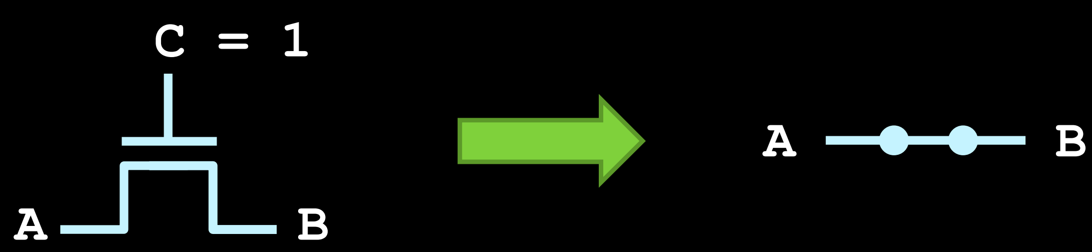
Transistors

Introduction to Transistors

- Transistors form the basic building blocks of all computer hardware.
- Invented by William Shockley, John Bardeen and Walter in 1947, replacing previous vacuum-tube technology.
  - Won Nobel Prize for Physics in 1956.
- Used for applications such as amplification, switching and digital logic design.

What do transistors do?

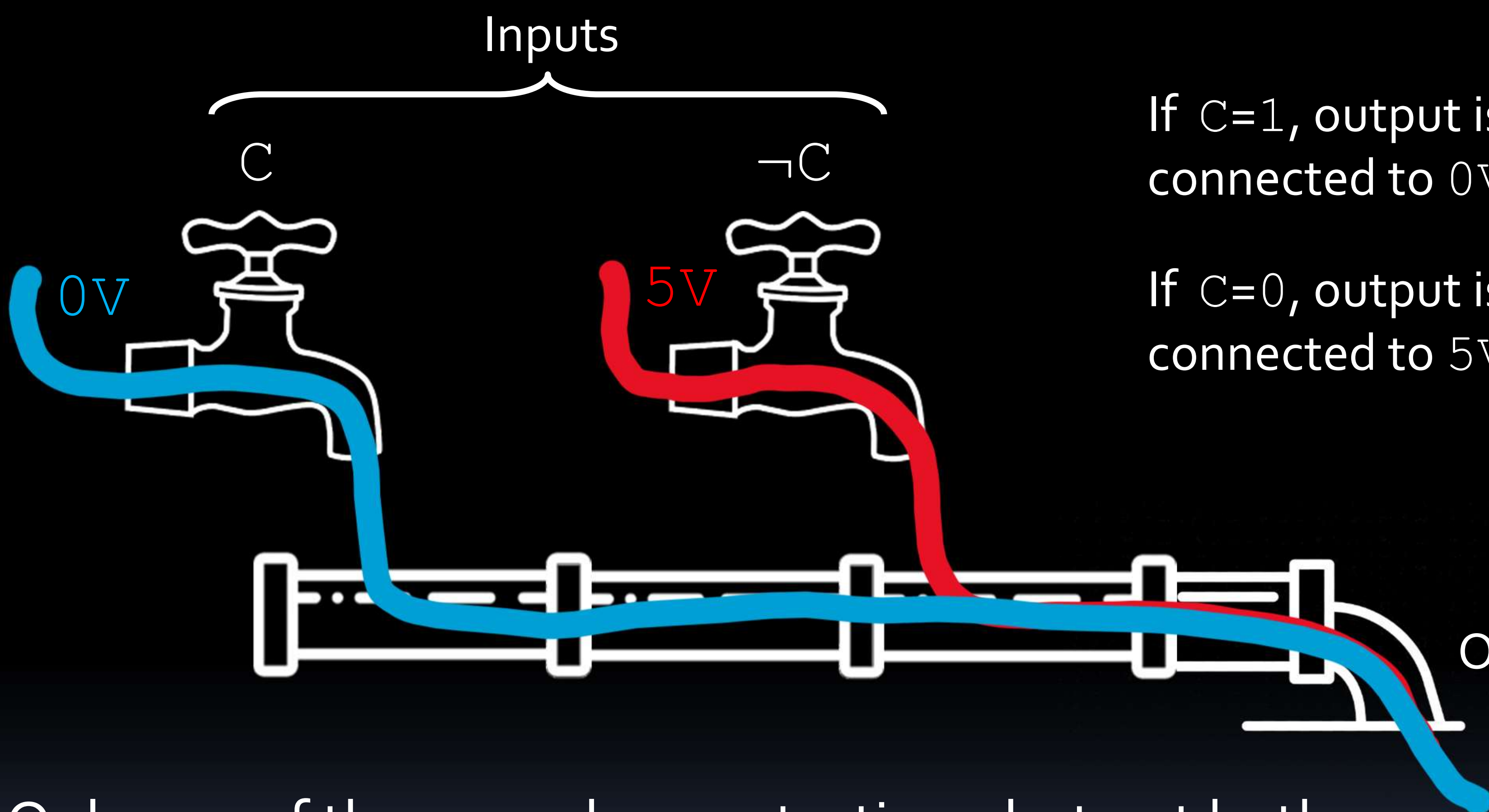
- Transistors connect Point A to Point B, based on the value at Point C.
  - If the value at Point C is high, A & B are connected.



  - And if the value at Point C is low, A & B are not.

  - Need to know a little about electricity now….

Electrical Faucets

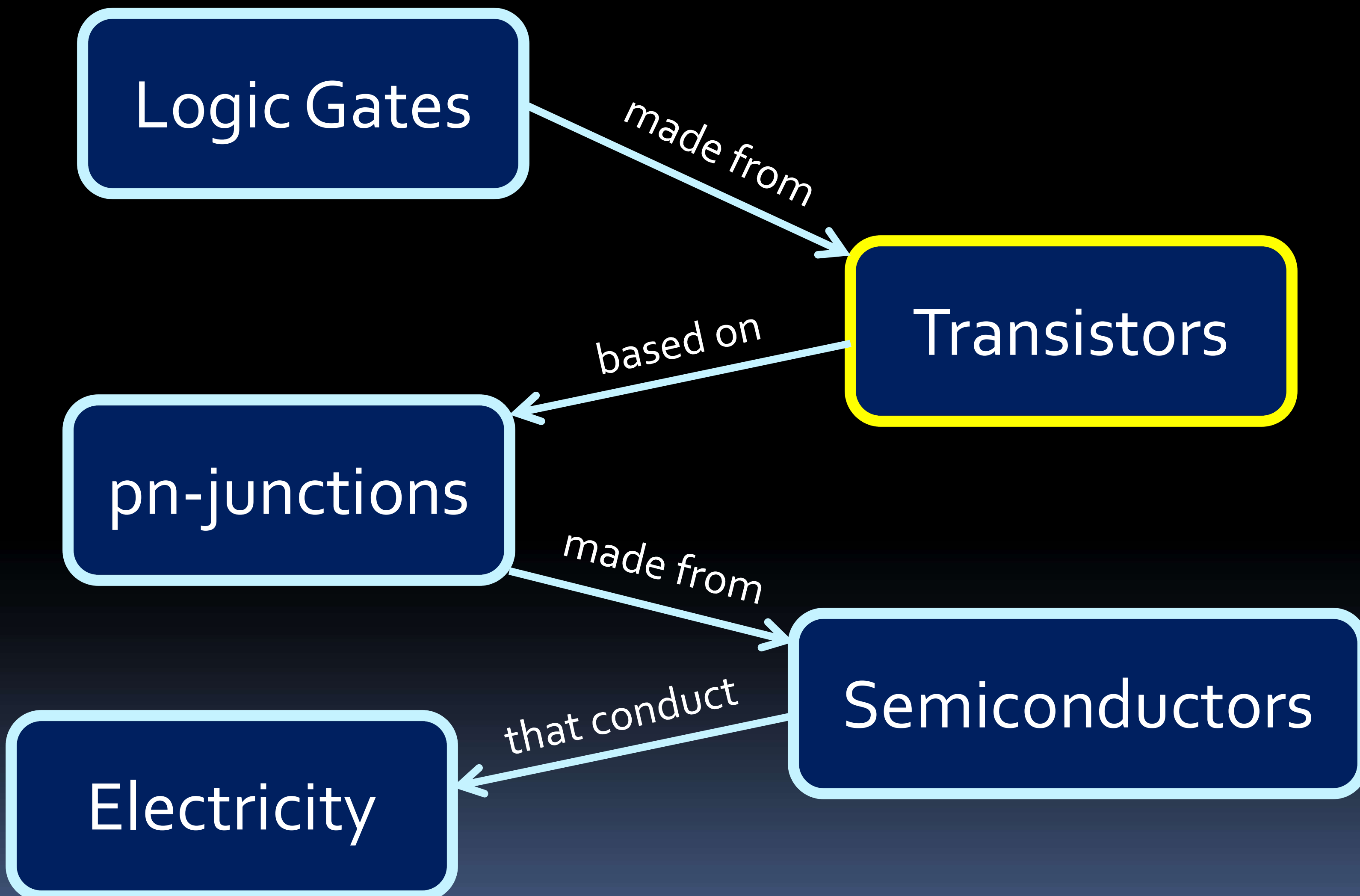


If C=1, output is connected to 0V.

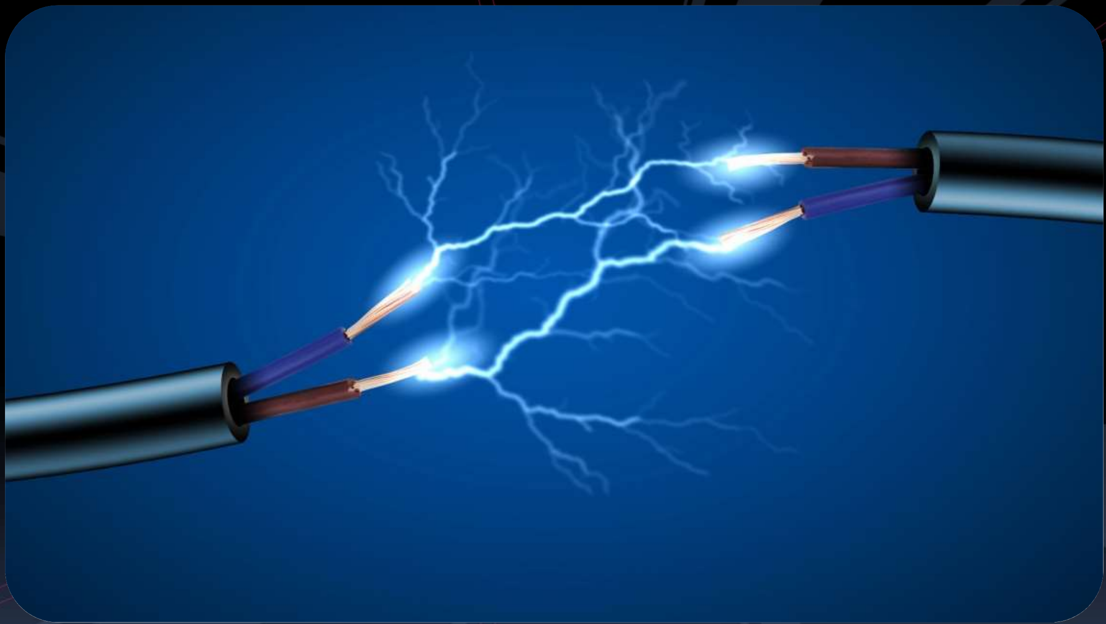
If C=0, output is connected to 5V.

Only one of these can be on at a time, but not both.
Also doesn't work if neither faucet is on.
More on this later….

Where do transistors fit?

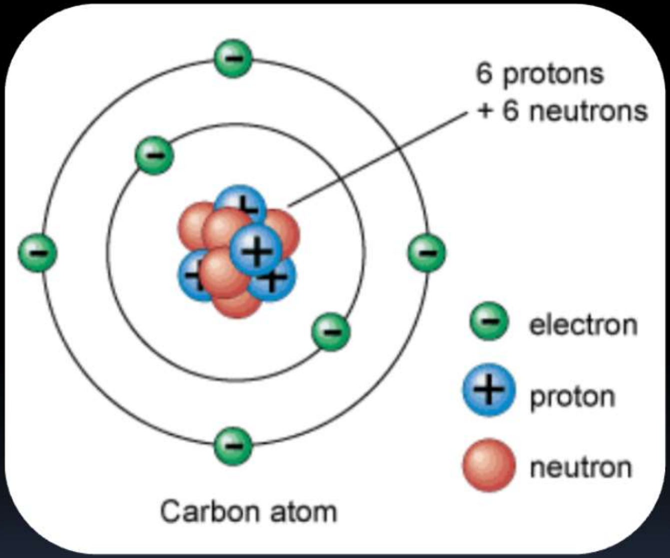


Electricity Basics



Intro to Electricity

- Electricity is the the flow of charged particles (usually electrons) through a material.
- These charged particles come from atoms, which are made up of protons (positive charge), neutrons (no charge) and electrons (negative charge)
  - Electricity stems from electron movement.



Electricity = electrons

- Electrical particles (like electrons) want to flow from regions of high electrical potential (many electrons) to regions of low electrical potential (not as many electrons).
  - Similar to gravitational potential
- This potential is referred to as voltage.
- The rate of electron flow is called the current.

Water Analogy

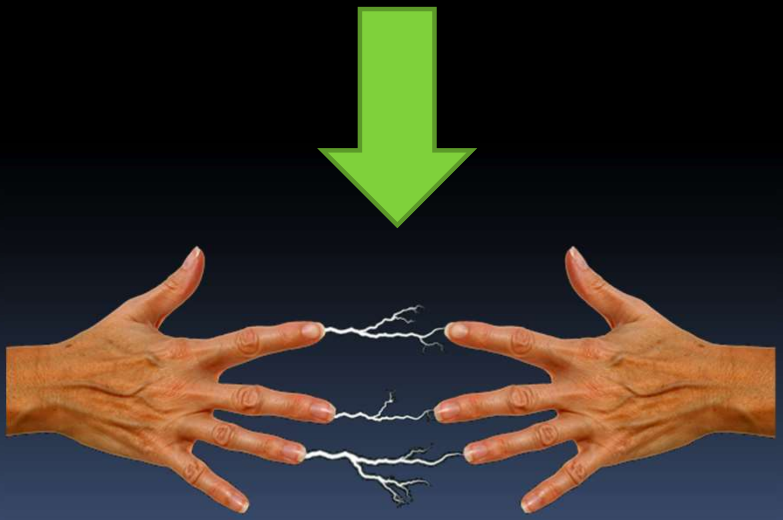
- To help picture this concept of voltage and current, imagine a reservoir:
  - Electrons flow from high to low potential like water would flow from the reservoir to the ground.
  - Voltage is like the elevation of the water above the ground.
  - Current is the rate at which the water flows.
- The relationship between voltage (V) and current (I) is called resistance: $R = V/I$

A Note about Current

- Even though current is caused by electrons flowing through a material, the convention is to measure current as the movement of positive charges.
  - *Protons don't actually move*. When electrons move from point A to point B, the result is that B becomes more negative and A becomes more positive.
  - Scientists historically viewed current in terms of this creation of positive charge in a material.
  - It's not completely clear why scientists decided this. Just go with it ☺

Static electricity example

- When you shuffle your feet back and forth on a carpet, you pick up extra electrons in your body and develop an electrical imbalance, relative to the ground.
- When you touch an object or person who is electrically balanced, those extra electrons transfer over to that object or person.



Van de Graaff Generator

Sources of electricity

- Where do these electrons (and this electricity) come from?
- Two common sources:
  - Batteries have a concentration of particles stored inside them up that will run out eventually (like water reservoirs).
  - Most electricity that we use comes from electrical outlets, that are constantly being supplied with electric particles that never run out (like waterfalls).
    - Discussion point: power bars.

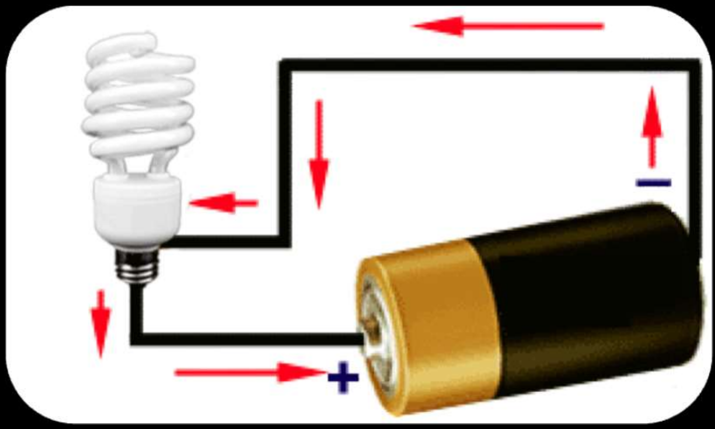
The path of electricity

- A few things to note about the path that electric particles like to take:
  - Current always flows toward the zero voltage point of a circuit.
    - Commonly referred to as ground.
  - Electricity always takes the path of least resistance from source to ground.
  - Remember: Even though electrical current is the flow of electrons through a medium, its direction is typically expressed as *the movement of the positive charges*.

Electricity Example

Using electricity

- Knowing that electric particles want to travel from areas of high concentration to areas of low concentration, we can use this to drive circuits.
  - Each of these circuits has a source of electrical particles, some path between this source and the ground, and some resistance along this path that dissipates these electrons.

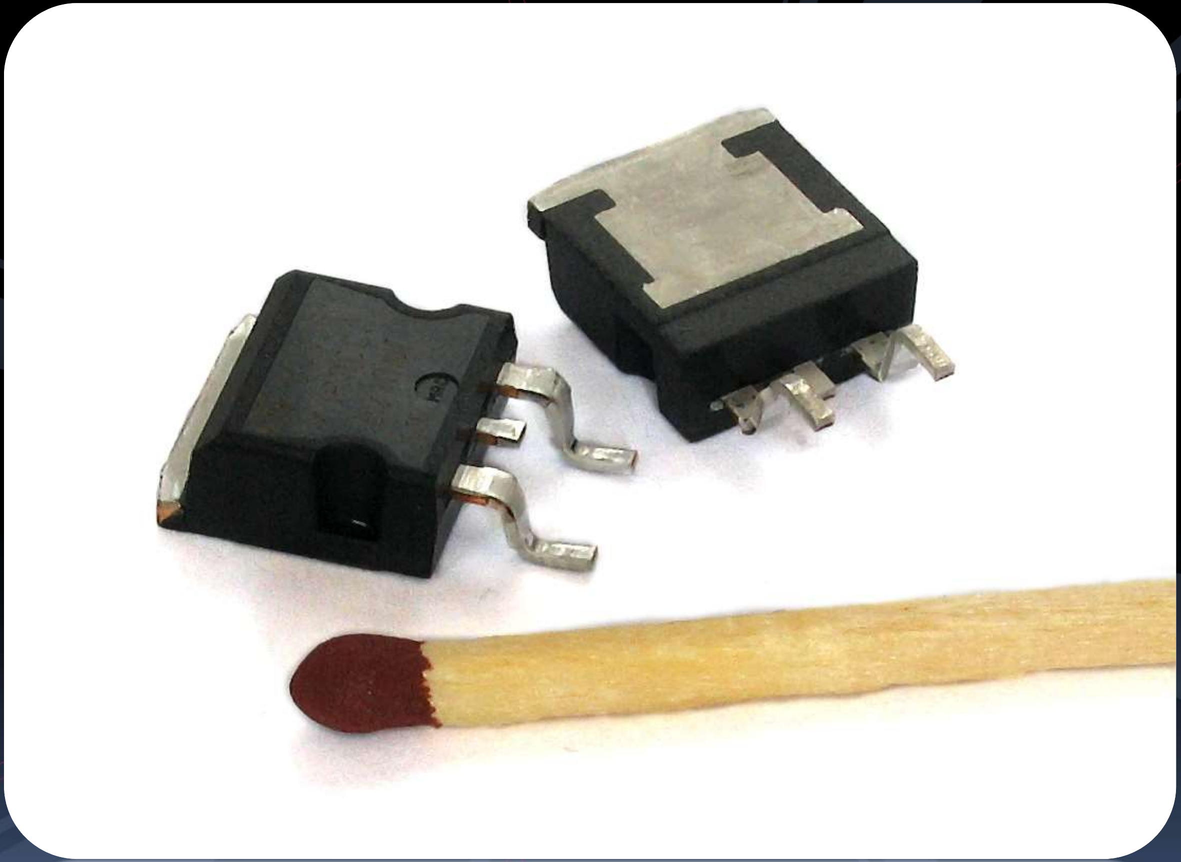


Resistance is Futile

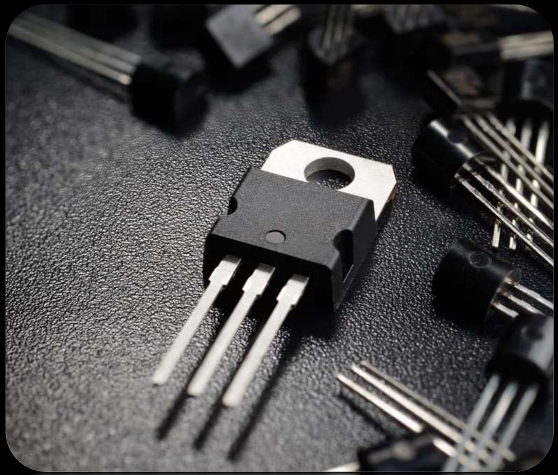
- In the water analogy, resistance would be measure how restrictive the pipe is that connects the reservoir to the ground.
  - Wide, smooth pipe = low resistance
  - Narrow, twisty pipe = high resistance
- Electrical resistance indicates how well a material allows electricity to flow through it:
  - High resistance (aka insulators) don't conduct electricity at all, or only under special circumstances.
  - Low resistance (aka conductors) conduct electricity well, and are generally used for wires.
  - These are largely determined by the position on the element on the periodic table.
  - Measured in ohms (Ω). More ohms, more resistance.
- Semiconductors are somewhere in between conductors and insulators.

If you're following the recorded lectures, please skip ahead to the slide on "How transistors work". We needed to reduce the lecture material in the fall semester, so you won't be responsible for the section on semiconductor material.

Using Transistors



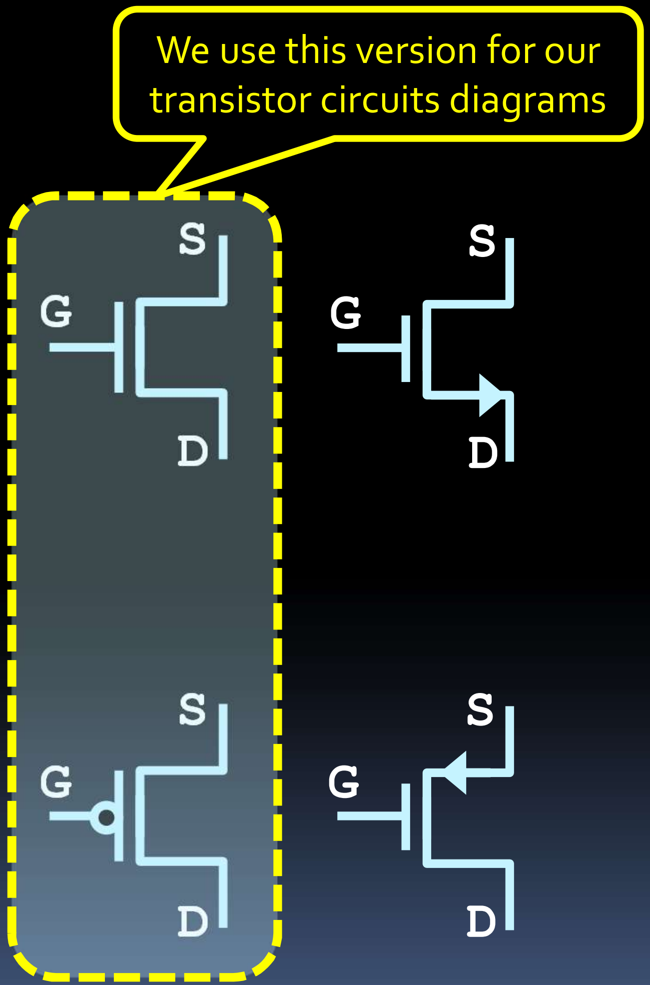
How transistors work



- Transistors are devices made of semiconductor material, which can act as a conductor in some cases and an insulator in others.
  - Transistors can be implemented in multiple ways, most commonly the MOSFET (Metal Oxide Semiconductor Field Effect Transistor).
- MOSFETs have three wires that define their behaviour: the source, the drain and the gate.

How transistors work

- There are two main types of MOSFETs we look at in this course:
  - nMOS transistors allow electricity to conduct between the source and the drain when a positive voltage is applied to the gate.
  - pMOS transistors allow electricity to conduct between the source and the drain when a negative voltage is applied to the gate.



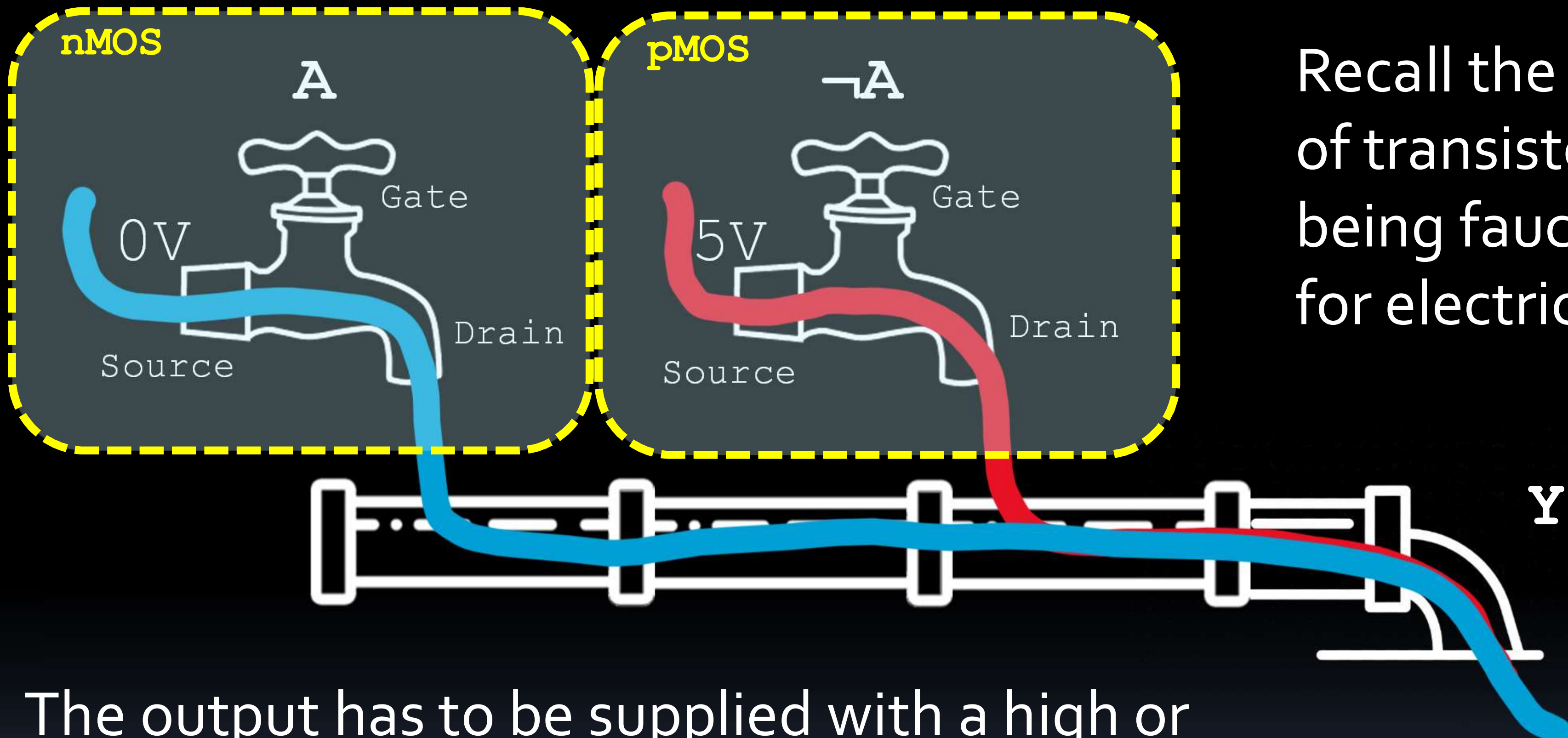
Transistors to Gates

- The gate voltage determines whether the source and drain are connected. But no current flows between them unless the source voltage is high.
  - i.e. nMOS truth table on the right.
- One final step: combining MOSFETS to create high and low voltage outputs, based on high and low voltage inputs.
  - General approach: create transistor circuits that make current flow to outputs from high or low voltage, based on transistor input values.

nMOS Truth Table

V_{DS}	V_{GS}	I_{DS}
Low	Low	Low
Low	High	Low
High	Low	Low
High	High	High

Revisiting the Faucet Analogy



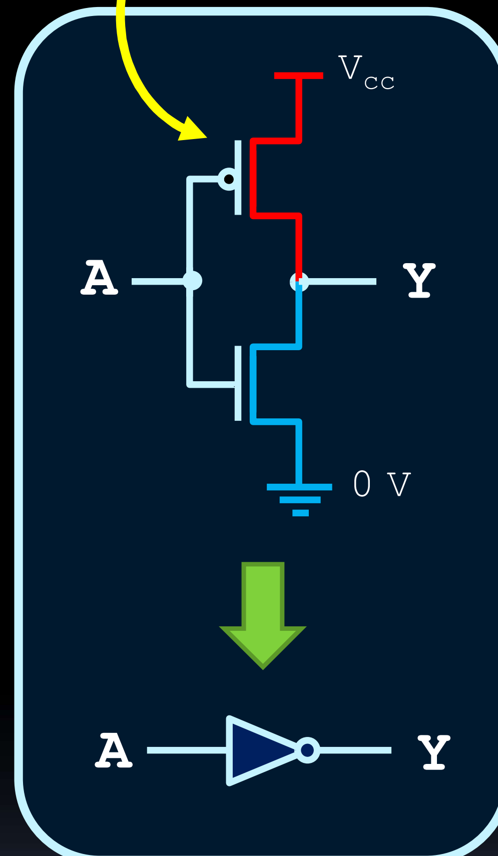
Recall the idea of transistors being faucets for electricity!

The output has to be supplied with a high or low electrical value from one of the inputs.
Not connecting the output to high voltage is not the same as connecting it to low voltage!

Making gates

- Since these transistors aren't simply on/off switches, digital logic gates (AND, OR, NOT) are created by a combination of transistors
  - Examples: NOT gate circuit in diagram.
- Physical data:
  - "High" input (aka V_{cc}) = 5V
  - "Low" input (aka Ground) = 0V
  - Switching time ≈ 120 picoseconds
  - Switching interval ≈ 10 ns
  - NAND is most common logic gate

Remember: This transistor turns on when A is 0!

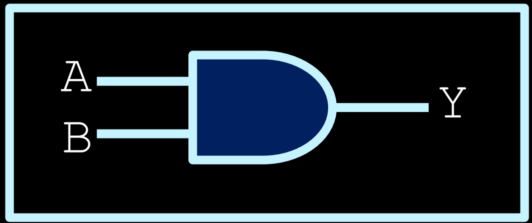


From Transistors to Gates

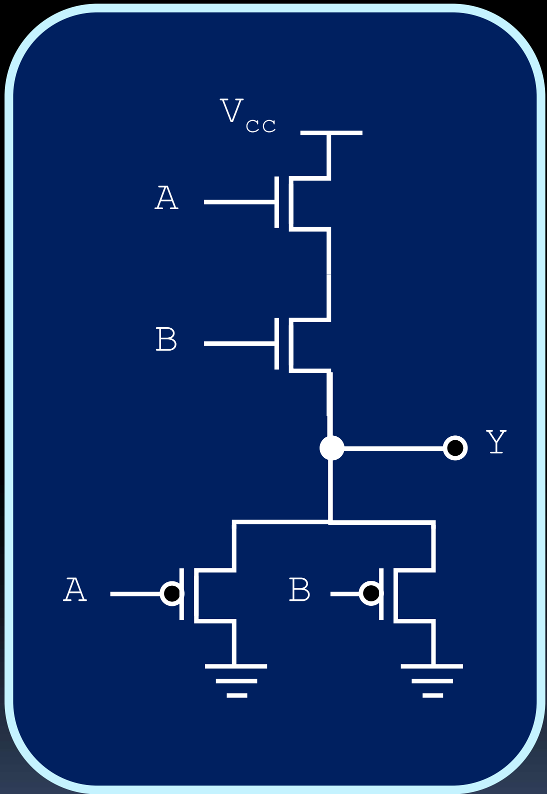
- Making a gate from transistors is easy. Just remember the following:
  - Every gate has one output and one or more inputs.
  - Every combination of input values **<u>must</u>** connect the output to either high voltage (V_{cc} = 5V) or low voltage (Ground = 0V)
  - Not connecting the output to high voltage isn't the same as connecting the output to low voltage.
  - Ask yourself: What input combinations connect the output to high voltage and what combinations connect it to low voltage?

Making two-input AND gates

- Consider the truth table for an AND gate:
  - Two inputs, one output.
  - Output is high when both A and B are high.
  - If A is low or B is low, output Y is connected to the ground.

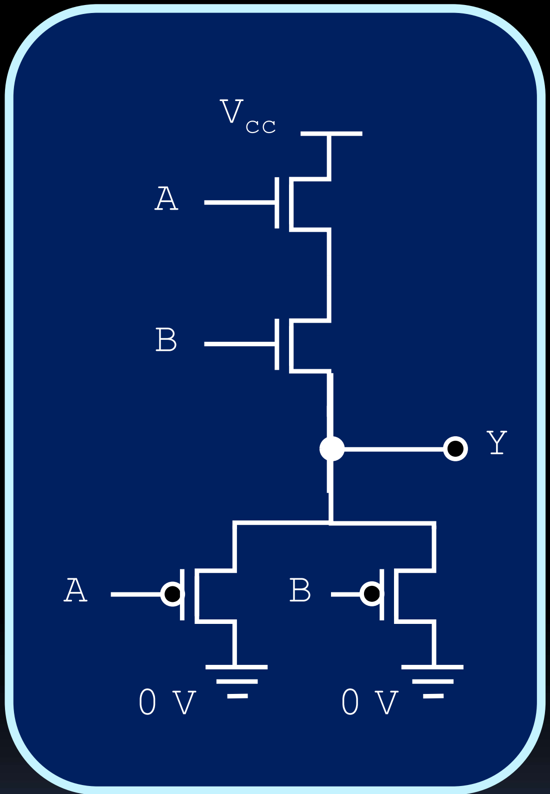


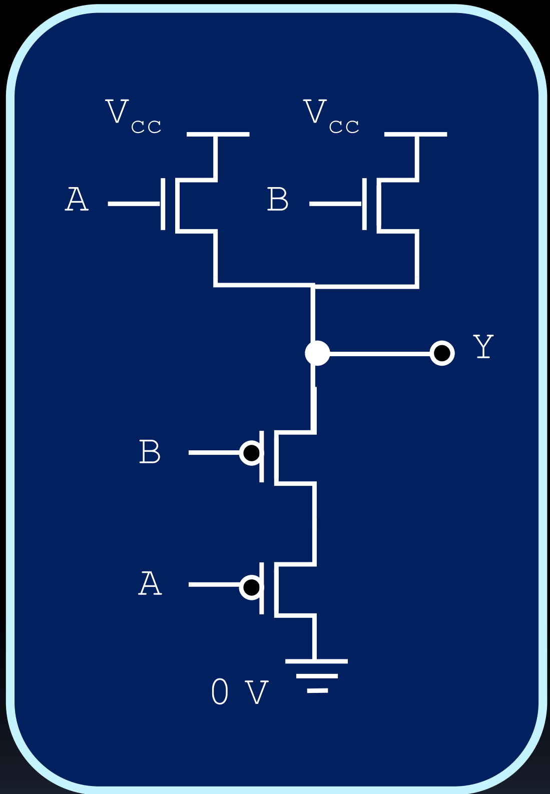
A	B	Y
0	0	0
0	1	0
1	0	0
1	1	1

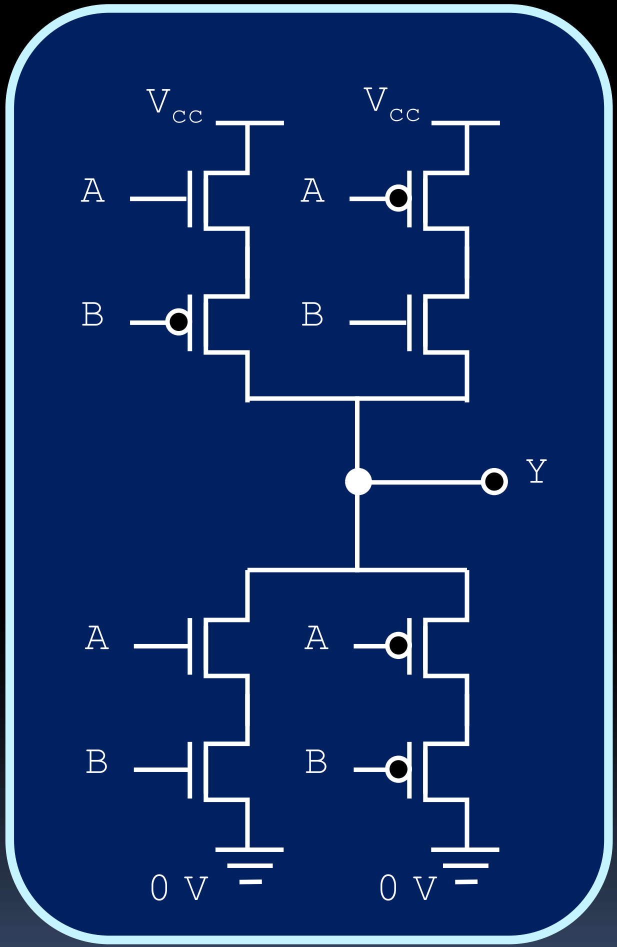


What gates do these make?

(Assume that all the wires labeled A and B refer to the same A and B source voltages)







Note: `Vcc` = "Common Collector Voltage"
= high voltage (5 V)

Multiple-input gates

- What if we wanted a 3-input OR gate?
  - The output for an OR gate is low only when the inputs are all low.
  - If any of the inputs are high, the output is then connected to 5 volts (V_{cc})
- What about making circuits out of gates?