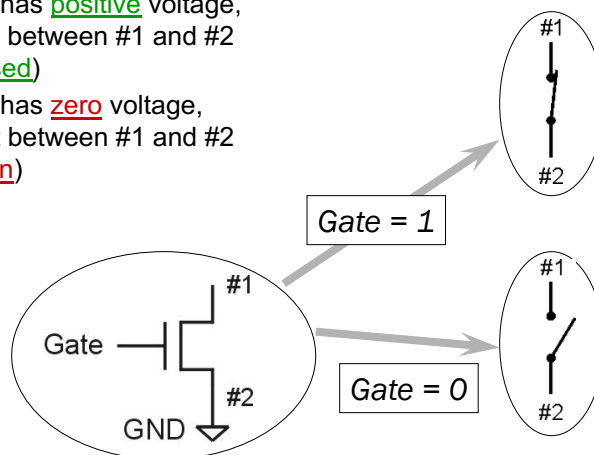
Important: For p-type, Terminal #1 must be connected to Voltage Source.

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Abstraction: Simplified view of n-type MOS Transistor

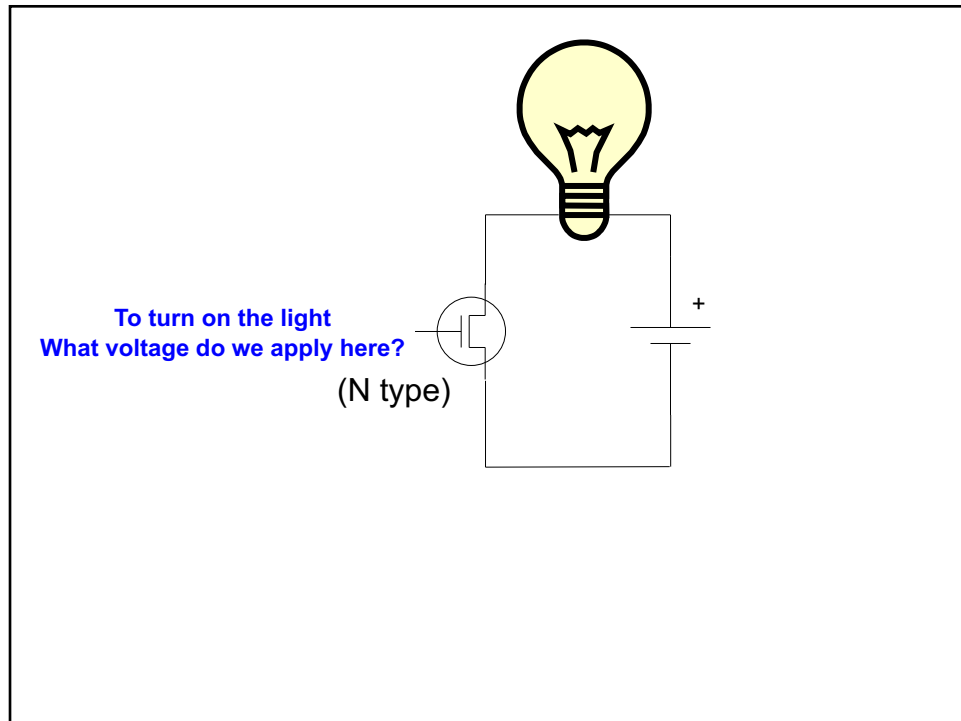
▪n-type *complementary* to p-type

- 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)

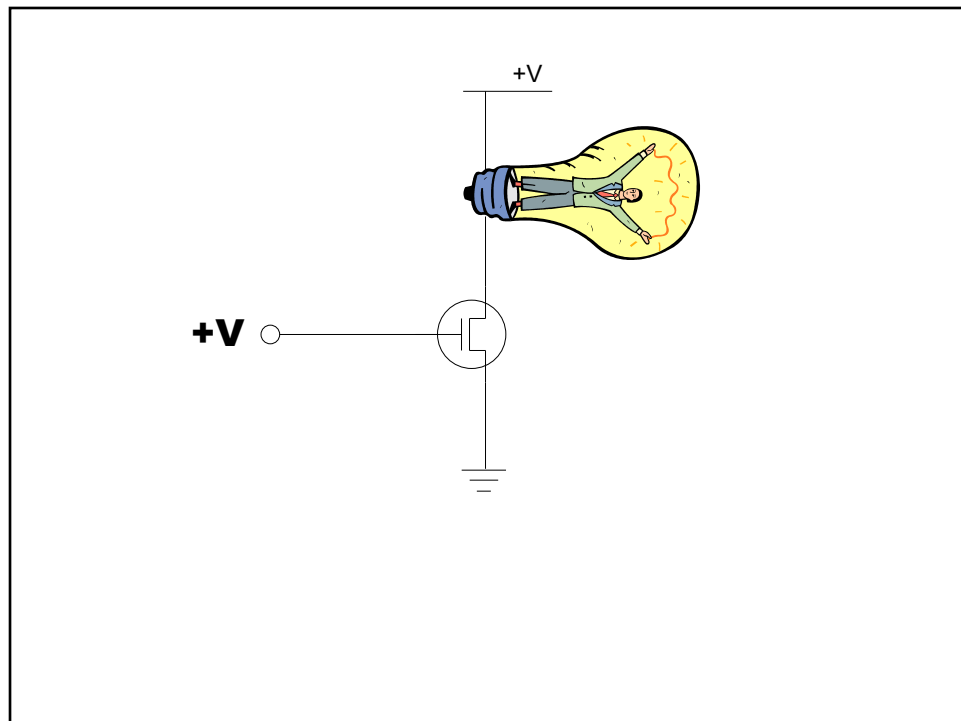


Important: For n-type, Terminal #2 must be connected to Ground (0V).

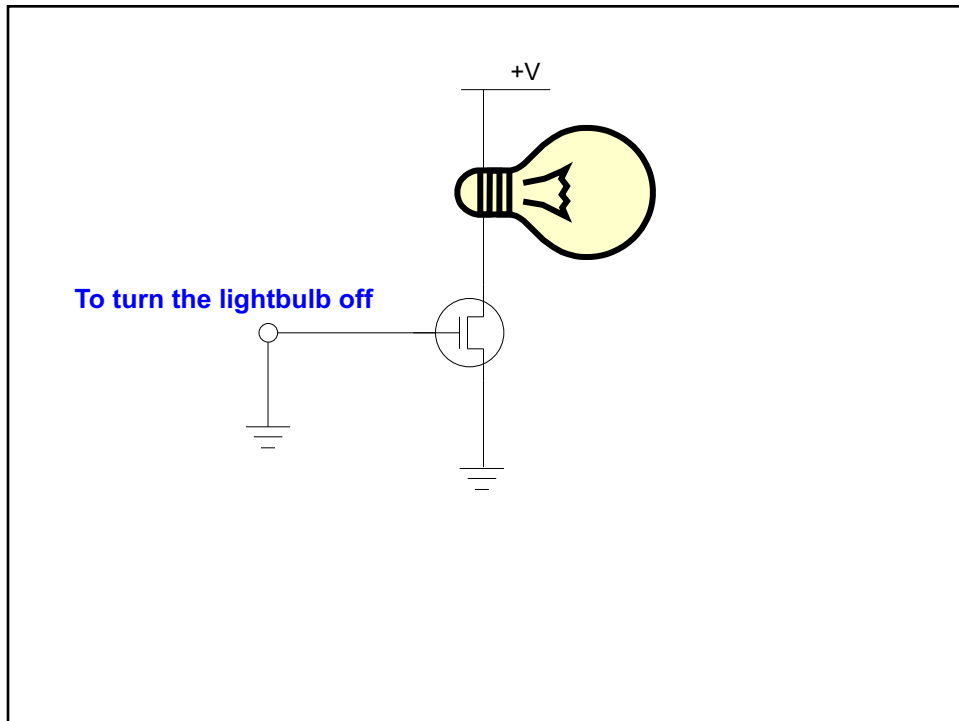
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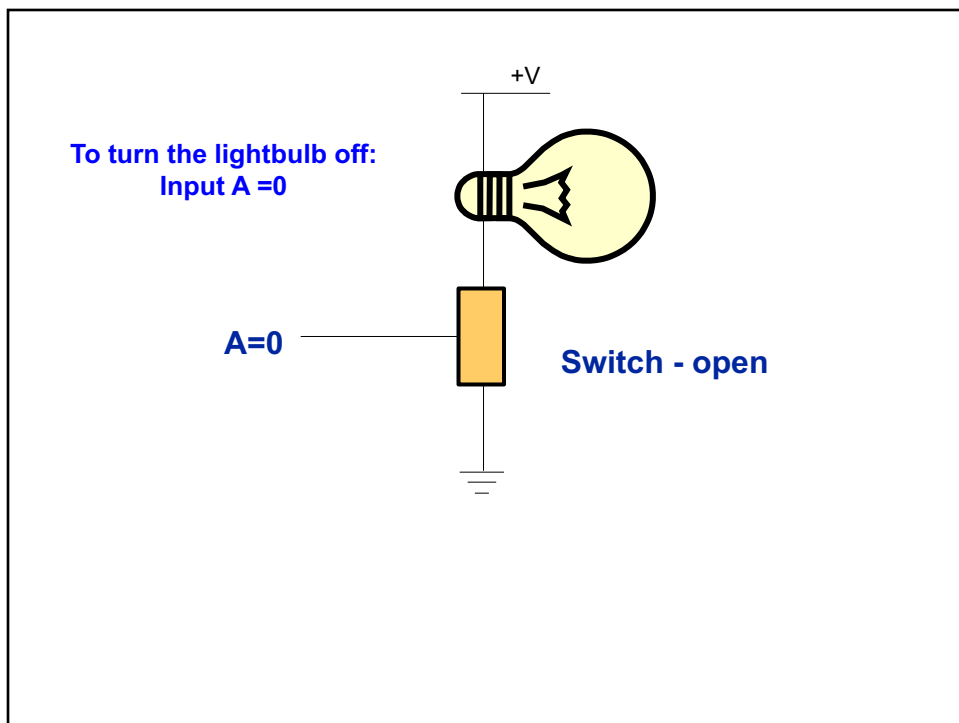
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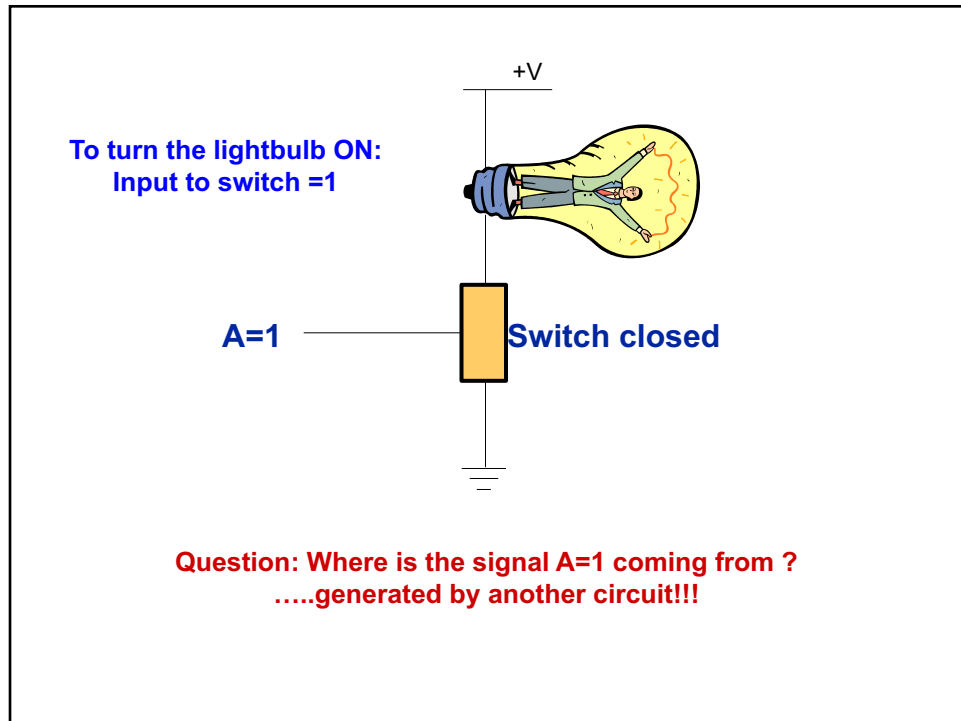
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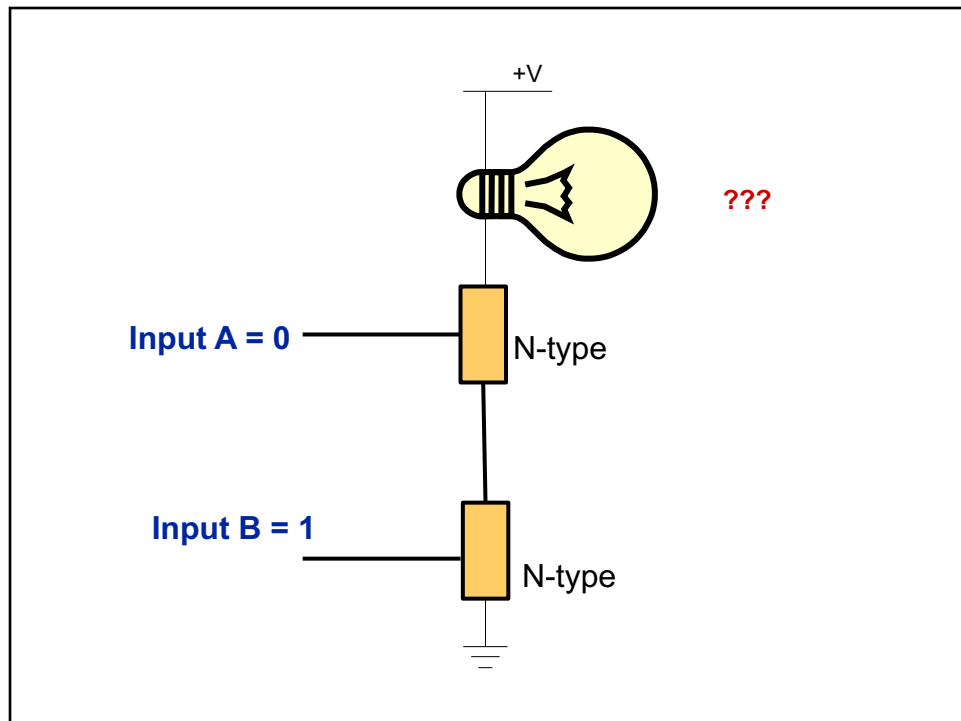
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Light bulbs and computer hardware –what the &@?#&#&!

- Let's look back at what we've learnt
 - Numbers can be represented as 0s and 1s
 - 1 is presence of voltage on line, 0 is no voltage on line
 - Arithmetic operations on these numbers
 - Logical operations on these numbers
- Starting point: how to implement the basic logic operators using transistors/switches ?
 - NOT, AND, OR
- Next: how to implement arithmetic operations and other functions
 - Combinational circuits; example: adder

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Logical Operations

- NOT, AND, OR, NAND, NOR, XOR
- These are binary functions
 - Input is binary, output is binary
- Boolean function – operates on boolean variables
 - Boolean function can be expressed using [truth table](#)
 - Eg: addition can be represented as a boolean function
- Recall from Discrete 1 - CS 1311: can **implement any boolean function** using AND, OR, NOT, etc.
 - In fact, can implement any bool function using just NAND
- Start by building these logical operator “gates” using transistors

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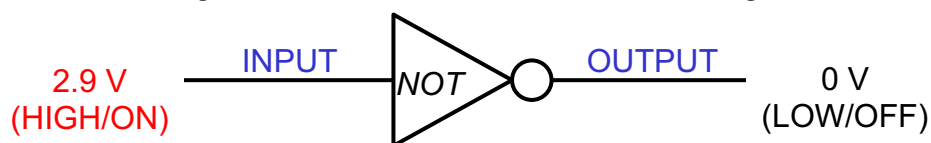
Ok....start building logic gates

- Use Complementary MOS (CMOS) circuits
 - Using N type **and** P type transistors
- Use switch behavior to implement logic functions/operators
- 'signal' is a 1 or 0 and nothing else
- Output value will be **voltage measured at some point in the "circuit"**
 - Need to **determine where** to designate the output point (i.e., where to measure)
 - *This output point must (at all times) have a path (connection) to Voltage source (1) or to ground (0)*
 - The path is selected based on the value to transistor gates
- Inputs will be applied to the transistor gate
 - A line in the circuit always tied to 1 (voltage source) and one always tied to 0 (ground)
- Start by looking at the truth table for the logic function

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So now what? How to go from "switch" to logic?

- Our first logic device will be an inverter: the NOT gate



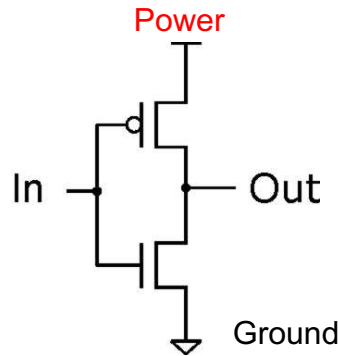
- Logical Behavior: "inverts" the incoming signal:
 - Input: LOW-> output: **HIGH**
 - Input: **HIGH**->output: LOW

INPUT	OUTPUT
LOW (0)	HIGH (1)
HIGH (1)	LOW (0)

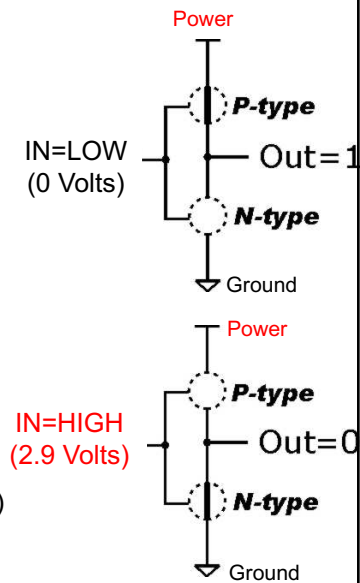
Truth Table
All possible
Combinations
Of inputs

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How do we configure transistors to make inverter?

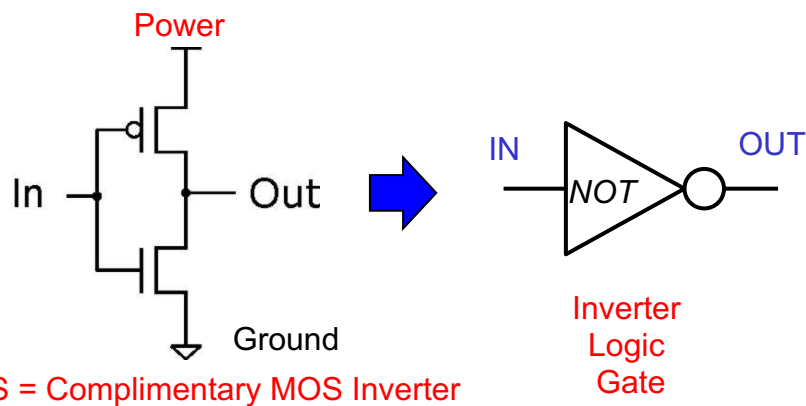


We take advantage of opposing nature!
 -If **pMOS** turns on when GATE=0 (Ground)
 and if **nMOS** turns on when GATE=1 (Voltage)
 -then *if we put them together & connect their gates, we get inverting behavior!*



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This configuration is called: CMOS



We have “jumped up” 1 level of abstraction
 --From transistors to “gate”
 --Technology inside the gate (CMOS here) isn’t as crucial as its behavior
 --could be: transistors, vacuum tubes, biological device, etc.

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Things to notice about a CMOS Circuit

- Uses both **n-type** and **p-type** MOS transistors

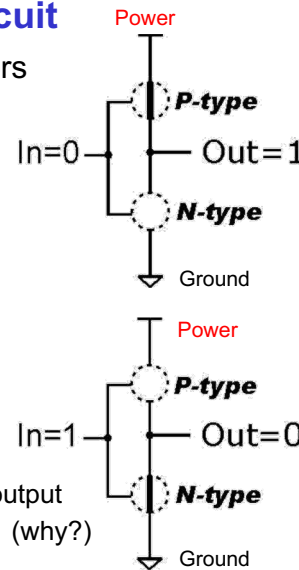
- p-type

- Attached to POWER (high voltage)
 - Pulls output voltage UP when input is zero
 - Call PMOS devices “pull up” devices

- n-type

- Attached to GROUND (low voltage)
 - Pulls output voltage DOWN when input is one
 - Call NMOS devices “pull down” devices

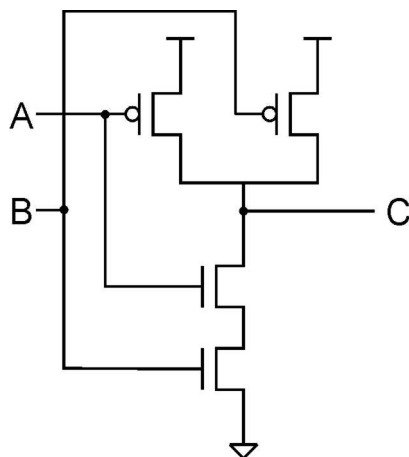
- For all inputs, this configuration makes certain that output
- connected to GROUND or to POWER, but not both! (why?)



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Circuit ?

Note: Output is being measured at some location in the circuit.
make sure that point can only be 0 or 1



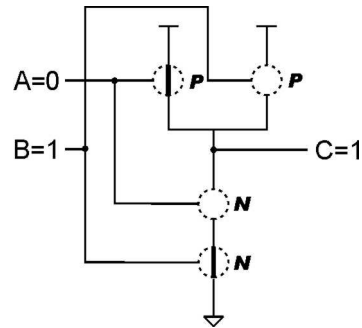
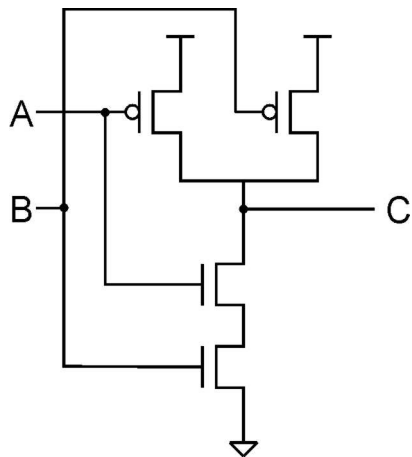
Note: Parallel structure on top, serial on bottom.

Truth table ?

A	B	C
0	0	
0	1	
1	0	
1	1	

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Example

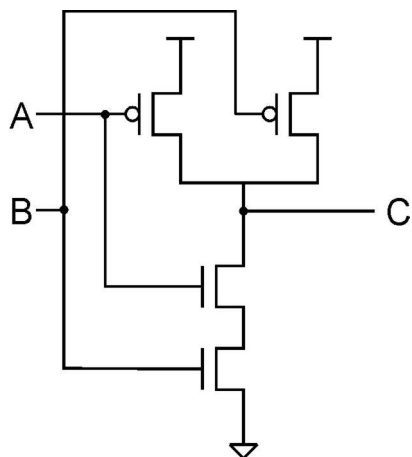


A	B	C
0	0	?
0	1	1
1	0	?
1	1	?

Note: Parallel structure on top, serial on bottom.

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NAND Gate (AND-NOT)



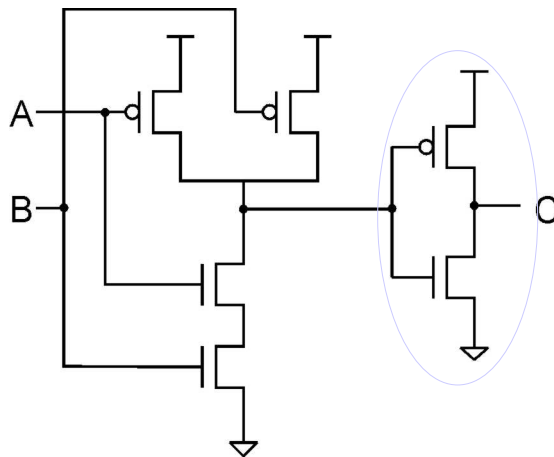
Truth Table

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

Note: Parallel structure on top, serial on bottom.

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AND Gate



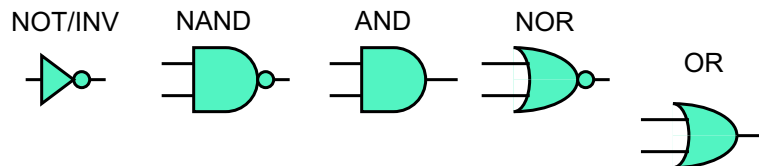
A	B	C
0	0	0
0	1	0
1	0	0
1	1	1

Add inverter to NAND.

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Basic Logic Gates

- From Now On... Gates
 - Covered transistors mostly so that you know they exist
 - Note: "Logic Gate" not related to "Gate" of transistors
- Logic gates ~ Propositional logic operators
 - Propositional logic formula = Boolean logic circuit !
- Will study implementation in terms of gates
 - Circuits that implement Boolean functions



- More complicated gates from transistors possible
 - XOR, Multiple-input AND-OR-Invert (AOI) gates

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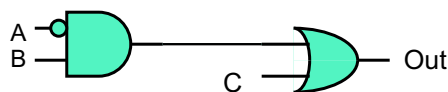
Truth Table for common 2 input gates

A	B	AND	OR	NAND	NOR	XOR
0	0	0	0	1	1	0
0	1	0	1	1	0	1
1	0	0	1	1	0	1
1	1	1	1	0	0	0

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Example: Your first combinational circuit

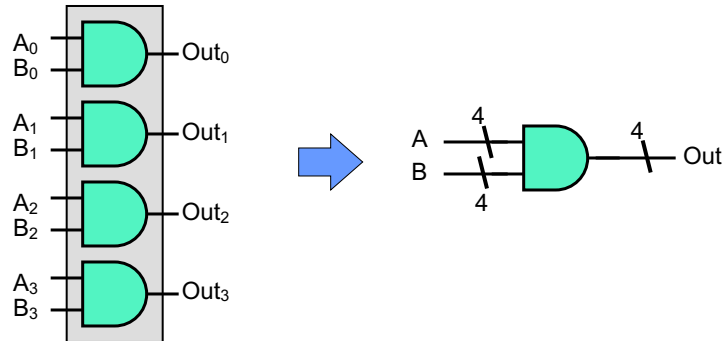
- Combinational logic circuits ~ propositional logic statements
- Use gates to implement the logic operators ('functions')
 - No necessity to show the circuit using transistors since each gate corresponds to an implementation using transistors
- Output = ((NOT A) AND B) OR C
- Need one AND gate and one OR gate (and one NOT gate/invertor)



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Visual Shorthand for Multi-bit Gates

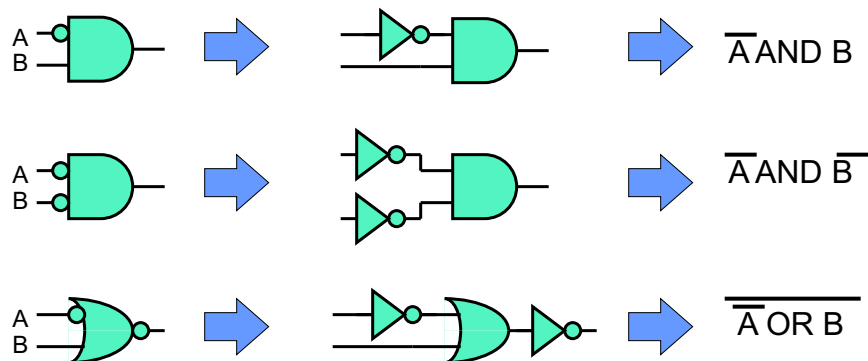
- Use a cross-hatch mark to group wires
 - Example: calculate the AND of a pair of 4-bit numbers
 - A_3 is “high-order” or “most-significant” bit
 - If “A” is 1000, then $A_3 = 1$, $A_2 = 0$, $A_1 = 0$, $A_0 = 0$



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Shorthand for Inverting Signals

- Invert a signal by adding either
 - a ● before/after a gate
 - a “bar” over letter



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Building Combinational logic circuits

- Integrated circuits (chips) package multiple gates into a single chip
 - Using a single gate requires connecting inputs to the appropriate pins on the chip and taking the output from a specific pin
 - A “datasheet” for each chip specifies how the pins are connected
- Labs this week: Using 7400 series chips to design logic circuits

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Reading

- Chapter 3
- Lecture notes posted on webpage
- and Notes linked from webpage
- Start using Cedar Logic (Windows) or Logisim (Mac)
 - Go over the Set1.cdl examples
 - Download and save the file, open in Cedar Logic/Logisim
- Review boolean algebra concepts from CS1311
 - Summary notes on Bool.Alg. Posted on my lectures webpage

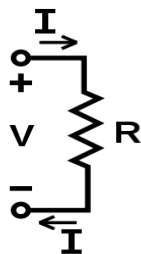
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Appendix: Additional Reading/Slides

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More Physics: Conductors, Insulators, Semiconductors

- Materials like metals are termed *conductors* because they allow the free flow of electrons
- Materials like rubber are termed *insulators* because they impede flow of electrons
 - Resistors are devices that will conduct some current if you encourage the electrons with a potential difference
- **Semiconductors** are poor *conductors* and poor *insulators*, hence “semi.” They can be used for either or both properties



Ohm's Law: $V = IR$

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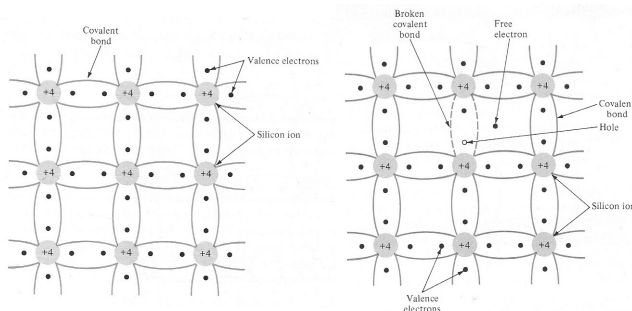
How does a transistor work – Semiconductor basics

- Most materials are either insulators or conductors
 - They don't "change" their properties
- Semiconductors: between insulator and conductor
- Semiconductors: Based on voltage applied to "gate" it is either insulator or a conductor
 - Electric field creates a circuit
 - Changes the device from an insulator to a conductor
- how does it work ??

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How does a transistor work?

- Begin at the beginning (*what is it made of ?*)
 - Currently transistors are etched on Silicon
 - Atomic symbol: Si – atomic number 14
 - In its crystalline state, silicon atoms form covalent bonds neighbors using their 4 outer electrons
 - At room temperature, Silicon is a semiconductor

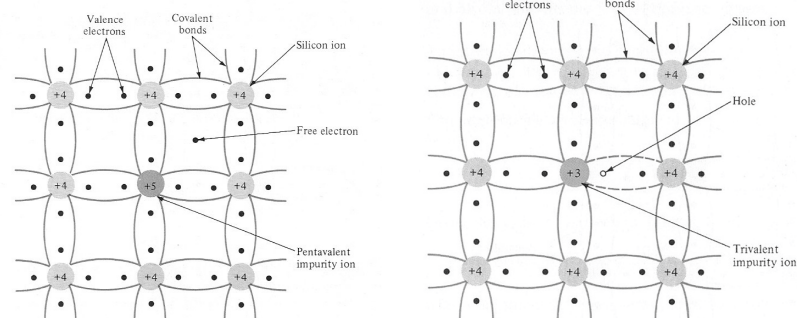


14	IVA	4A
6	C	Carbon 12.011
14	Si	Silicon 28.0855
32	Ge	Germanium 72.64
50	Sn	Tin 118.71
82	Pb	Lead 207.2
114		

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Doping – not what you think

- We can improve the conduction of Silicon by doping it with other elements.
 - N-type regions are formed by adding small amounts of elements that have more than 4 electrons in their outer shell and, these extra electrons can serve as charge carriers.
 - P-type materials are formed by adding elements that have 3 electrons in their outer valence shell. These atoms create spaces in the lattice of covalent bonds into which electrons can flow.



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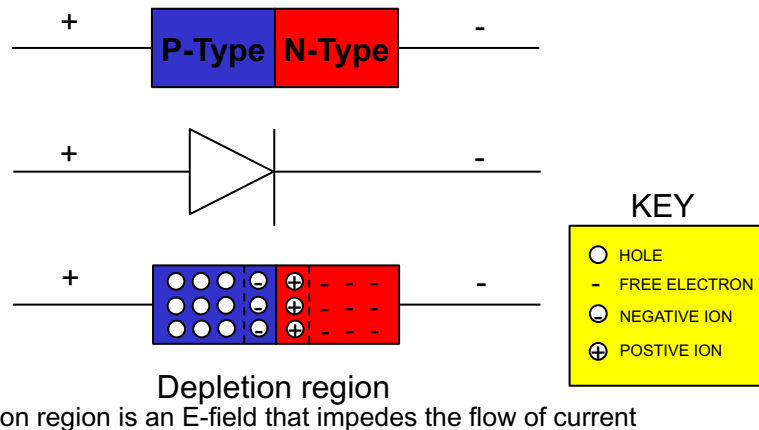
Bottom Line

- N-type materials are good semiconductors because they have extra electrons which are negatively charged and can be used to carry a current.
- P-type materials are good semiconductors because they have extra spaces into which electrons can move. These 'holes' can be thought of as positive charge carriers.
- Now we are ready to describe our building block: MOSFET transistor

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A Diode (a pn-junction) – recall LED from lab

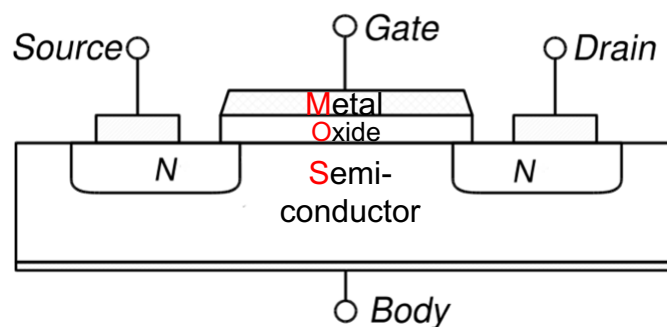
- A union of P-type and N-type materials
- Functions as a one-way “valve” in an electric circuit
- Only allows current to flow in one direction



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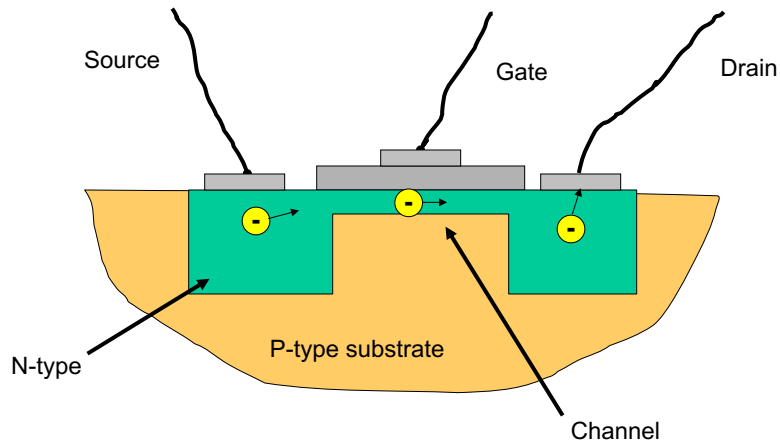
the MOSFET (your 1st Transistor!)

- MOSFET : **M**etal **O**xide **S**emiconductor **F**ield **E**ffect **T**ransistor
- Picture shows a cross section of such a device.
- Notice it has 4 electrical terminals: Source/Drain/Gate/Body



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MOS FET (Metal Oxide SemiConductor)



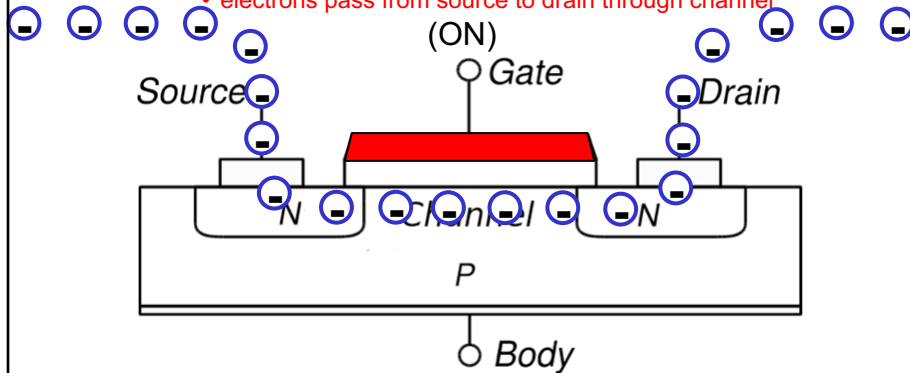
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How we want it to work...

- Goal: Pass current through this device (from drain to source)
 - BUT we want to control that current (using the gate terminal)

– If GATE is ON

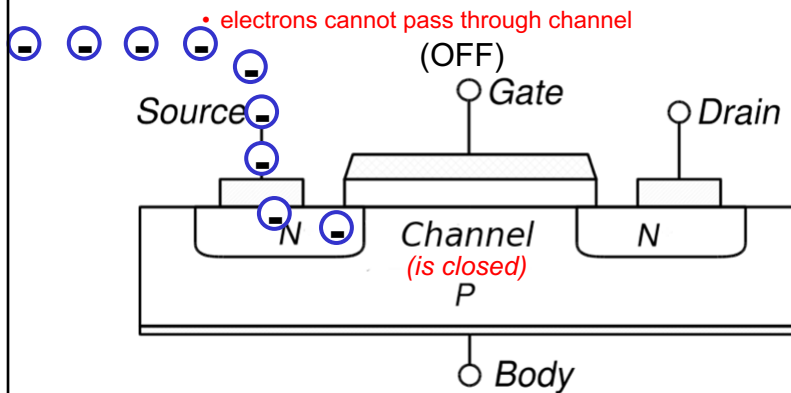
- electrons pass from source to drain through channel



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How we want it to work...

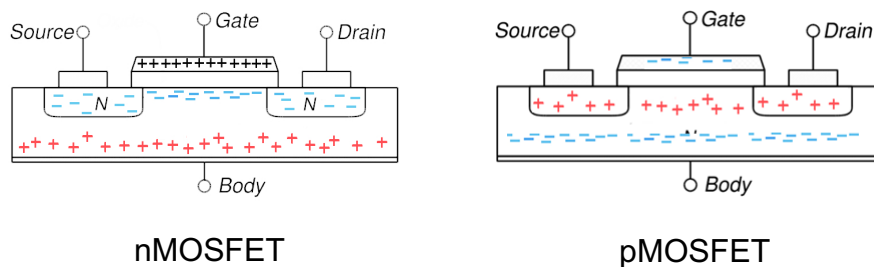
- Goal: Pass current through this device (from drain to source)
 - BUT we want to control that current (using the gate terminal)
 - If GATE is OFF



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Two types of MOSFETs: nMOSFET and pMOSFET

- nMOSFET (nMOS): channel carries negative charges (electrons)
 - GATE MUST BE (+) to be ON
- pMOSFET (pMOS): channel carries positive charges (holes)
 - GATE MUST BE (-) to be ON

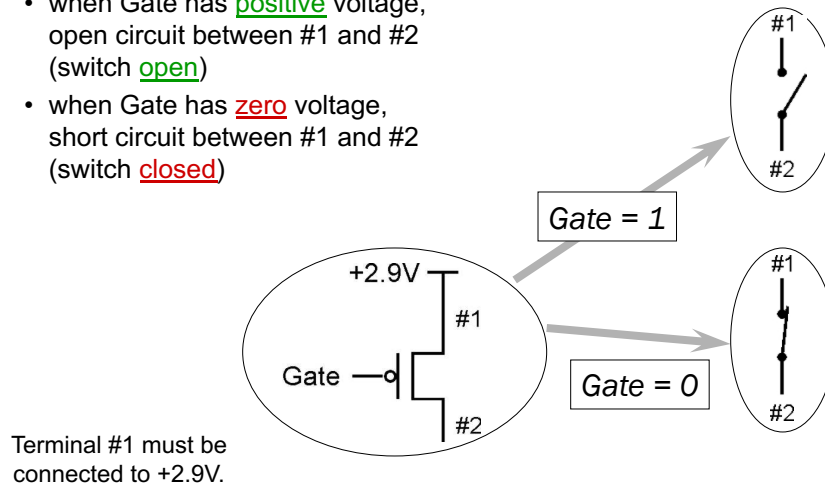


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Simplified view: p-type MOS Transistor

▪p-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)

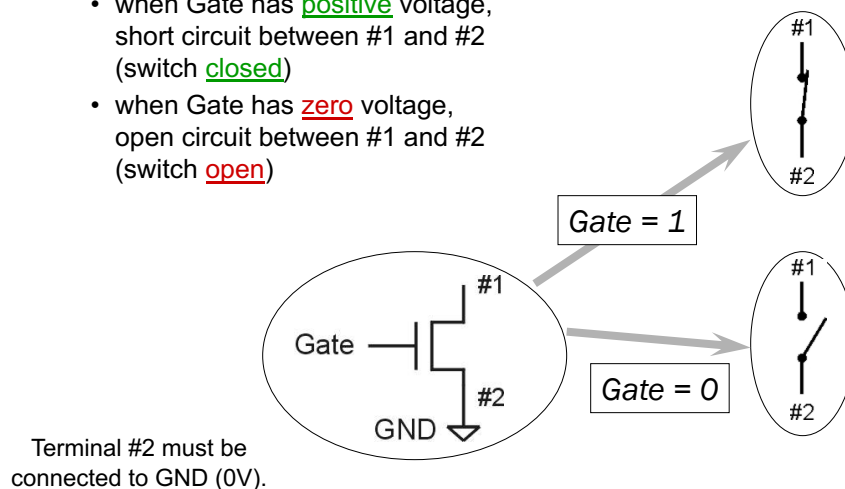


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Simplified view: n-type MOS Transistor

▪n-type *complementary* to p-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)



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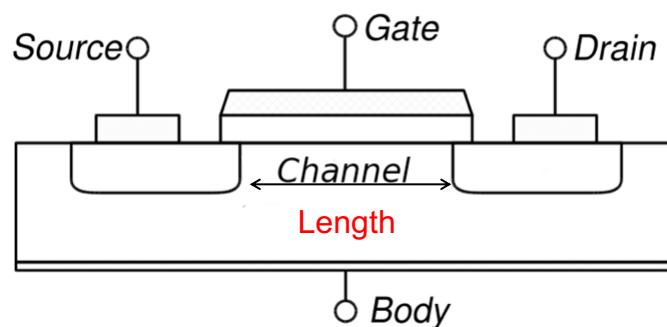
Some observations about CMOS – why does your laptop get hot ?

- Note that when the circuit is fully ON or fully OFF there is no path from the high voltage to the low voltage so no current flows
- However, when the output is in the process of switching from one logic level to another, there can be overlap of the two switches being on
 - this causes a momentary short
 - (current goes from pwr-to-gnd)
 - Longer the short, more current you burn (more power wasted)!
- When current flows, device gets hot
 - The faster you switch the circuit, the more current flows, the more heat is generated, the hotter your laptop gets.
 - This has proven to be an important barrier to speeding up CMOS circuitry
 - led to wide use of Multi-Core processors....

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Speed of MOSFET

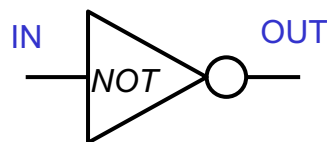
- Dependent on many factors, 1 crucial factor: Length of Channel
 - Why? Electron takes less time to travel across smaller distance!
 - Currently, 11nm in length!
 - Smaller the length, faster the 'speed'



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Gate Delays How fast is your computer

- With any logic circuit there will be a short delay between the time you change one of the inputs and the time the output settles to its final value.
- This time is referred to as the gate delay.
- For modern circuitry, these gate delays are on the order of nano seconds (10^{-9} seconds) or pico seconds (10^{-12} seconds) .
- Nonetheless, these delays ultimately limit the rate at which you can compute – limiting the number of operations you can perform per second.



Inverter Logic Gate

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The “Logic” Behind CMOS Gate Implementation

Transistors in series implement “AND”

- Current flows only if both are “ON”

Transistors in parallel implement “OR”

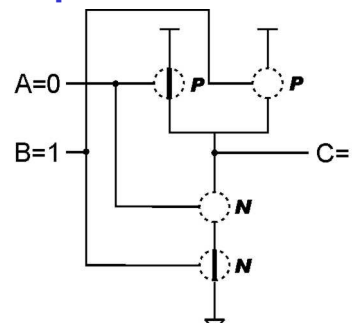
- Current flows if either is “ON”

CMOS is naturally inverting

Result: n-network implements function

NAND example

- n-network transistors in series gives AND
- Natural inversion gives NAND



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

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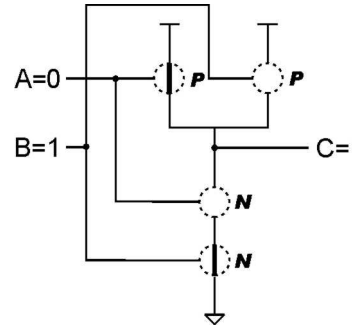
The “Logic” Behind CMOS Gate Implementation

P-network is complement of n-network

- Series n-network → parallel p-network
- Parallel n-network → series p-network

NAND example

- p-network transistors in parallel
- Designing in CMOS:
 - We always design the n-network (aka – the pull-down network) first
 - Then, complement it and you’ve figured out the p-network (aka – the pull-up network)

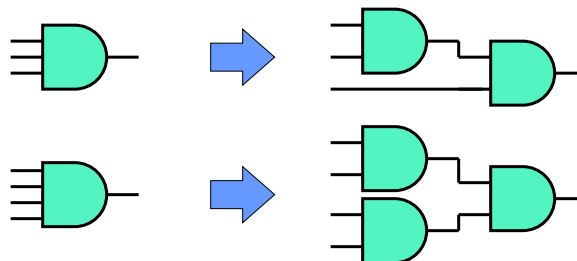


A	B	C
0	0	1
0	1	1
1	0	1
1	1	0

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More than 2 Inputs? Arbitrary Functions?

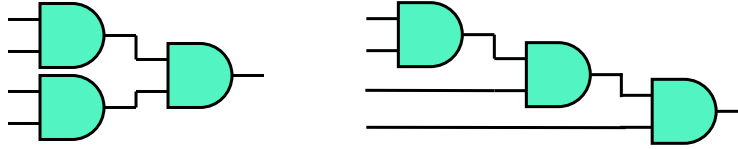
- AND/OR can take any number of inputs
 - AND = 1 if all inputs are 1
 - OR = 1 if any input is 1 (0 if all inputs are 0)
- Implementation
 - Multiple two-input gates or single CMOS circuit



- Can implement arbitrary boolean functions as a gate
 - More complex n- and p- networks

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Gate Delays



- Which is the better implementation of 4-input AND?
 - One on the left
 - Why? It's faster, 2 "gate delays" instead of 3
- **Gate delays:** longest path (in gates) through a circuit
 - Grossly over-simplified, ignores gate differences, wires
 - Good enough for our purposes