Transistors

Learning Goals

- After this lecture, you should be able to:
  - Understand basic principles of electric circuits
  - Illustrate how doped semiconductor materials can be configured to create transistors
  - Combine transistors to create logic gates

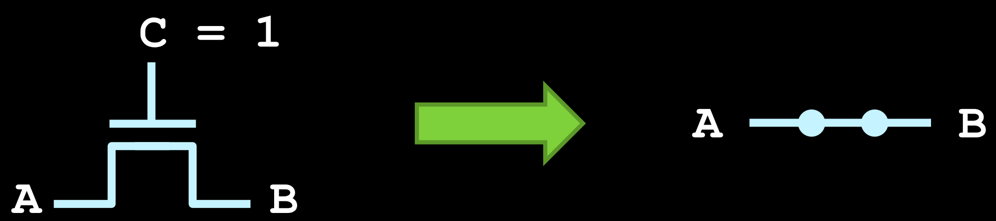
Introduction to Transistors

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

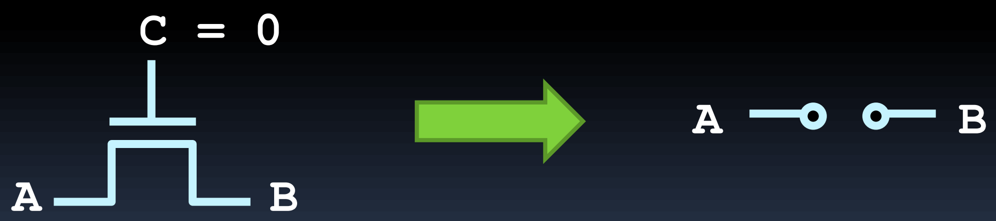
control of electric signal to electric signal

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.

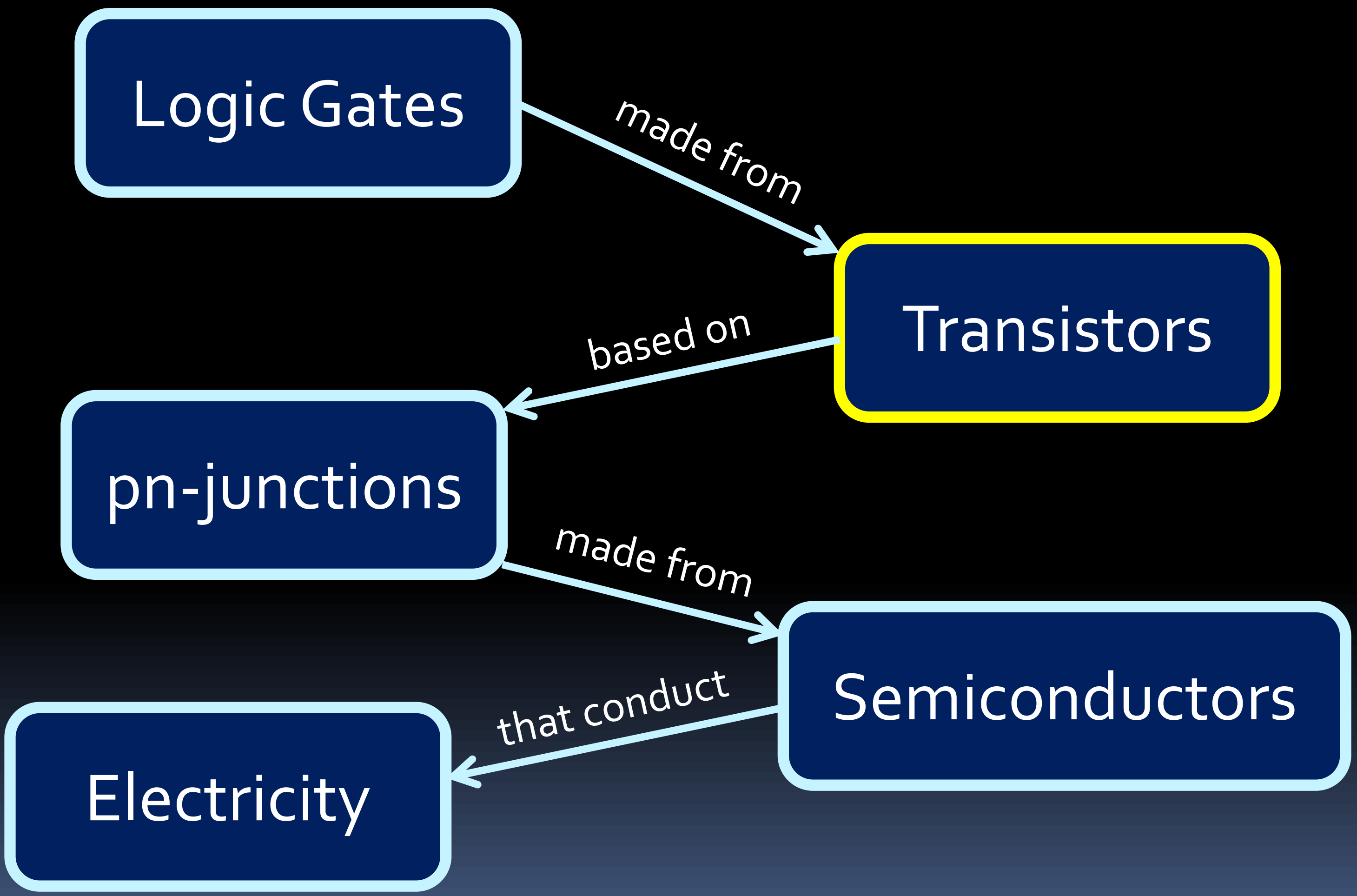


  - And if the value at Point C is low, A & B are not.



  - Need to know a little about electricity now….

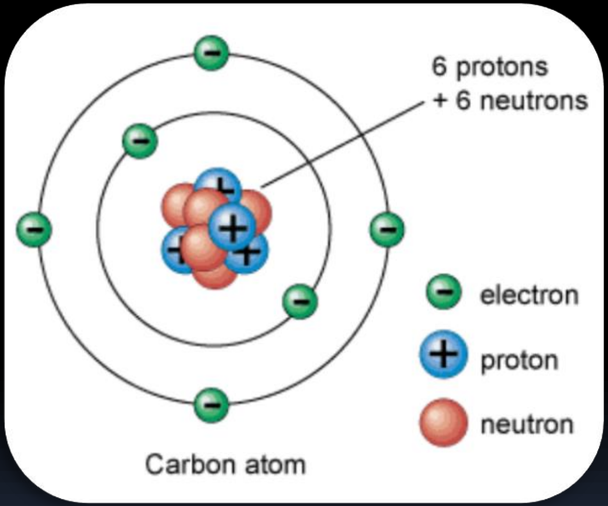
Where do transistors fit?



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).

  outer shell that is not full conduct electricity

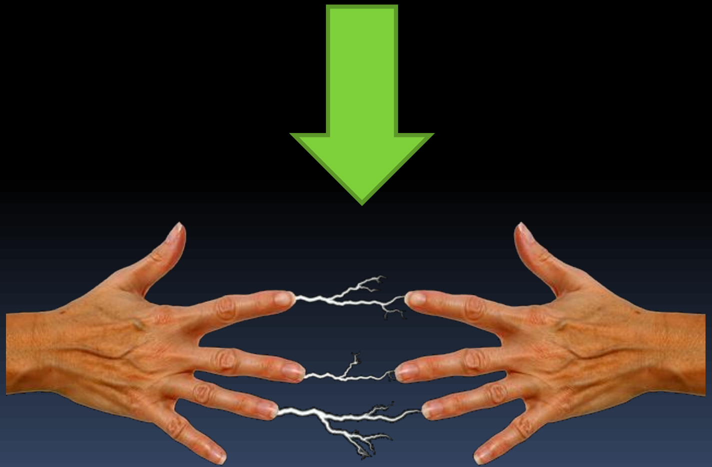
  - Similar to gravitational potential
- This potential is referred to as voltage.
- The rate of electron flow is called the current.

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

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

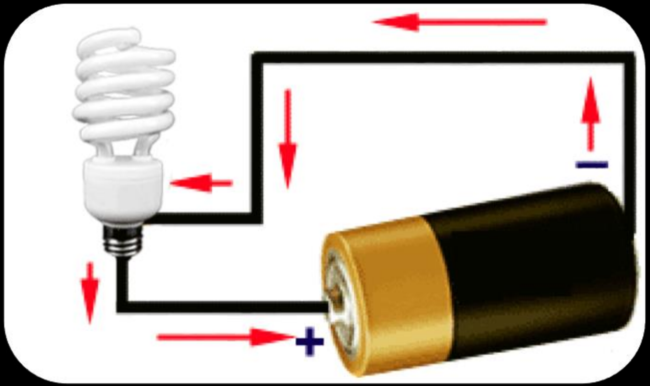
- A few things to note about the path that electric particles like to take:
  - Current always flows toward the zero voltage point of a circuit.
    - Commonly referred to as ground.
  - Electricity always like to take the path of least resistance, from source to ground.
  - Even though electrical current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

i.e.
1. electron direction - >>> +
2. positive charge direction = conventional flow + >> -

Electricity Example

Using electricity

- terminal has surplus of electron

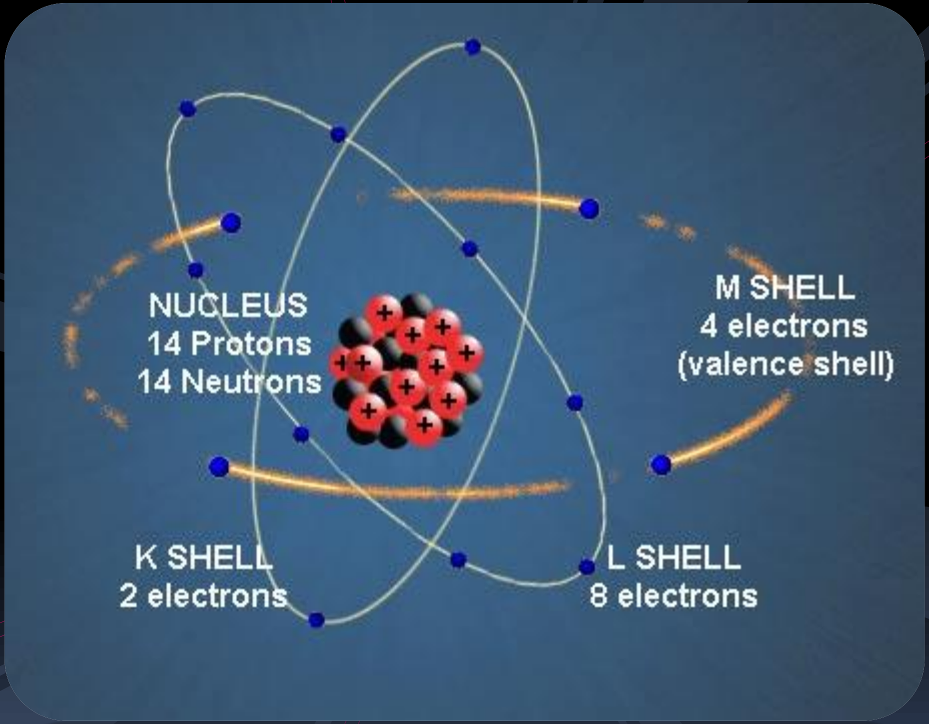


- Knowing that electric particles want to travel from areas of high concentration to areas of low concentration, we can use this to drive circuits.
  - Each of these circuits has a source of electrical particles, some path between this source and the ground, and some resistance along this path that dissipates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

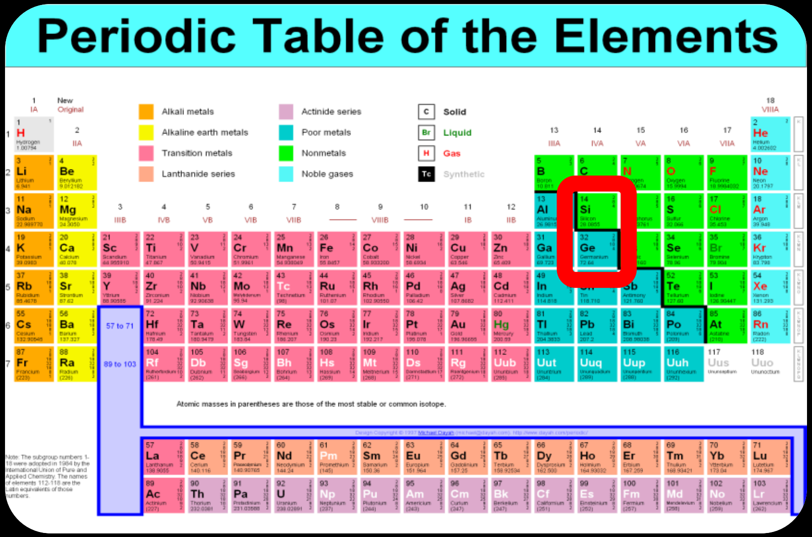
Semiconductors



What are semiconductors?

i.e. conductor usually have 1 valence electron

- Electricity can flow freely through a solid if there are free valence electrons in the outer layer after the solid is formed.



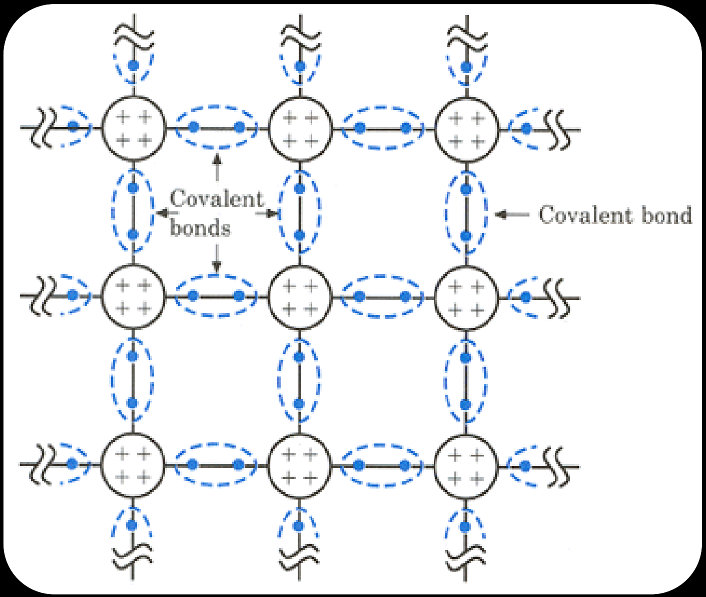
- Semiconductor materials (silicon, germanium) straddle the boundary between conductors and insulators, behaving like one or the other, depending on factors like temperature and impurities in the material.

semiconductor have 4 valence electron, which bond with neighboring atoms to form a lattice.

Semiconductor Conductivity

normally have 4 valence electrons that form covalent bonds with 4 neighbors, forming a lattice. -> poor conductance

- Semiconductors are solid and stable at room temperature, but energy can make electrons from the valence layer become loose.

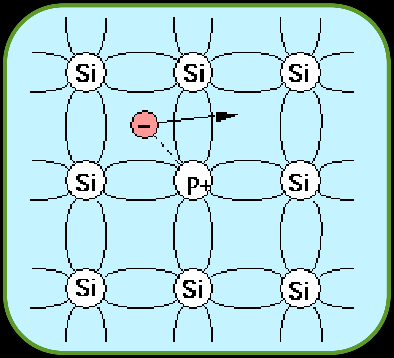


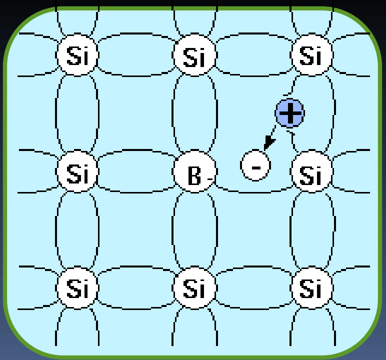
- At room temperature, a weak current will flow through the material, much less than that of a conductor.

Doping greastly increases number of charge carriers.

Adding Impurities

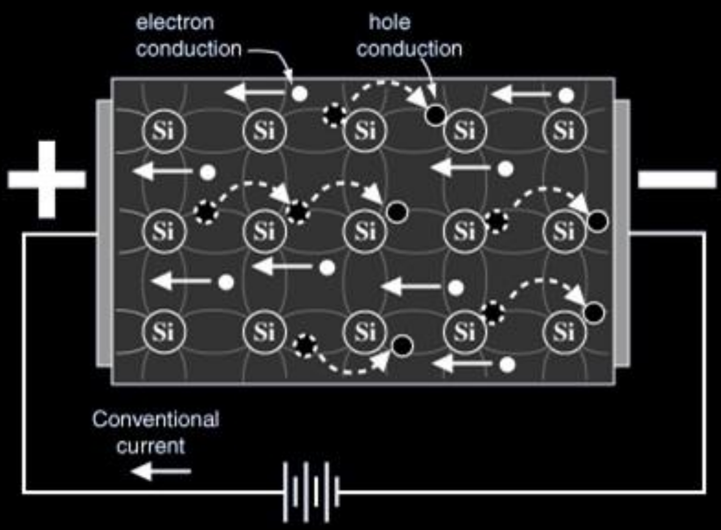
- Semiconductors don't conduct electricity naturally.
  - Silicon has 4 electrons in its outer (valence) electron layer.
  - Each atom wants 8, forms a lattice with its neighbours.
- To encourage the semiconductor's conductivity, impurities are introduced the fabrication process, to increase the number of free charge carriers.
  - n-type: adding elements from group 15, which have 5 electrons in its valence layer (e.g. phosphorus, arsenic).
  - p-type: adding elements from group 13, which have 3 electrons in its valence layer (e.g. boron).
- This process is also referred to as doping the semiconductor.





Impurities

<<<< electron direction

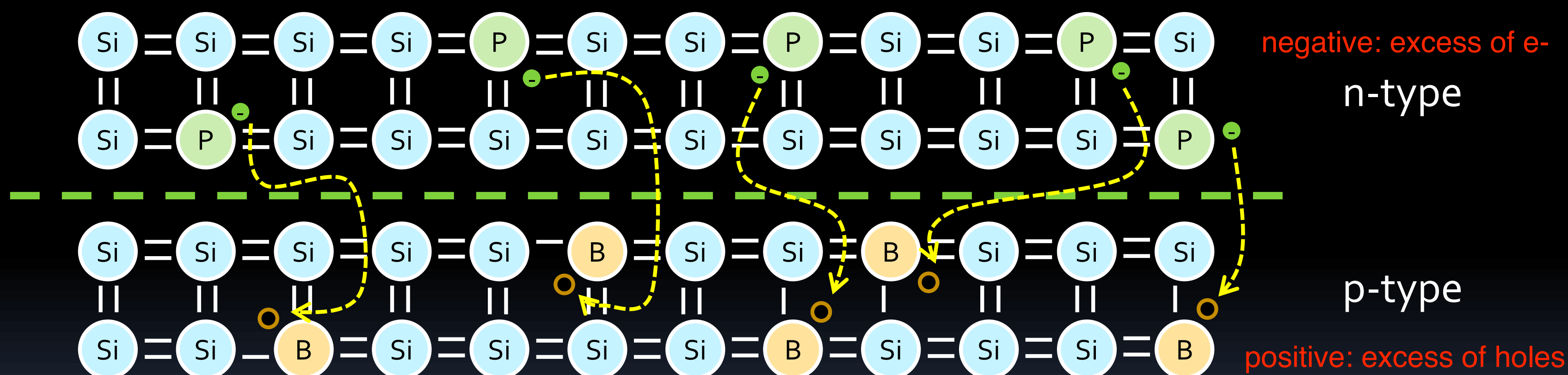


- In the case of n-type semiconductors, the carriers are electrons that are not bound to the solid, and can flow more freely through the material.
- For p-type semiconductors, the carriers are called holes, to represent the electron gap as a particle as well.

Bringing p and n together

- What would happen if you brought some p-type material into contact with some n-type material?

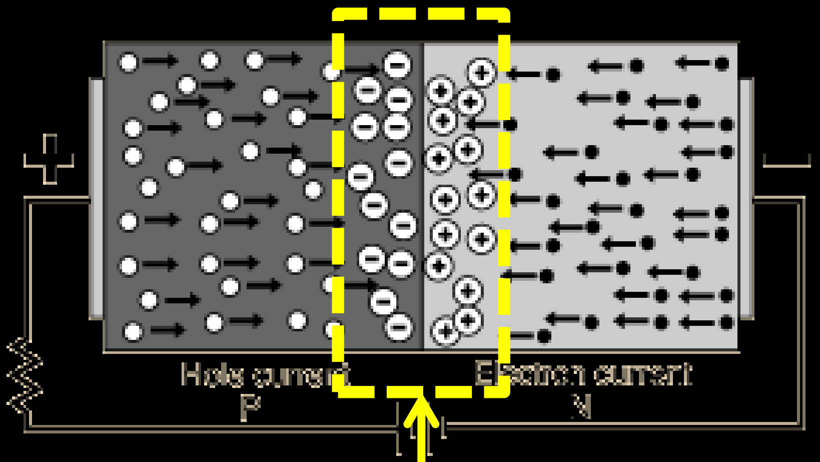
boron: group 13: 5 electrons 3 valence electrons



- The electrons at the surface of the n-type material are drawn to the holes in the p-type.

electron in n move to p; leaving behind positively charged ion in n region. And the p region gets excess of electron. This forms electric field dire

p-n Junctions

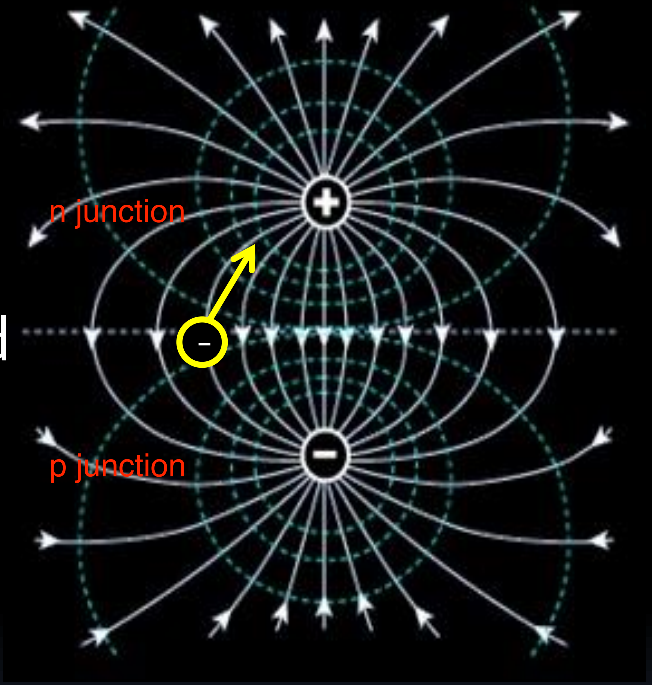


- When left alone, the electrons from the n section of the junction will mix with the holes of the p section, cancelling each other out, and creating a particle-free section called the depletion layer.
- Once this depletion layer is wide enough, the doping atoms that remain will create an electric field in that region.

direction of electric field is defined as movement of a test positive charge in the field

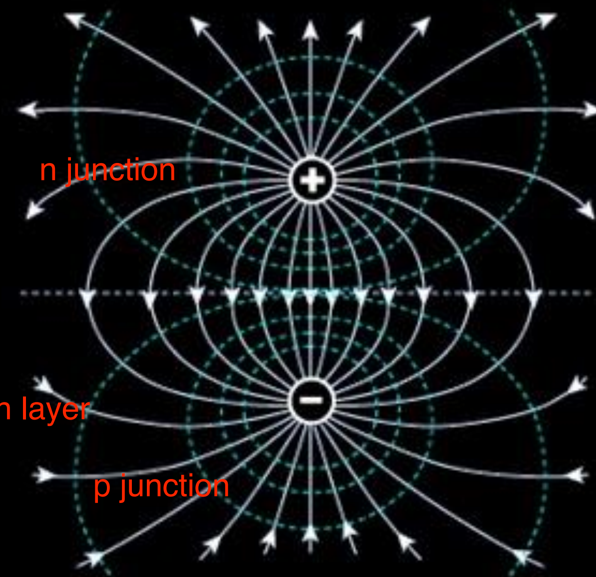
Electric fields

- What is an electric field?
  - An electric field is created when a charge difference exists between two regions.
  - Any electrons in the middle would be attracted to the positive side and repelled by the negative side.



- Example: depletion layer
  - When a phosphorus atom loses its electron, that atom develops an overall positive charge.
  - Similarly, when a boron atom takes on an extra electron, that atom develops an overall negative charge.
  - This creates an electric field in the depletion layer.

Electric fields



- A depletion layer is made up of many of these electrically imbalanced phosphorus and boron atoms.

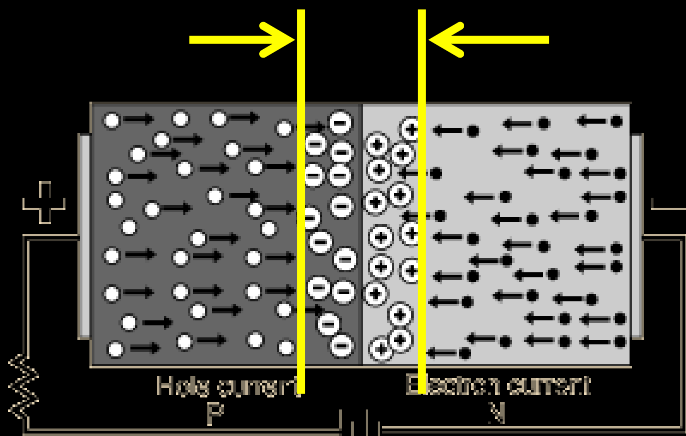
  no electron movement in depletion layer
  1. lessen the layer for conduction
  2. widen the layer for insulation

- The electric field caused by these atoms will cause holes to flow back to the p section, and electrons to flow back to the n section. i.e. counteract electron movement from n -> p junction
  - The current caused by this electric field is called drift.
  - The current caused by the initial electron/hole recombination is called diffusion.
- At rest, these two currents reach equilibrium.

  electric field opposes the diffusion process for both electron and holes

Forward Bias

<< diffusion
>> electric force on electron



- What happens when a voltage is applied to this junction?
  - It depends on the direction in which the voltage is applied.
- Forward bias:

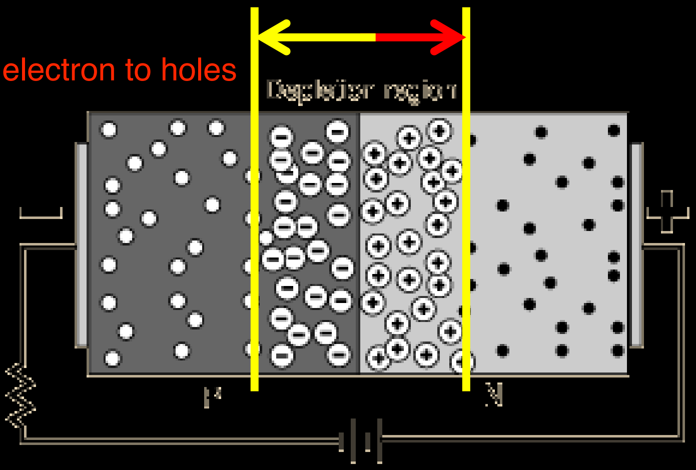
depletion layer narrows because - terminal repels electron and + terminal repels holds

  - When a positive voltage is applied to the p end of this junction, electrons are injected into the n-type section.
  - This narrows the depletion layer and increasing the electron diffusion rate.
- With a smaller depletion layer, the electrons travel more easily through to the p-type section, and back into the other terminal of the voltage source

i.e. reduced resistance

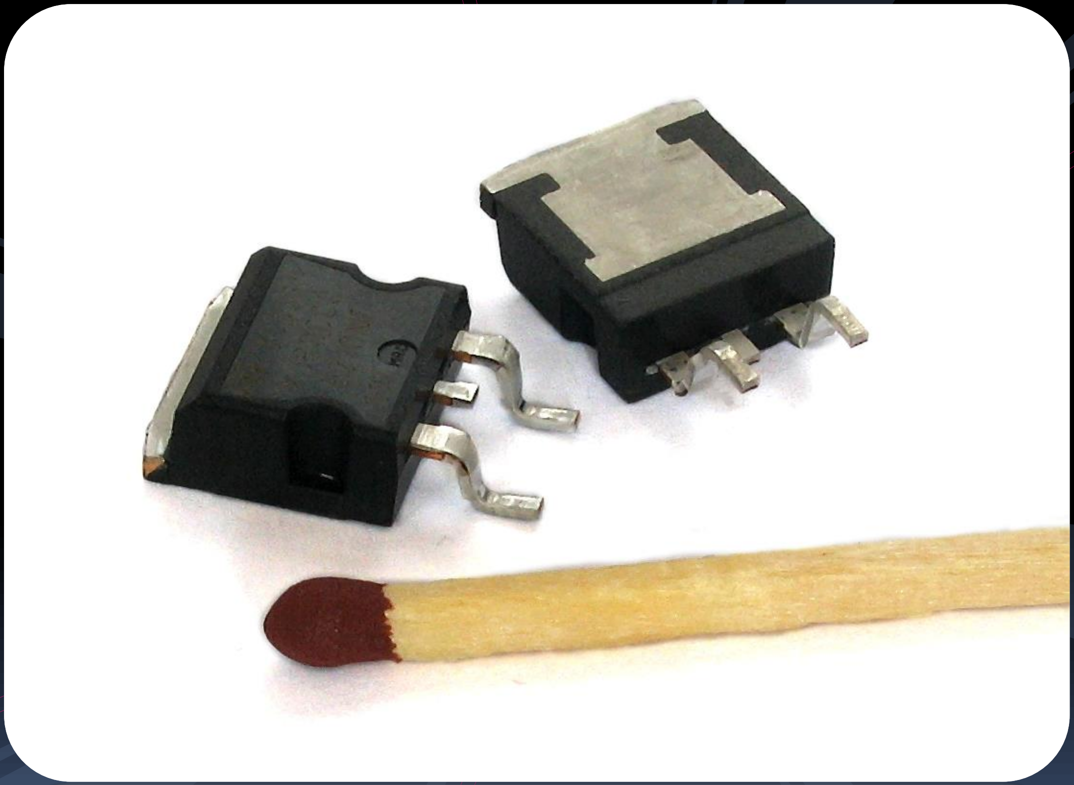
Reverse Bias

insert electron to holes



- Reverse bias:
  - When a positive voltage is applied to the n side of the junction, the depletion region at the junction becomes wider, preventing the carriers from passing.
  - a small current still flows through the circuit, but it is weak and does not increase with an increase in the applied voltage.
- So when a junction is forward biased, it becomes like a virtual short-circuit, and when the junction is reverse biased, it becomes like a virtual open-circuit. open circuit: circuit that is not complete
  - This is the basis of transistors!

Transistors, finally

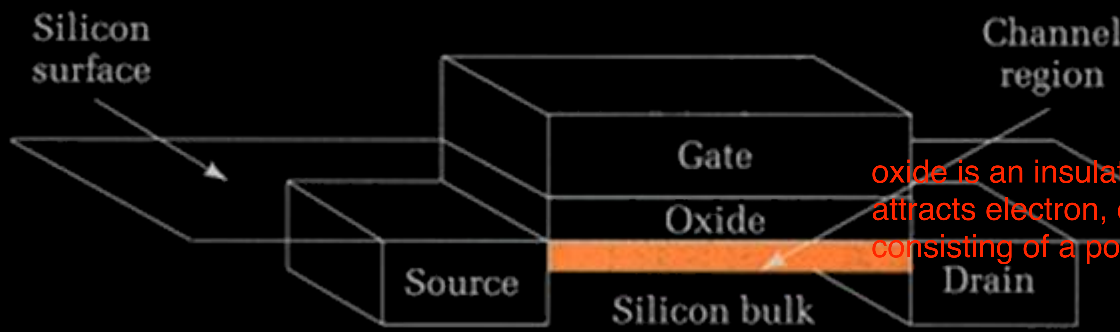


Creating transistors

- Transistors use the characteristics of p-n junctions to create more interesting behaviour.
- Three main types:
  - Bipolar Junction Transistors (BJTs)
  - Metal Oxide Semiconductor Field Effect Transistor (MOSFET)
  - Junction Field Effect Transistor (JFET)
- The last two are part of the same family, but we'll only look at the MOSFET for now.

The MO of MOSFETs

electric signal applied to gate -> cause current to flowthrough



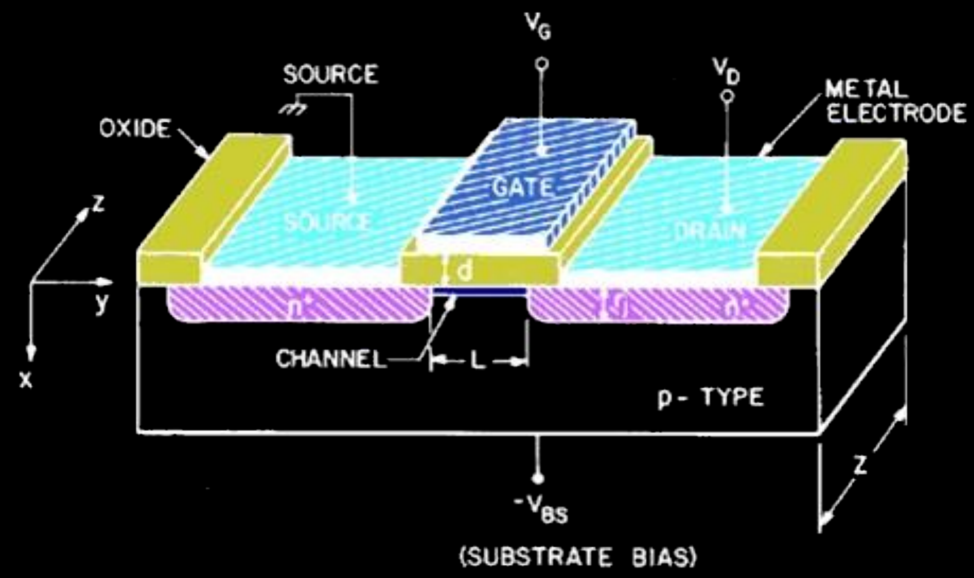
oxide is an insulator: populated with + charge attracts electron, creating a channel region consisting of a pool of electrons

n p n

voltage source in both directions —> no electricity

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

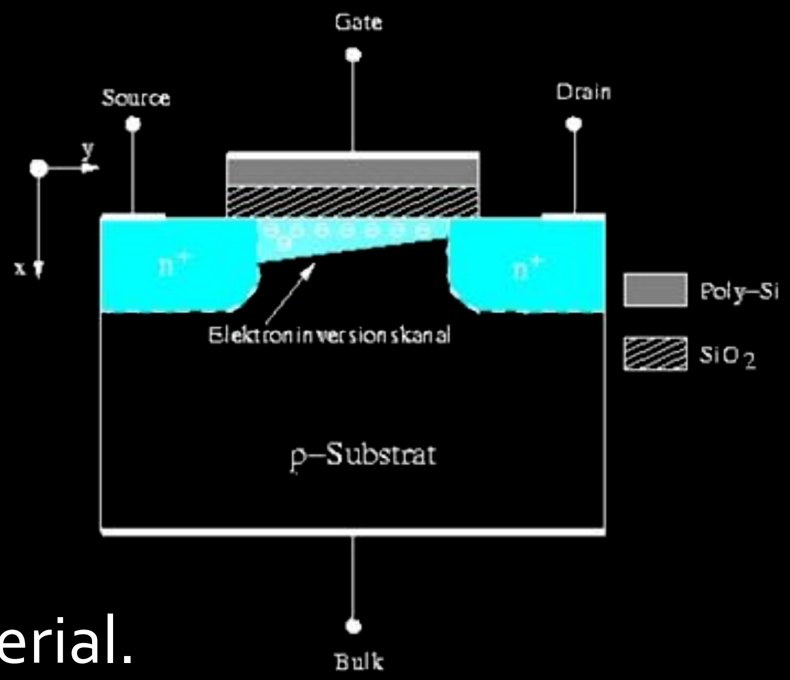
The S of MOSFETs



- The semiconductor sections are two pockets of n-type material, resting on a substrate layer of p-type material.
- A voltage is applied across the two n-type sections, called the drain and the source. No current will pass between them though, because the p section in between creates at least one reverse-biased pn junction.

n-channel MOSFETs

- However, when a voltage is applied between the source and the metal plate (the gate), positive charges are built up in the metal layer, which attracts a layer of negative charge to the surface of the p-type material.

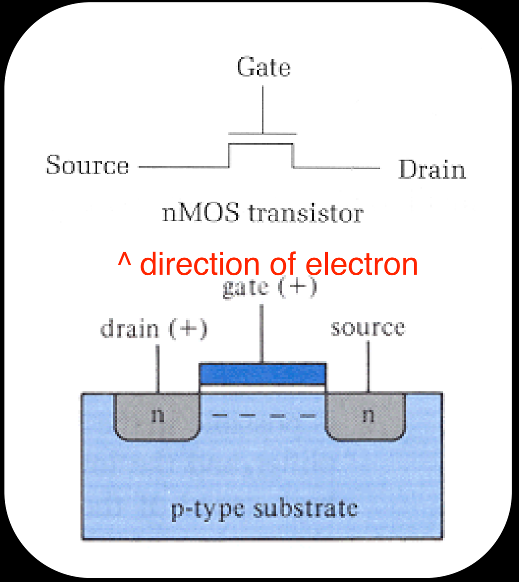


- This layer of electrons creates an n-type channel between the drain and the source, connecting the two and allowing current to flow between them.
  - the wider the channel, the higher the current

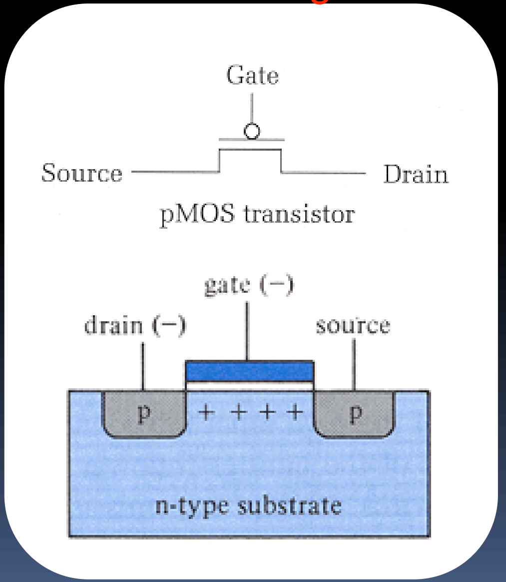
nMOS vs pMOS

- Two types of MOSFETs exist, based on the semiconductor type in the drain and source, and the channel formed.
  - nMOS transistors (the design described so far) conduct electricity when a positive voltage (5V) is applied to the gate.
  - pMOS transistors (indicated by a small circle above the gate) conduct electricity (i.e., act as a closed switch) when the gate voltage is logic-zero.

turns on when gate is high



turns on when gate is low



Transistors to Gates

- MOSFETs can make current flow, based on the voltage values in the gate and drain.
  - i.e. the 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.

MOSFET Truth Table

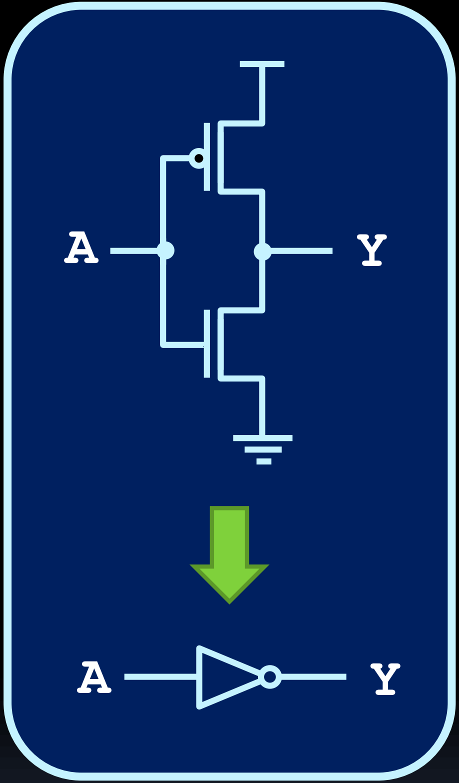
V_{DS}	V_{GS}	I_{DS}
Low	Low	Low
Low	High	Low
High	Low	Low
High	High	High

Making gates

when A is low, top -> 1 — Y connected to voltage source
when A is high, bottom -> 1 — Y connected to ground

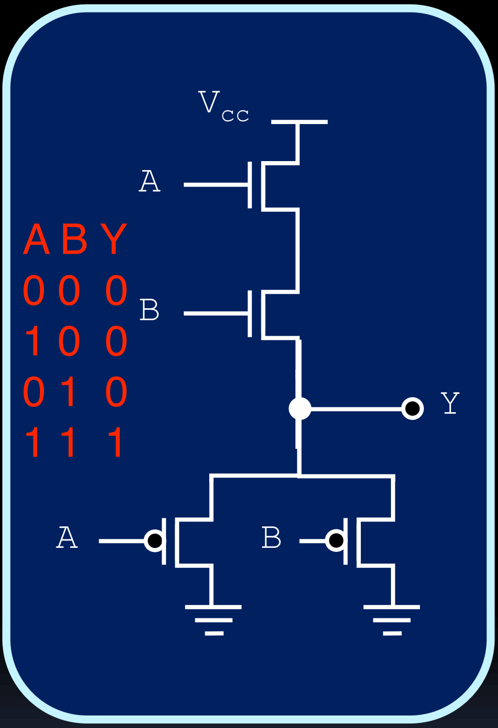
- Since these transistors aren't simply on/off switches, digital logic gates (AND, OR, NOT) are created by a combination of transistors
  - Examples: NOT gate circuit in diagram.
- Physical data:
  - "High" input = 5V
  - "Low" input = 0V
  - Switching time ≈ 120 picoseconds
  - Switching interval ≈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

not gate consists of 2 transistors



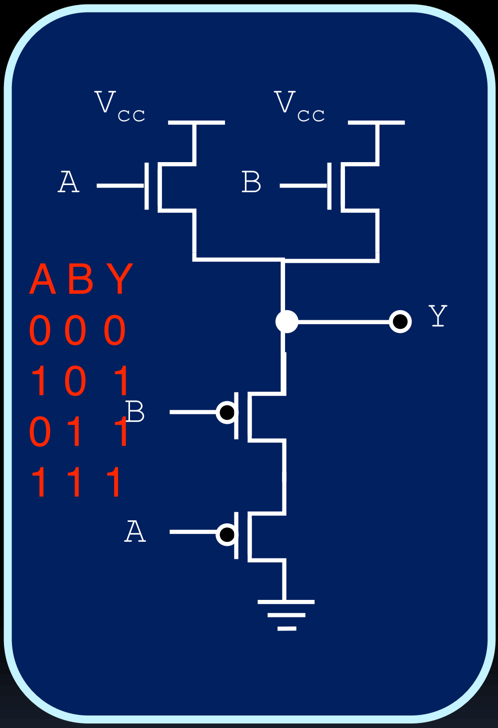
Transistors into gates

AND gate



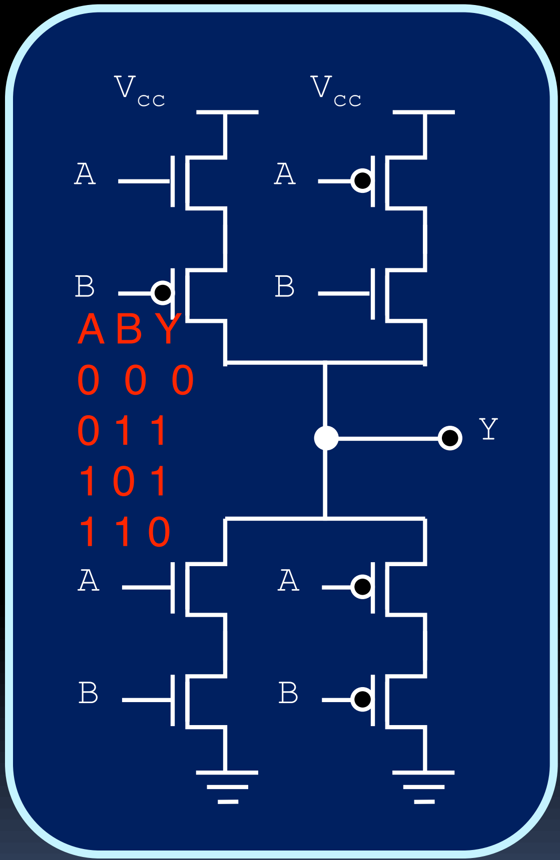
A	B	Y
0	0	0
1	0	0
0	1	0
1	1	1

OR Gate



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

XOR gate

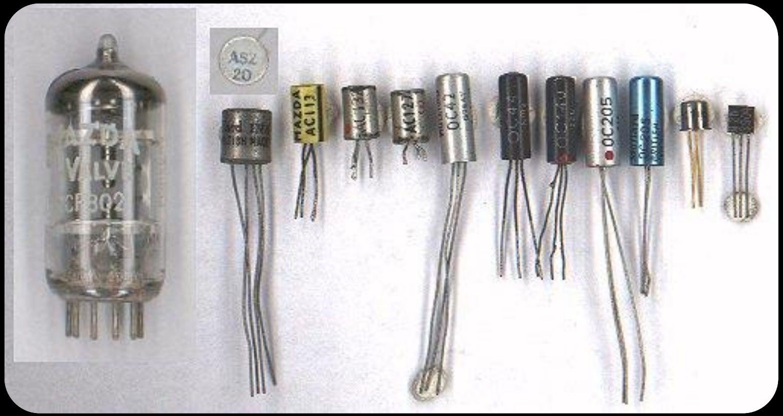


A	B	Y
0	0	0
0	1	1
1	0	1
1	1	0

have to ensure every input value combination has an output; also have to avoid direct connection from source to ground (short circuit)

Transistor Fabrication

- Transistors are not formed by pushing large chunks of n- and p-type semiconductors together.
- Transistors are now made by bombarding silicon with doping substances to create the layers for each junction
  - surface is oxidized in between stages to ensure that only the necessary sections are doped.



Fabrication Process