CSC258: Computer Organization

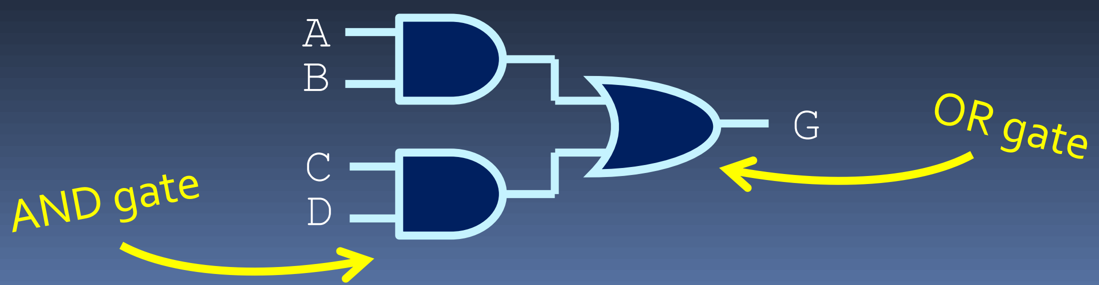
Transistors

Review

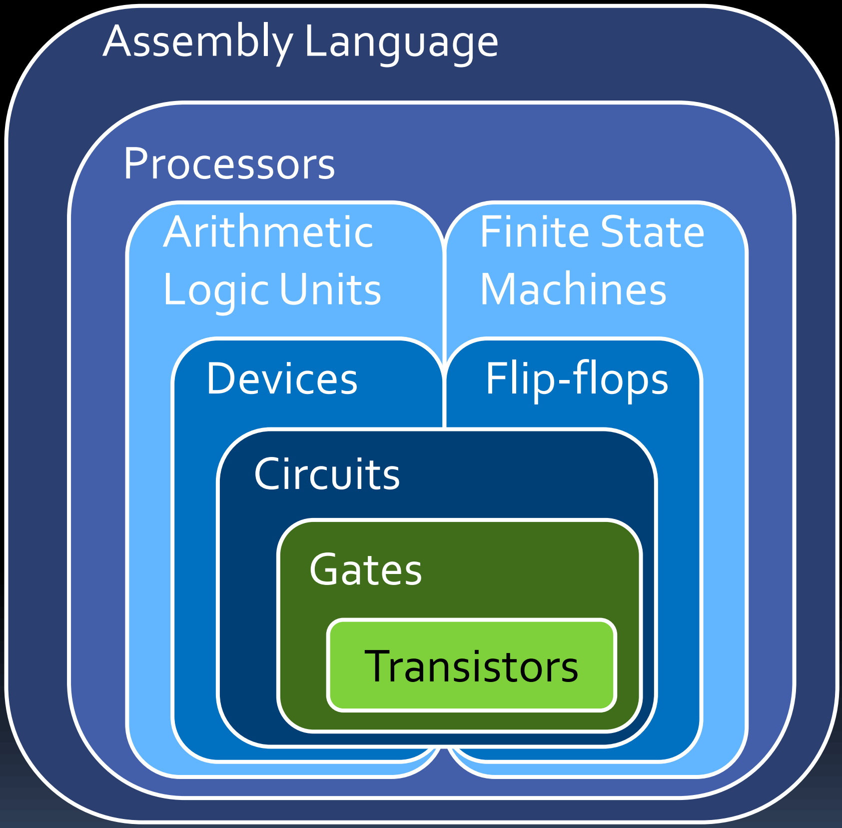
- Example: Create an expression that is true if the variables `A` and `B` are true, or `C` and `D` are true.

```
G = (A & B) | (C & D)
```

- Now create a circuit that does the same thing:

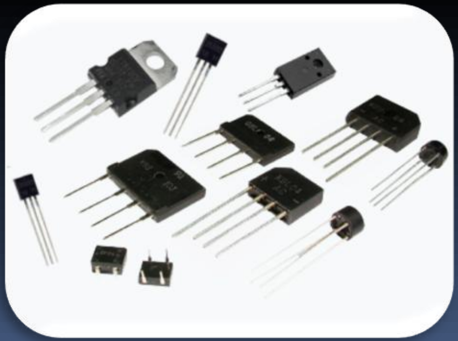


The course at a glance

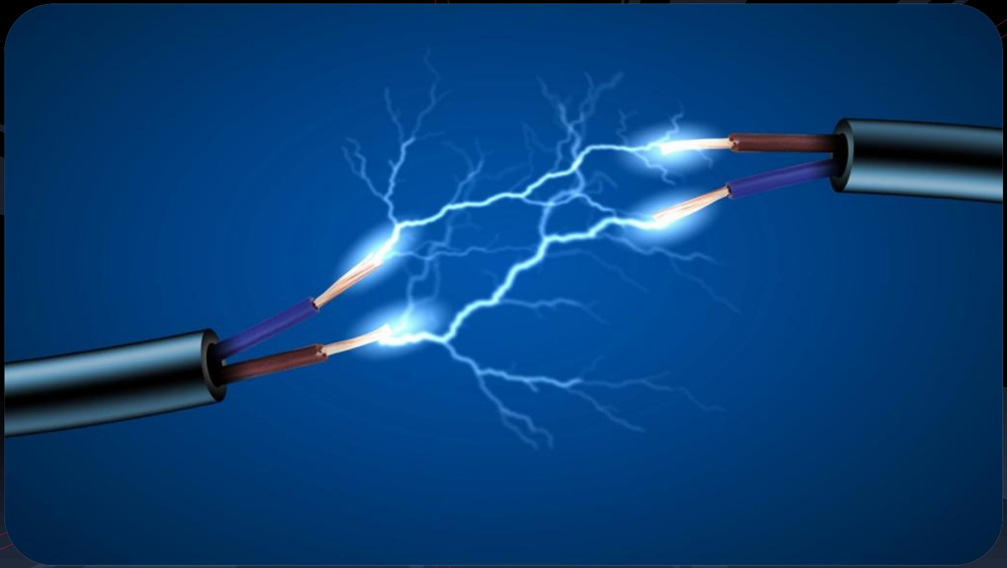


Starting from the bottom

- Gates can combine values together like logical operators in C or Java.
- But how do gates work?
  - First, we need to understand electricity.
  - Then, we need to understand transistors.

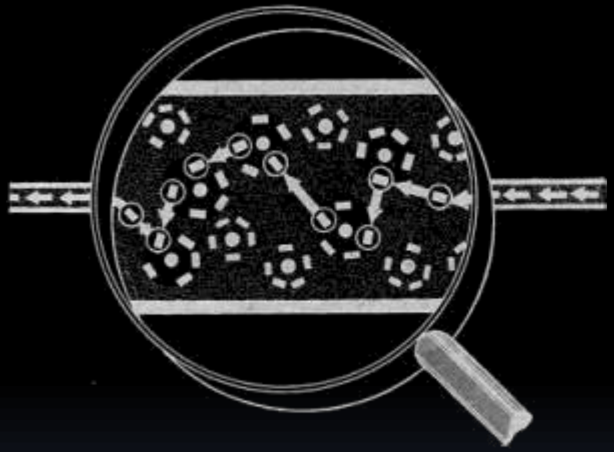


Electricity Basics



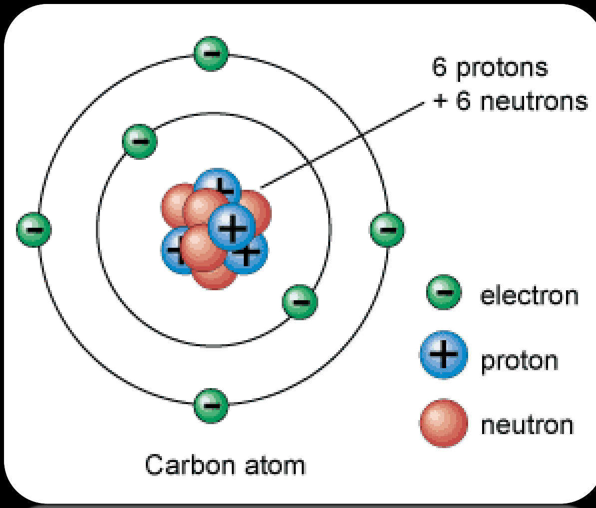
Intro to Electricity

- Electric current is the flow of charged particles (usually electrons) through a material.
  - Electric current could also be caused by the flow of protons or ions, but this is less relevant for this course.



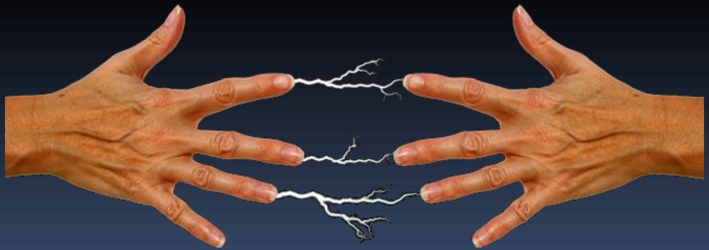
Electricity = electrons

- Electrons are negatively charged particles
- Protons are positively charged particles
- Particles of the same polarity experience ________________
- Particles of the opposite polarity experience ________________
- When material (e.g. atom) has equal number of electrons and protons it is electrically neutral



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

Voltage and current

- Any charged particle produces an electric field in its surrounding
- If one object has more electrons than protons, and another object has fewer electrons than protons, connecting the two causes electrons to flow such that the difference is neutralized
- The two objects have different ________________
  - Similar to gravitational potential
- The difference in electric potential between two objects is referred to as ______________________
- The rate of flow of electrons when the two objects are connected is called the

  ____

Water Analogy

- To help picture this concept of voltage and current, imagine a reservoir:
  - Electrons flow from high concentration of electrons to low concentration 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.

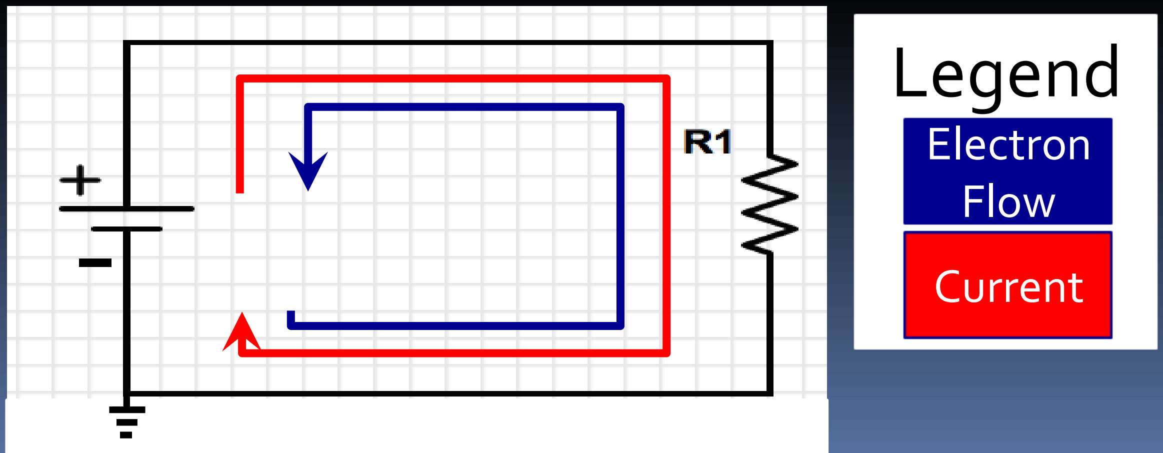
Sources of electricity

- 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).

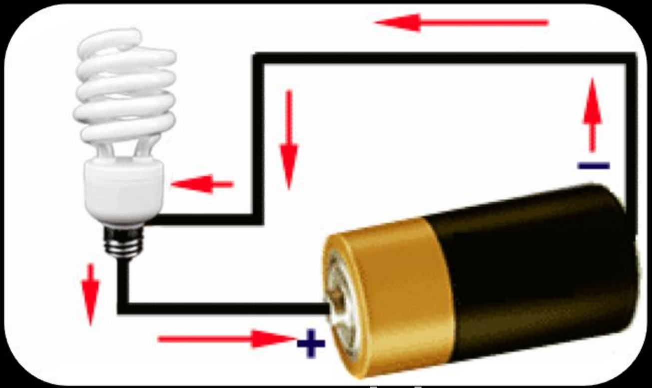
  - Most electricity that we use comes from electrical outlets, that are constantly being supplied with electric particles that never run out (like waterfalls).

The path of electricity

- In electric circuits, it is very useful to define a reference point that all other voltages are expressed against:
  - This point is known as zero voltage point of a circuit.
    - Commonly referred to as ground.
  - As a convention, current is always said to flow towards ground
    - This is actually opposite direction of the flow of electrons
    - Don't let this confuse you; it's just a convention



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 circuit has a source of electrical particles, some path between this source and the ground, and some resistance along this path that dissipates the energy from the source.

Ohm's Law

- The relationship between voltage (V) and current (I) is called resistance
- $R = V/I$
- $I = V/R$
  - Given constant resistance, increasing voltage (potential) increases current (flow)

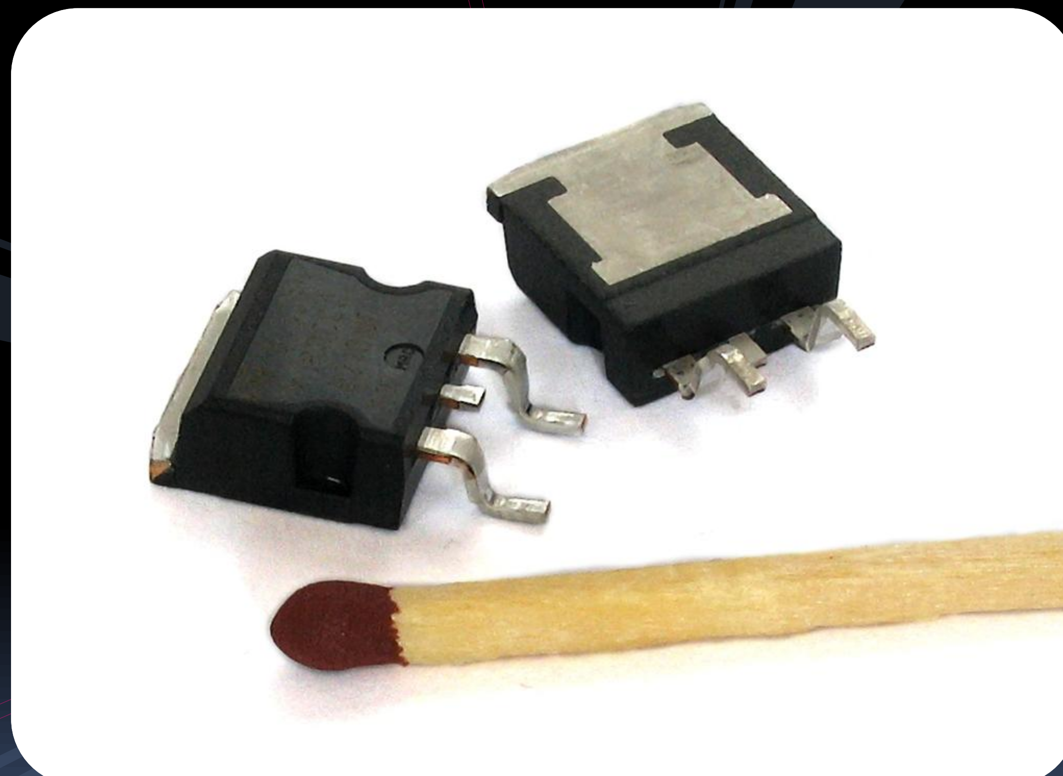
Resistance is Futile

- 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:
  - Resistance measured in ohms (Ω). More ohms, more resistance.
  - Insulators have high resistance and don’t conduct electricity at all, or only under special circumstances.
  - Conductors have low resistance and conduct electricity well. Wires usually made of conductive material.

Semiconductors

- Semiconductor are materials that straddle the boundary between conductors and insulators
- Behave like insulators or conductors, depending on factors like
  - ________________
  - ________________
- Example: silicon (Si)

Transistors



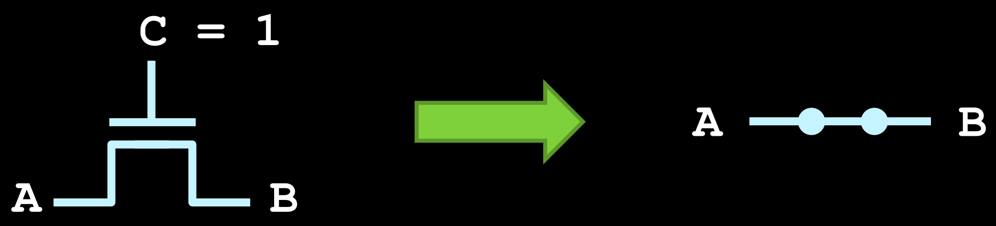
Introduction to Transistors

- Transistors form the basic building blocks of almost 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.

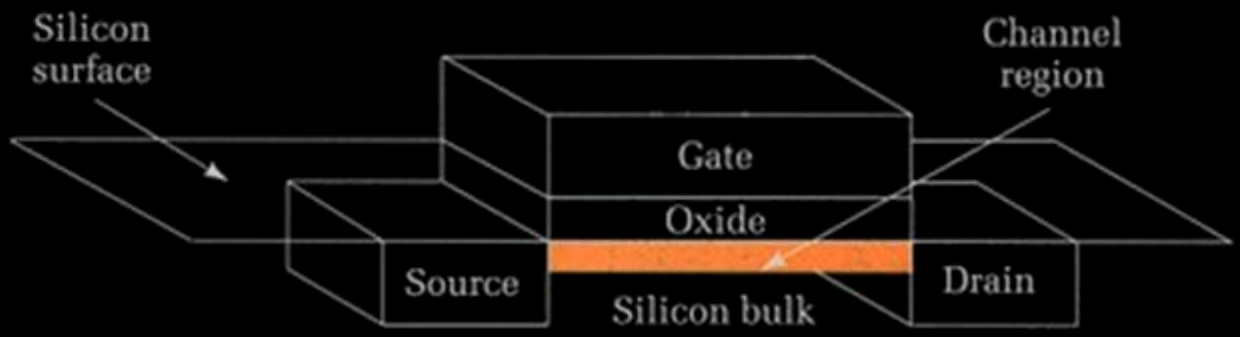


  - If the value at Point C is low, A & B are not connected

Creating transistors

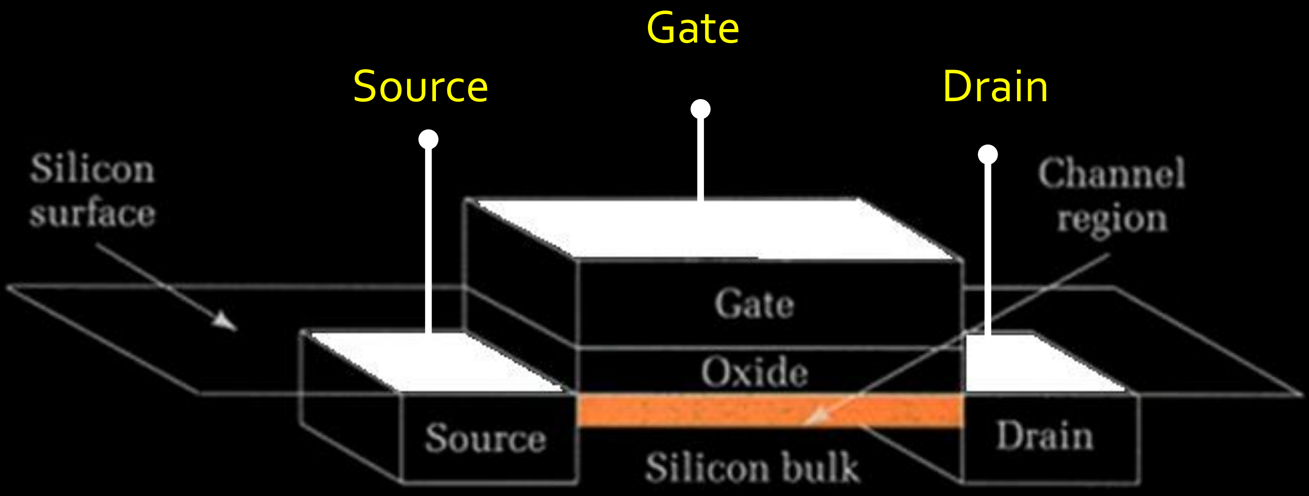
- Transistors use the characteristics of semiconductors to implement useful behaviours, such as amplification and switching.
- Several different types of transistors exist
- We will only discuss MOSFET

The MO of MOSFETs



- Metal Oxide Semiconductor Field Effect Transistors are composed of a layer of semiconductor material, with two layers on top of the semiconductor:
  - A metal layer (called the gate), that can have an electric charge applied to it
  - An oxide layer that doesn't conduct electricity

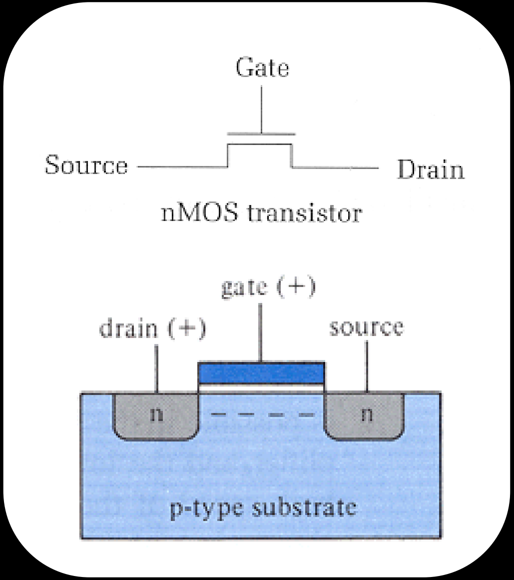
Electrodes

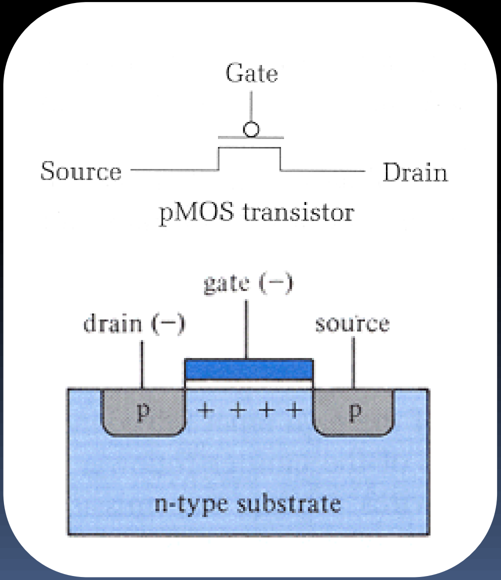


- Due to properties of semiconductors comprising the transistor, channel region does not conduct electricity unless appropriate voltage is applied to the gate
  - The “appropriate” voltage depends on transistor type

nMOS vs pMOS

- Two different types of MOSFETs exist, based on the type of semiconductor in the drain and source.
- nMOS conducts electricity between source and drain when positive voltage (5V) is applied to the gate
- pMOS conducts electricity between source and drain when ground (0 V) is applied to the gate





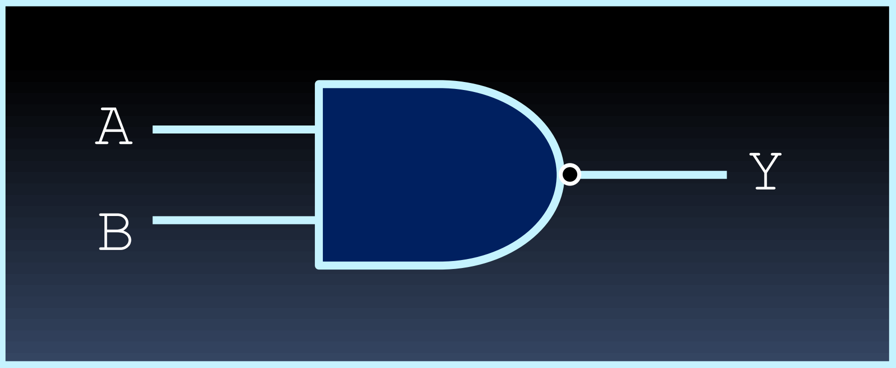
Making gates

- We can combine nMOS and pMOS transistors to create gates
- Simplest gate is the NOT gate
- By combining nMOS and pMOS, both output 1 and output 0 are guaranteed to be at desired logic level

A	Y
0	1
1	0

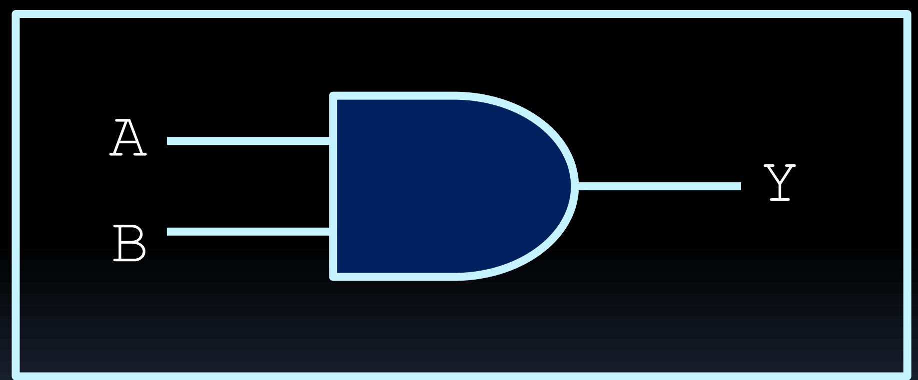
NAND gate

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



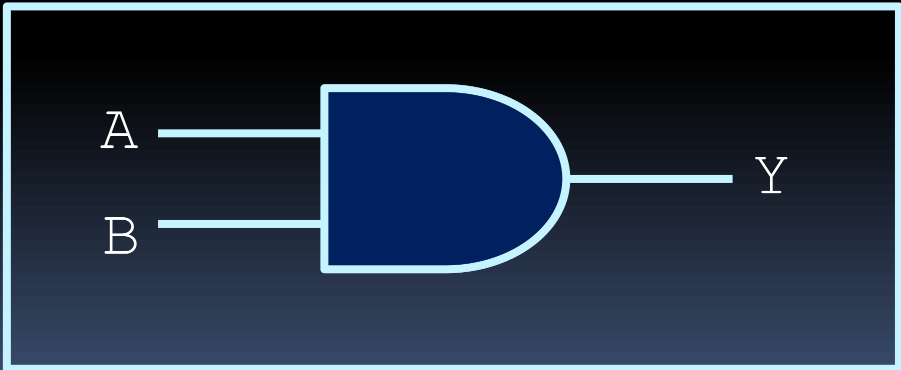
AND gate?

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



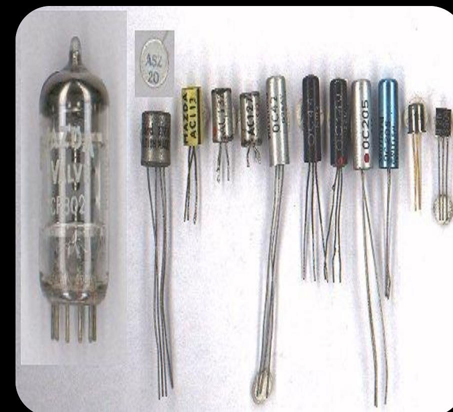
And gate (the right way)

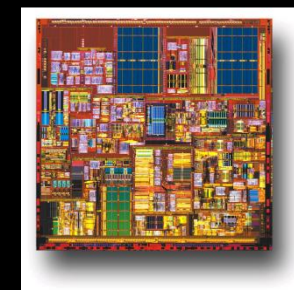
A	B	Y
0	0	0
0	1	0
1	0	0
1	1	1



Transistor/chip Fabrication

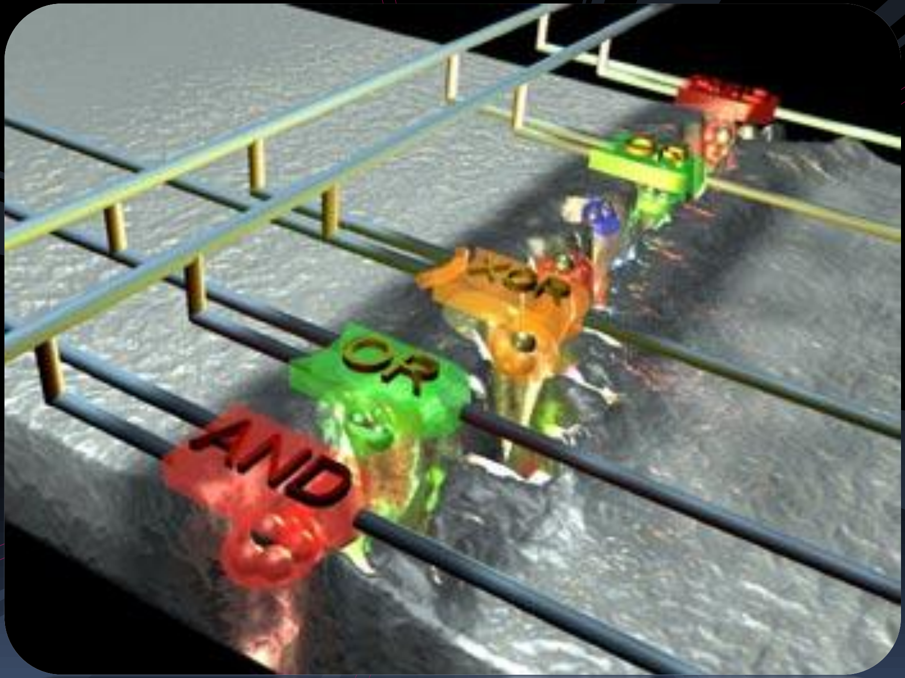
- Large numbers of transistors are commonly placed on a single chip
- Chips are made by bombarding silicon with doping substances (impurities) to create the required semiconductor and metal layers
  - Surface is protected between stages to ensure that only the necessary sections are doped.





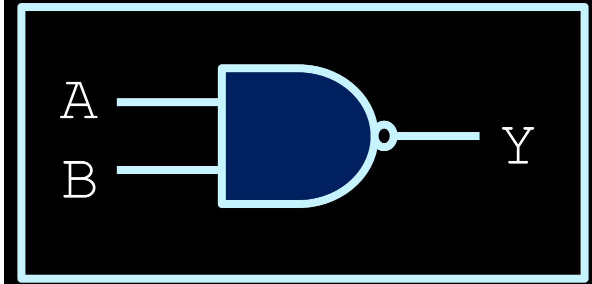
Watch for more: https://www.youtube.com/watch?v=aWVywhzuHnQ

Creating circuits with gates



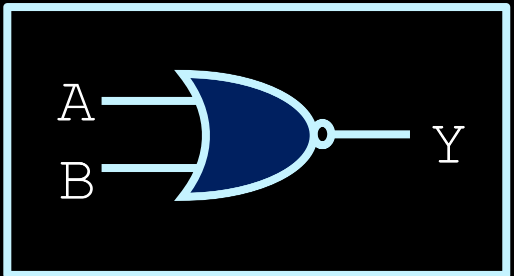
More common gate types

NAND



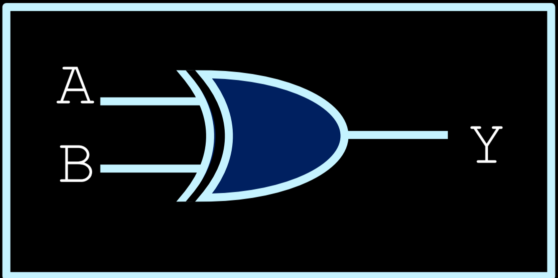
A	B	Y
0	0	1
0	1	1
1	0	1
1	1	0

NOR



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

XOR



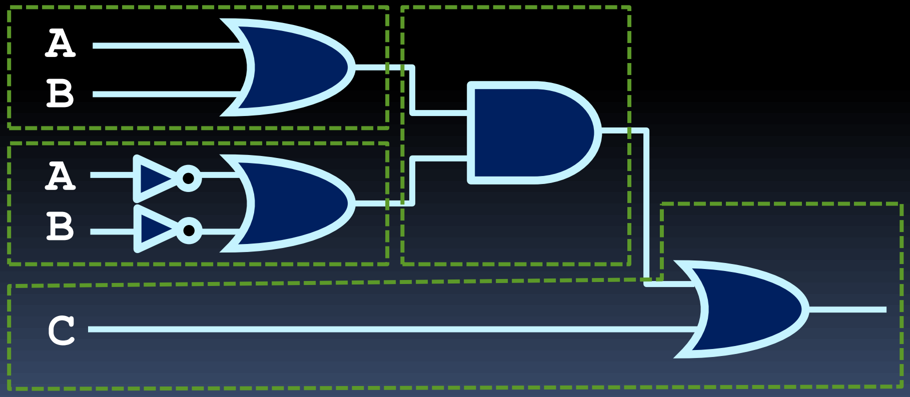
A	B	Y
0	0	0
0	1	1
1	0	1
1	1	0

Implementing Boolean expressions

- How to implement Boolean expressions using logic gates?

```
Y = (A or B) and (not A or not B) or C
```

- Like so:

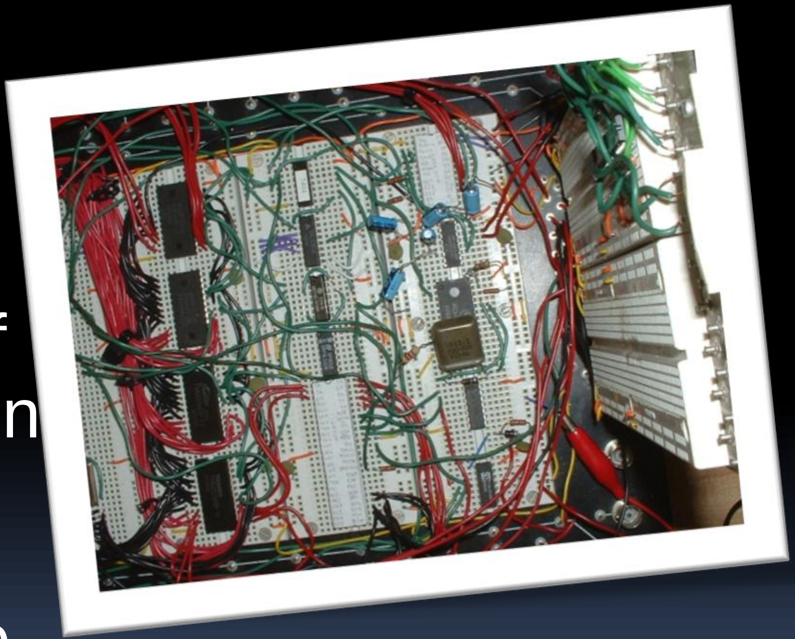


The Big Picture

- What are Boolean expressions good for?
- Controlling a robot
  - `Stop` = `BatteryLow` OR `ObstacleDetected`
  - `S = B | D`
- Mars rover
  - `Turn Left` = (`ObstacleAhead` AND `ObstacleRight` AND not `ObstacleLeft`) OR `AlienLeft`
  - $T_L = (O_A \mathbin{\&} O_R \mathbin{\&} !O_L) \mid A_L$

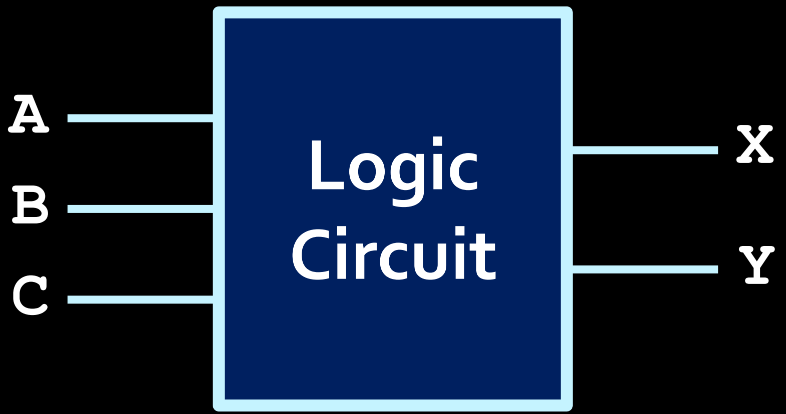
Creating complex circuits

- What do we do in the case of more complex circuits, with many inputs and more than one output?
  - If you're lucky, a truth table is provided to express the circuit.
  - Usually the behaviour of the circuit is expressed in words, and the first step involves creating a truth table that represents the described behaviour.



Circuit example

- The circuit on the right has three inputs (A, B and C) and two outputs (X and Y).



- What logic is needed to set `X` high when all three inputs are high?
- What logic is needed to set `Y` high when the number of high inputs is odd?

Combinational circuits

- Small problems can be solved easily.

- Larger problems require a more systematic approach.

Creating complex logic

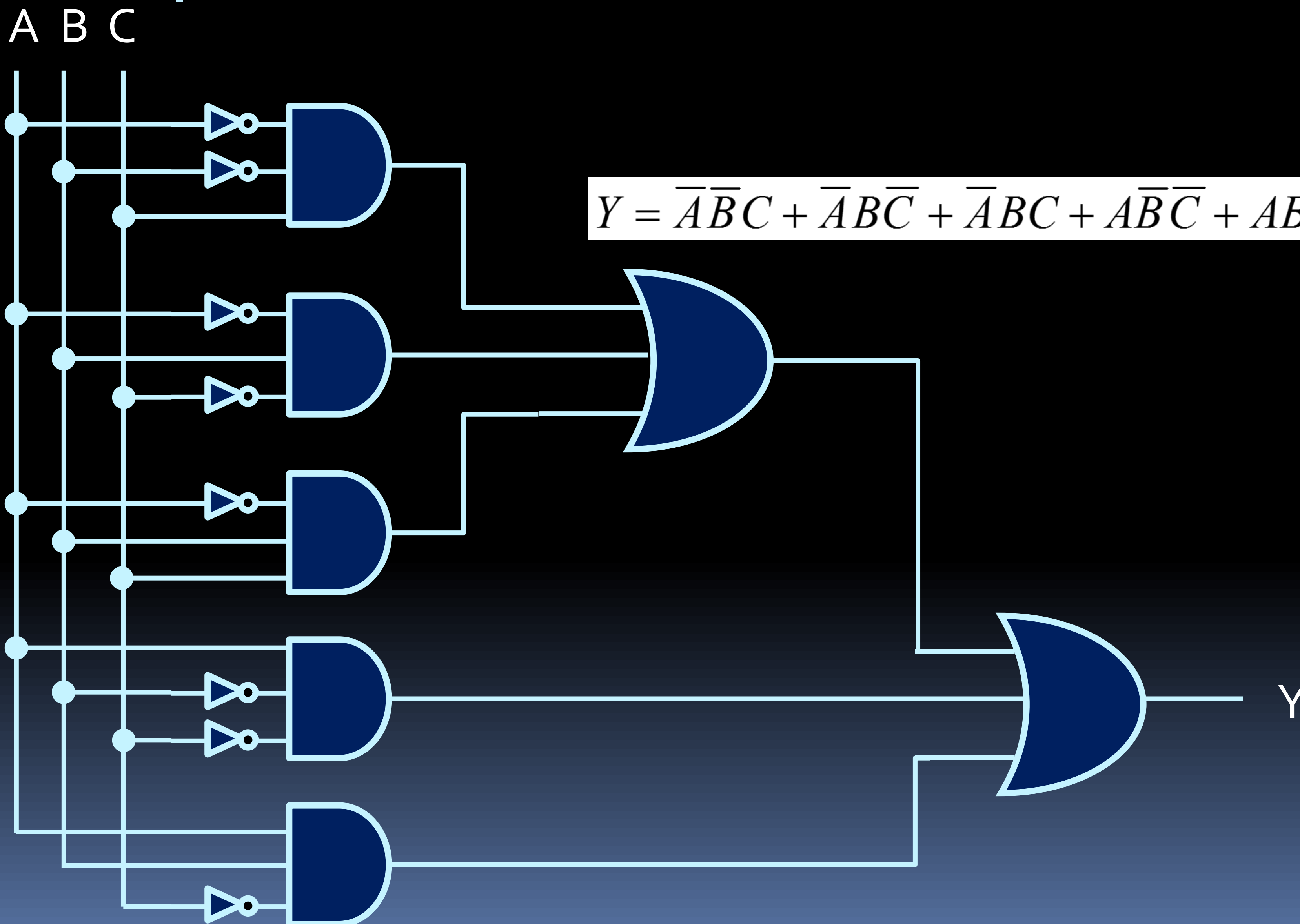
- How do we approach problems like these (and circuit problems in general)?
- Basic steps:
  1. Create one or more truth tables.
  2. Express as Boolean expression.
  3. Convert to gates.
- The key to an efficient design?
  - Spending extra time on Step #2.

Example truth table

- Consider the following example:
  - *"Given three inputs A, B, and C, make output Y high whenever any of the inputs are low, except when all three are low or when A and C are high."*

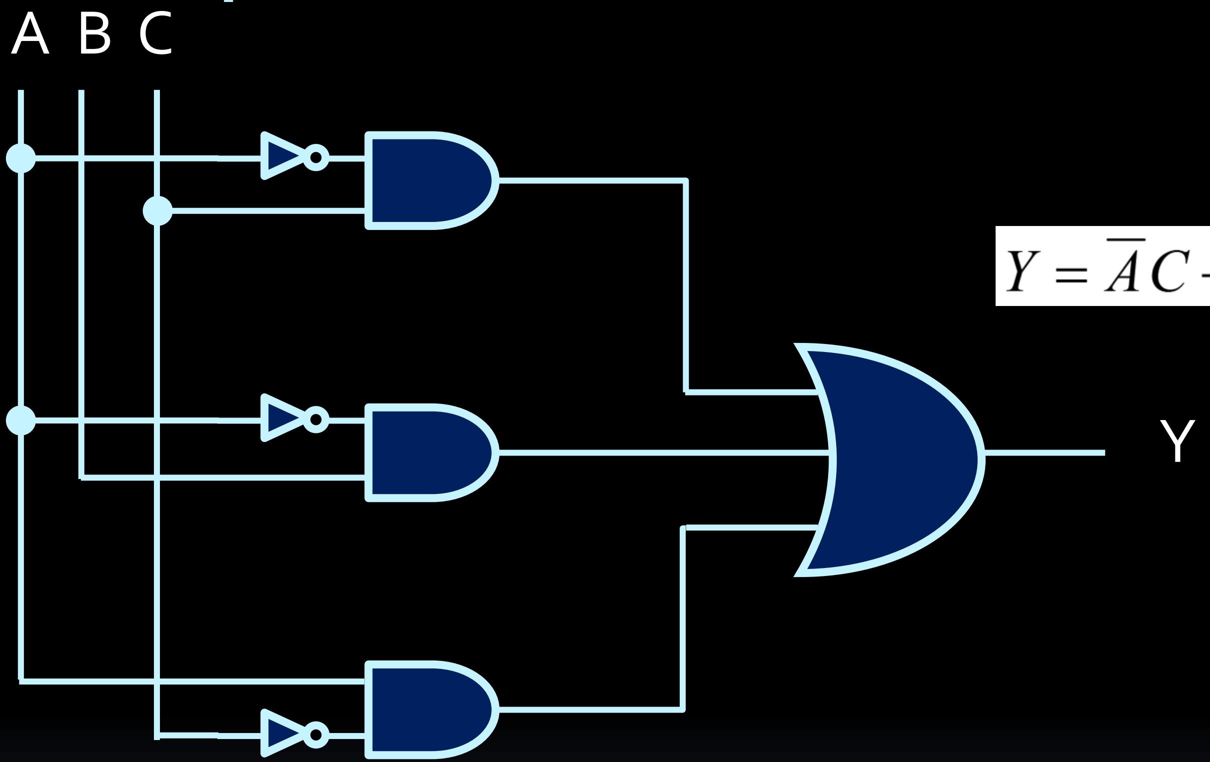
A	B	C	Y
0	0	0	
0	0	1	
0	1	0	
0	1	1	
1	0	0	
1	0	1	
1	1	0	
1	1	1	

Implementation 1



$$Y = \overline{A}\,\overline{B}C + \overline{A}B\overline{C} + \overline{A}BC + A\overline{B}\,\overline{C} + AB\overline{C}$$

Implementation 2



$$Y = \overline{A}C + \overline{A}B + A\overline{C}$$

- Which implementation would you prefer?