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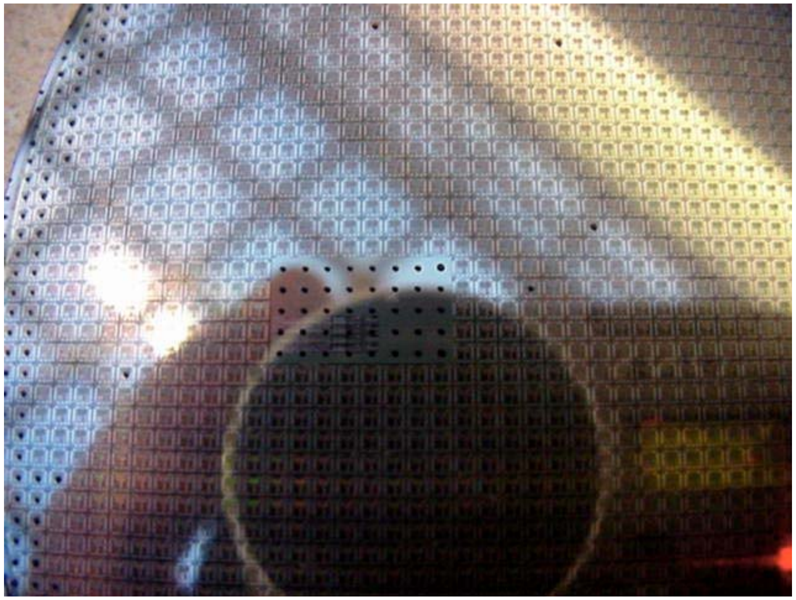
Transistors 101



Each die on our wafers is mostly made up of "transistors"

Prerequisites

I. Big Picture:

- What transistors do and their basic designs.

II. More Detailed

- How elements in the periodic chart relate to transistors

III. Nitty-Gritty Details

- The transistor's PN junction and how it works

PREREQUISITES

(Four things this lecture assumes you already know)

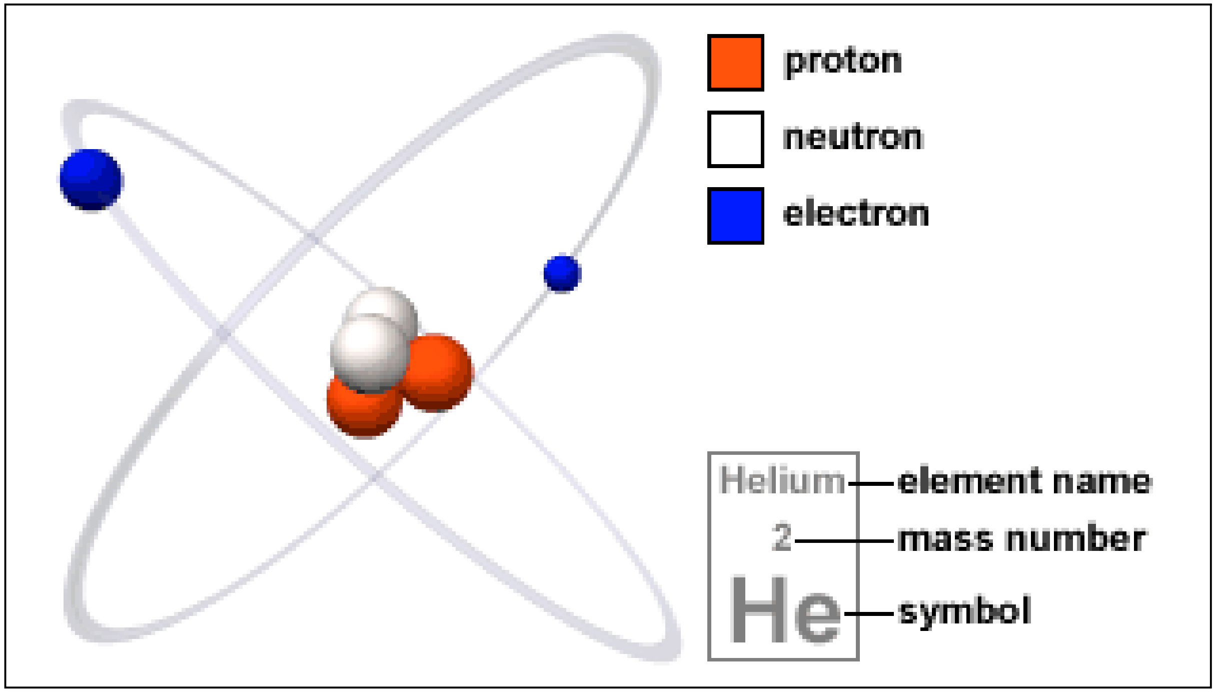
1. Current (amps) is a measure of electron flow
   - electrons are negative
   - current flows in a negative to positive direction.
   - analogous to wafer flowing through a pipe (gal/min)
   - an easy concept

2. Voltage (volts) is “potential energy” for electrons
   - analogous to a block lifted up and ready to drop (ft-lbs)
   - analogous to water pressure (psi)
   - this is a harder concept

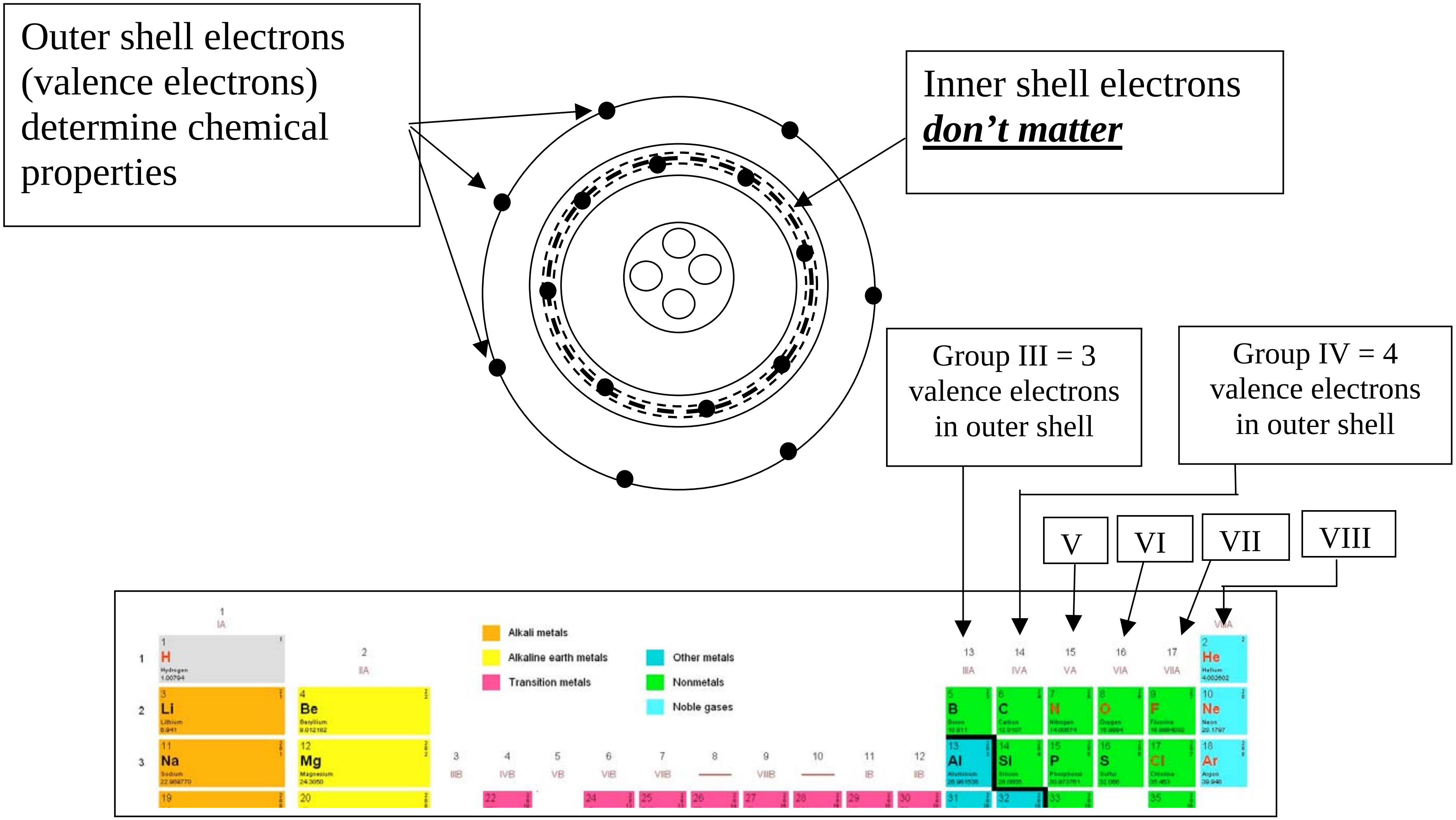
   Crimp a garden hose and you turn kinetic energy into potential energy.

   Stop a current flow with an increased resistance and you get a voltage across the resistance (more on this later).

3. An atom has protons an neutrons in the nucleus, with electrons orbiting around the nucleus.



- the outermost orbit (the "valence" electrons) determine what chemical reactions the atom will participate in



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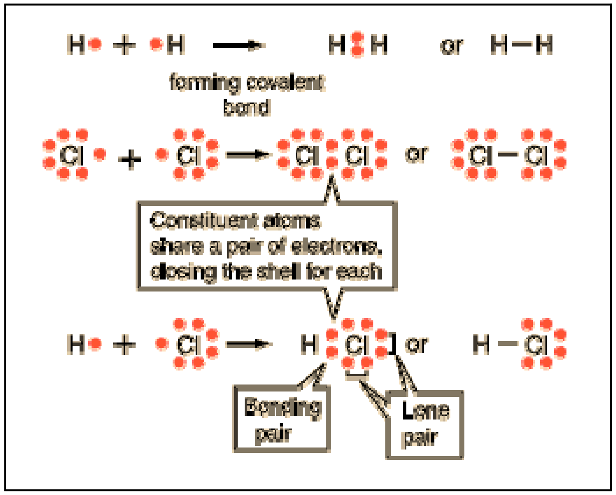
4. Two kinds of atomic bonds are:

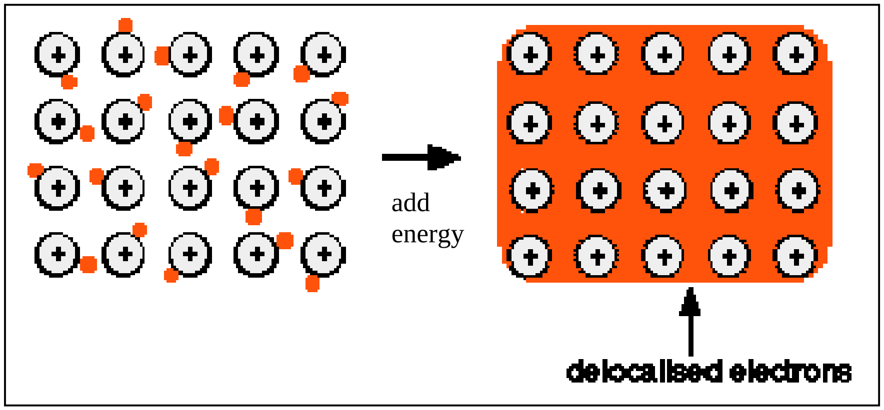
a) Covalent: Atoms are joined by sharing electrons
e.g. H-H Cl-Cl H-Cl



b) Metallic: Atoms share their outer shell (="valence") electrons freely i.e.,

The electrons can move freely within these molecular orbitals, and so each electron becomes detached from its parent atom. The electrons are said to be delocalised. The metal is held together by the strong forces of attraction between the positive nuclei and the delocalised electrons

They conduct electricity.

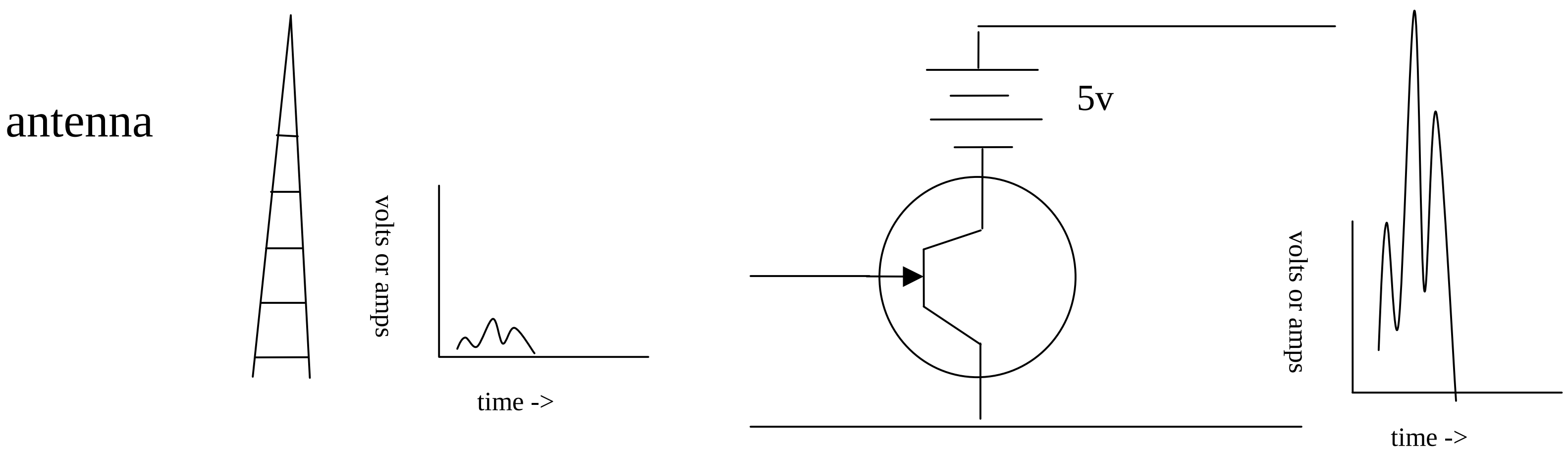


The electrons in a "semi" conducting material flip between (non-conducting) covalent bonds and (conducting) metallic bonds

(I) BIG PICTURE: What Does a Transistor Do?

A transistor is used for two things:

1. ANALOG CIRCUITS: To “shape” electronic signals (e.g. as an amplifier)

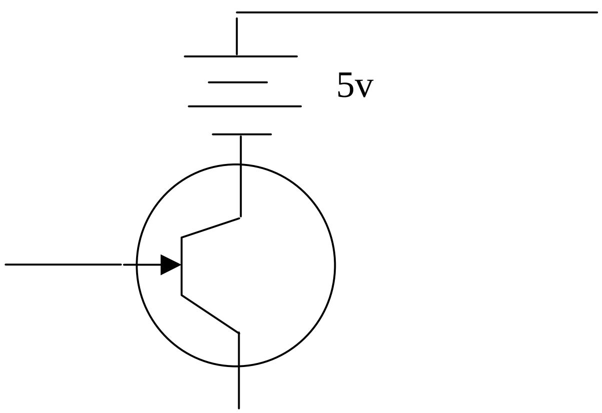


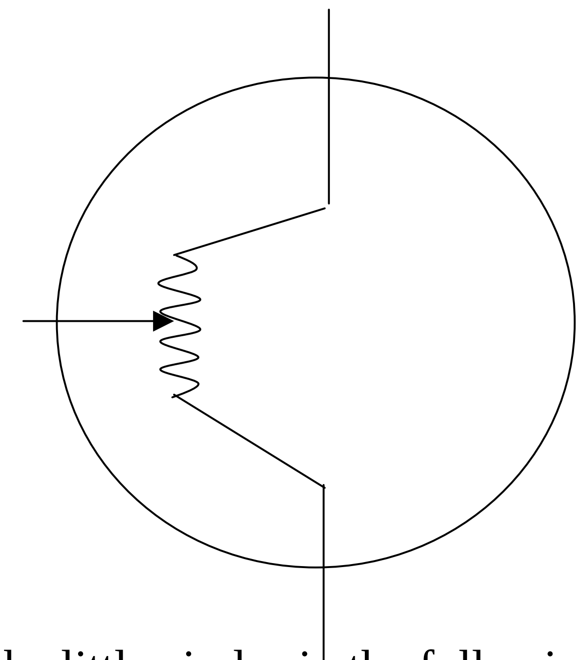
e.g. - with a transistor (or a vacuum tube) the weak signal from an antenna can be amplified to drive a speaker

Question: If the incoming signal is in the millivolt range, how high can the outgoing signal get in the above circuit?

Answer: 5 volts. Note that the transistor in the amplifier circuit does not create power, it just controls it.

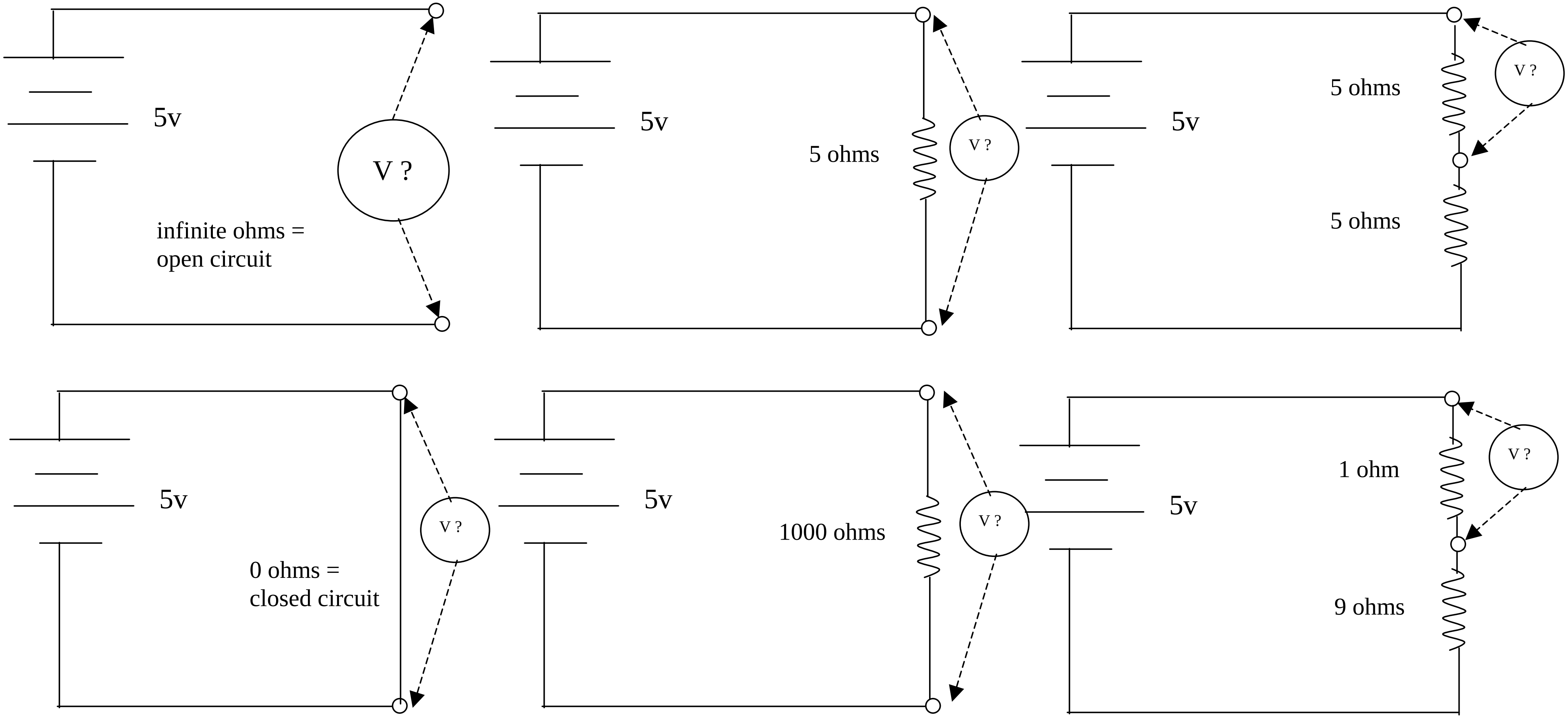
A transistor is actually a “trans - resistor”
The resistance of the (variable) resistor changes with the input





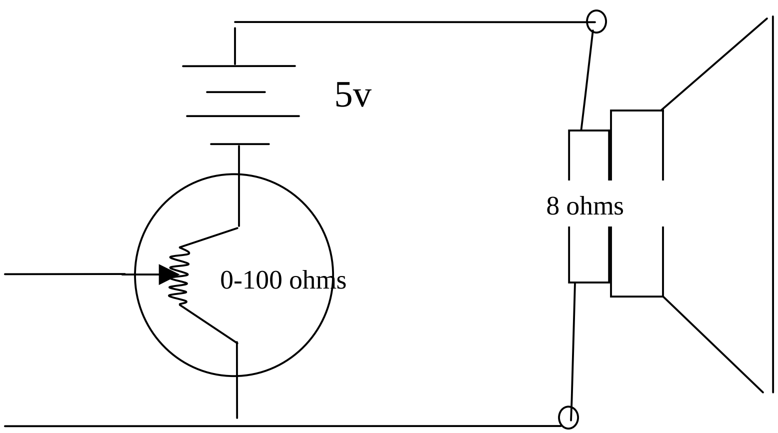
Pop Quiz: What would the voltmeter read across the little circles in the following circuits (don't worry about polarity):

Voltage Divider - Amplifier Exercise



Given that:

1. We're going to hook up an 8 ohm speaker to the output of our amplifier
2. Our variable resistor (trans-resistor) can vary from 0 to 100 ohms



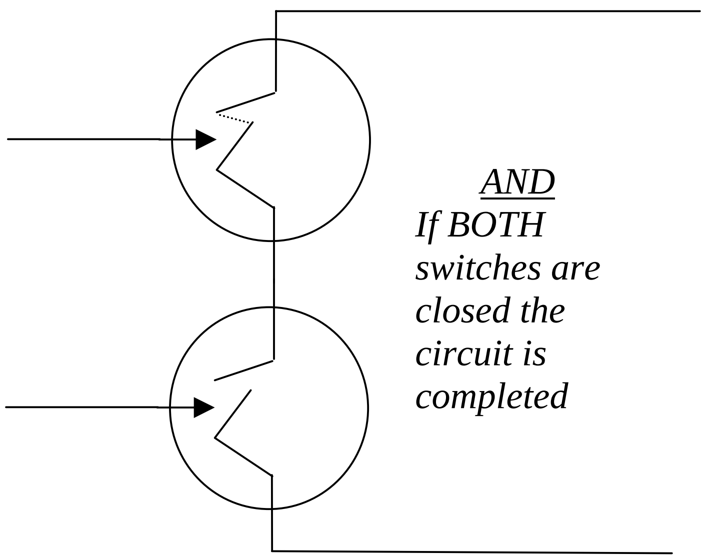
When the trans-resistor is:	The voltage drop across the speaker is:
0 ohms	5v x 8/(8 + 0) = 5 v
8 ohms	5v x 8/(8+8) = 2.5 v
100 ohms	5v x 8/(8+100) = 0.37 v

2. DIGITAL CIRCUITS: You can use a transistor as a switch

(i.e., the trans-resistor has either zero ohms or infinite ohms)

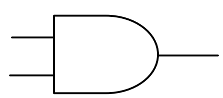
Given that we have light switches, and relays, what’s the big deal about a small relay-like switch?

Well, with switches we can make:

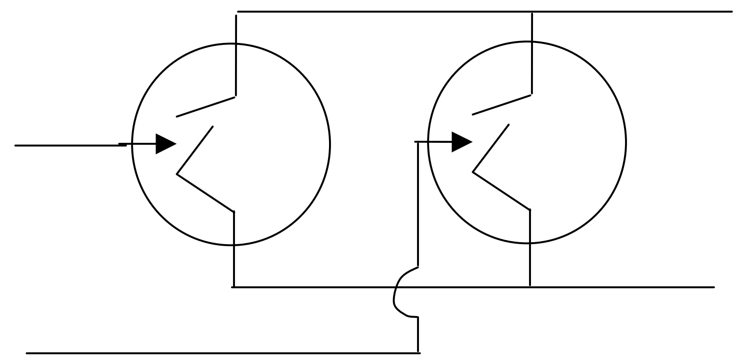


AND
If BOTH switches are closed the circuit is completed

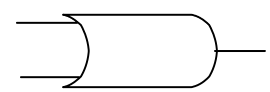
an “**AND**” gate:



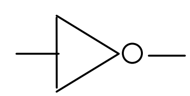
OR
If EITHER switch is closed the circuit is completed



an “**OR**” gate:



a “**NOT**” gate:



NOT
also called an inverter

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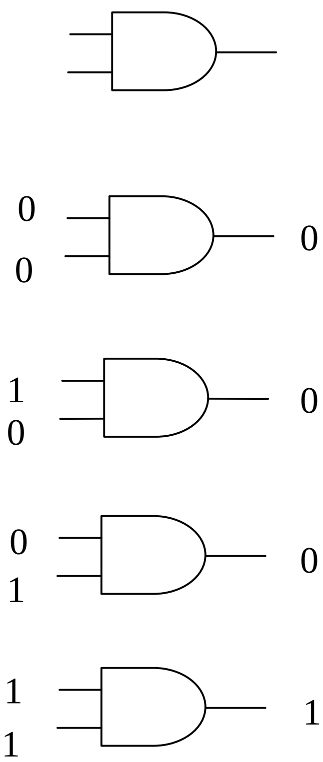
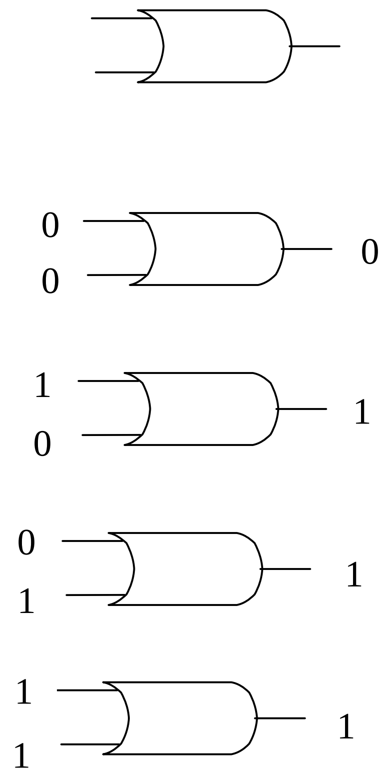
What’s the big deal about an AND gate, an OR gate, and a NOT gate?

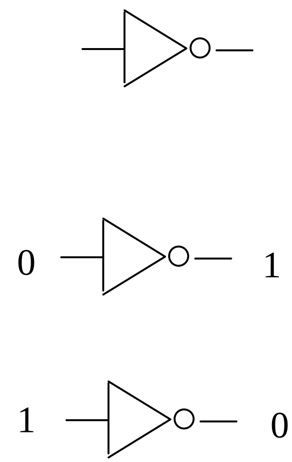
AND gate



OR gate



Inverter (aka NOT gate)



... is this a nerd thing?

PROFOUND STATEMENT #1:

- It turns out that **with these three gates** (made out of transistors, vacuum tube, relays or whatever),

we can construct *ANY* type of digital computer.

- The smaller the mechanical gate, the smaller the computer
  - vacuum tube computers were bigger.

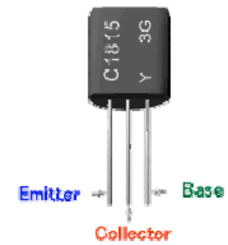
That's all there is to digital electronics! -- these three gates.

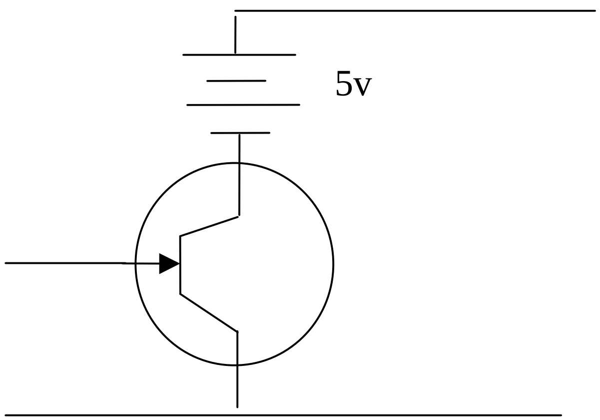
- A course in digital electronics will show you some examples of this
- A course in "automata theory" will prove things like this
- The book "Goedel, Escher Bach, an Eternal Golden Braid" popularizes a lot of what the automata theory course covers.

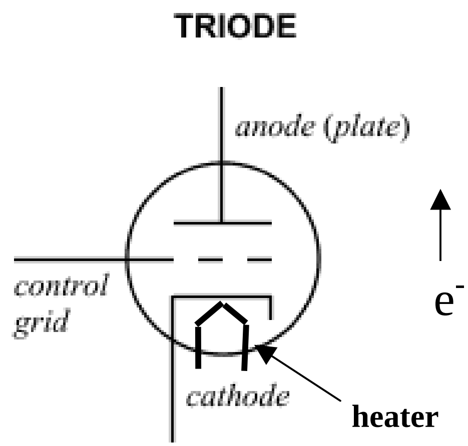
Vacuum Tube - Transistor Analogy

Anywhere where you use a transistor, you could also use a vacuum tube (or any other type of switch you can think of) to perform the same *function*.

- Functionally transistors and vacuum tubes they are equivalent.
  - But vacuum tubes are bigger, and use more power







transistor: invented 1947

triode vacuum tube: invented 1906

In a vacuum tube, electrons move through a vacuum

In a ***perfect*** crystal (i.e. material with no grain boundaries, all its atoms line up), electrons line-up and hit each other like billiard balls.

Profound Statement #2:

The movement of electrons in a *perfect* crystal, is analogous to electrons moving in a vacuum.

- To control the flow of electrons in a vacuum tube we use grids
- But how do we insert a grid into a perfect crystal to control the flow of electrons?

anwser: we use a different mechanism called "doping" (… a lot more on this later)

Historical Perspective -

The **concepts** came first (they realized the vacuum tube-crystal analogy)
The **practicality** came second (how to make a crystal act like a vacuum tube?)
The **theory** came third (why does it work?, so we can make it better)

Transistors, the first step in the modern computer age, were invented in 1947; and William Shockley, John Bardeen and Walter H. Brattain shared the 1956 Nobel Prize in physics for the achievement.

Everyone could see how useful these devices would be, but **the physics of how transistors worked were poorly understood**. At M.I.T., Noyce in his 20's became a groundbreaking expert.

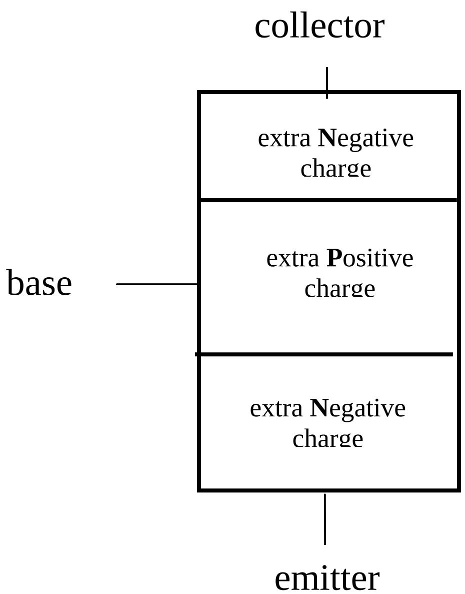
He quickly drew the attention of Shockley, who hired him to help make specialized transistors for military and business-machine companies like. Their work was more alchemy than science; **they'd shove transistors in furnaces and bombard them with chemical fumes, with few clues as to what would work**. (The engineers referred to these processes as "witches' brew" and "black magic.').'

… what resulted from all this work follows…

How Do We Design a Transistor?

Two ways. First take some "perfect crystal" and then make:

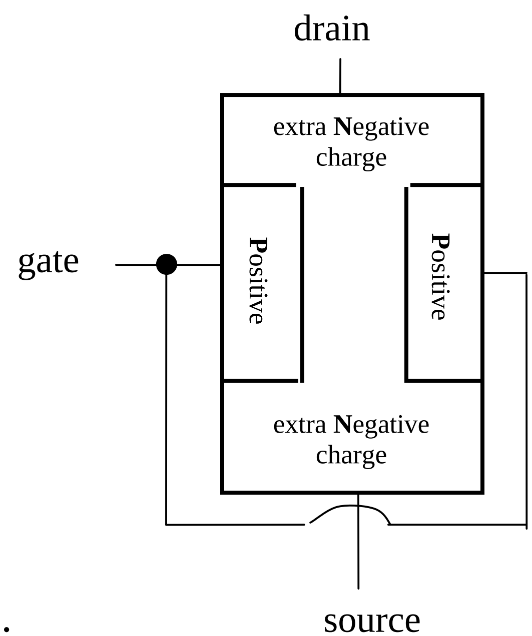
a Biased Junction Transistor (BJT)



works via "avalanche" effect from current entering the base

1. 10x faster than a FET of same size
2. 10x more power consumption and heat than an FET of same size
3. Works with current
4. Invented first, but harder to understand

a Field Effect Transistor (FET)



works via "pinch-off" effect from the gate field, when a voltage is applied to the gate

1. 10x slower than a BJT of same size
2. 10x less power consumption and heat than an BJT of same size
3. Works with voltage
4. Easier to understand

Question:

Which design do you think predominated in IBM mainframes through the 1990's?

Different FET Representations, Pinch Off

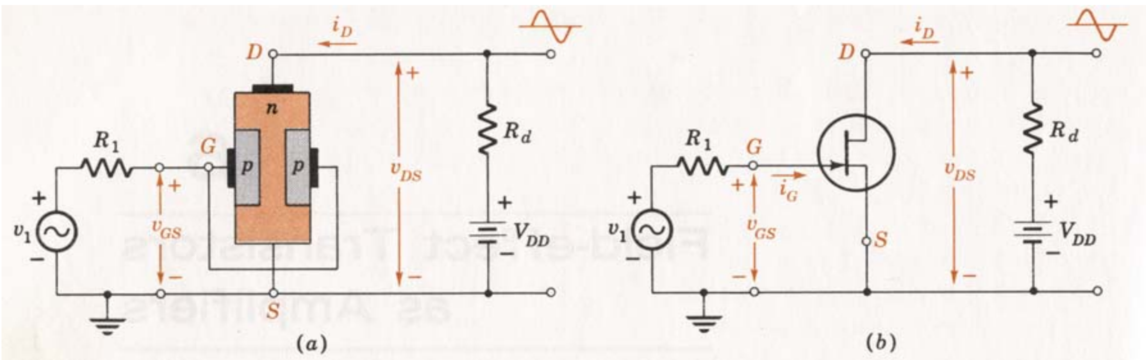
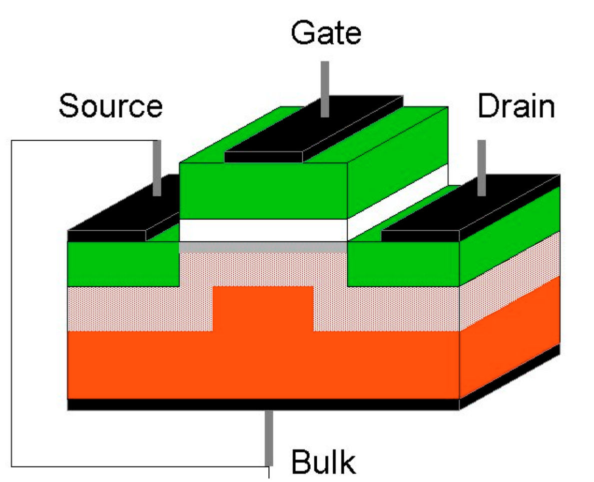


Fig. 6-1 The basic FET amplifier. (*a*) Pictorial representation; (*b*) schematic representation.



Here's what a (planar) FET looks like on a wafer

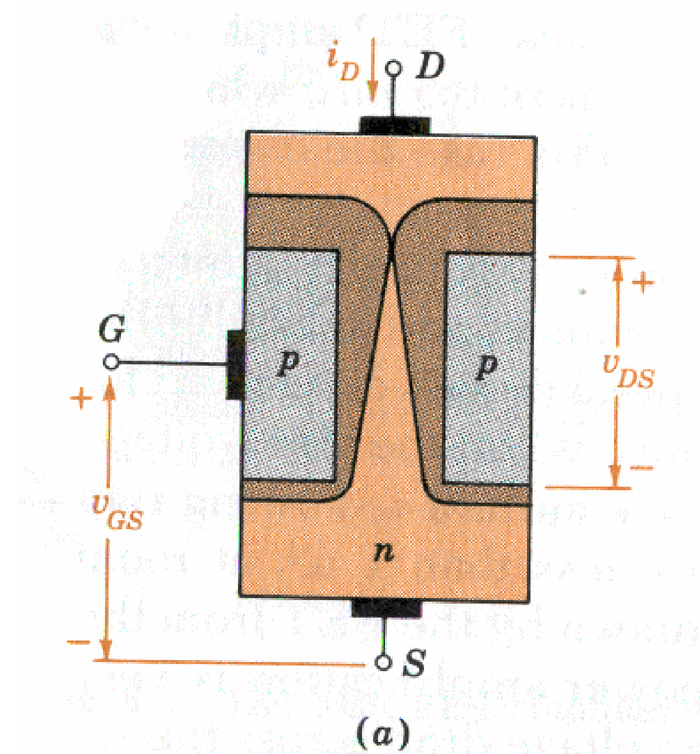


Fig. 6-2 Gate control of the FET. function of gate and drain voltages.

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Different BJT Representations, Avalanche

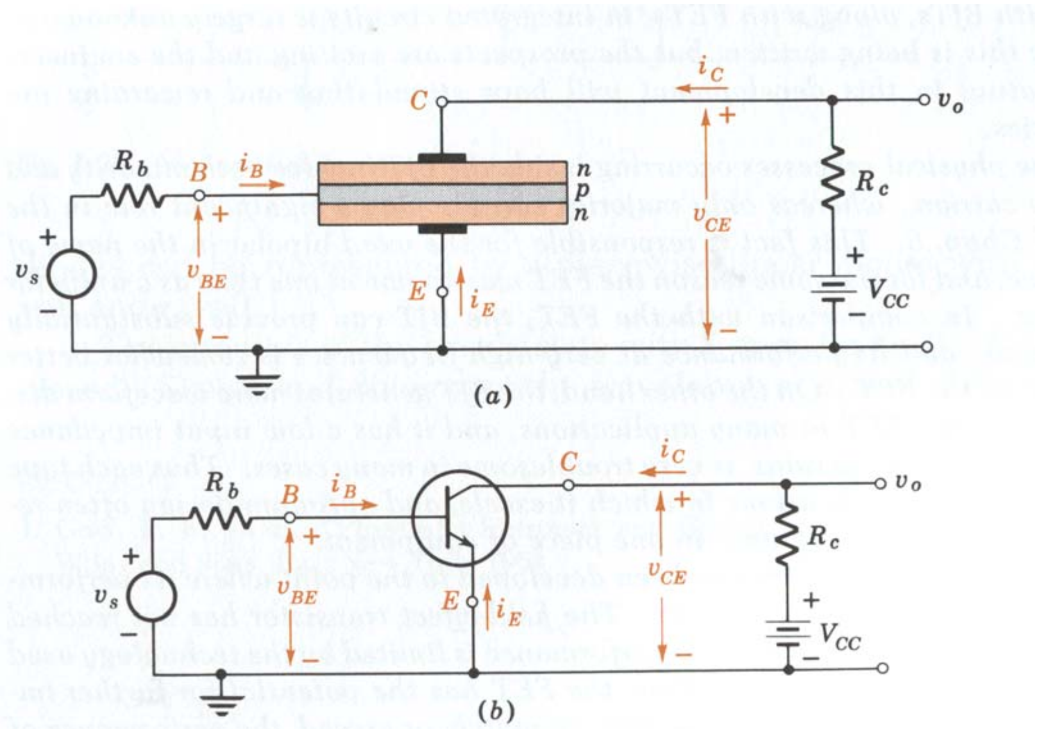
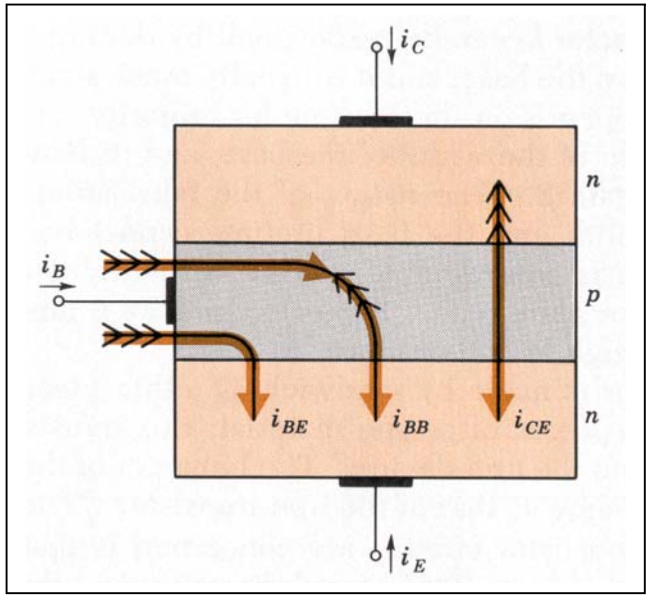


Fig. 9-1 The basic BJT amplifier. (*a*) Pictorial representation; (*b*) symbolic representation.



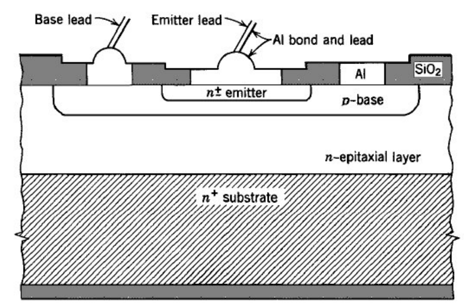
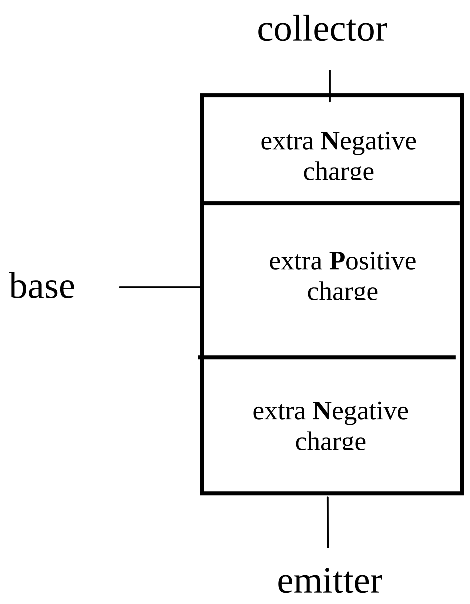
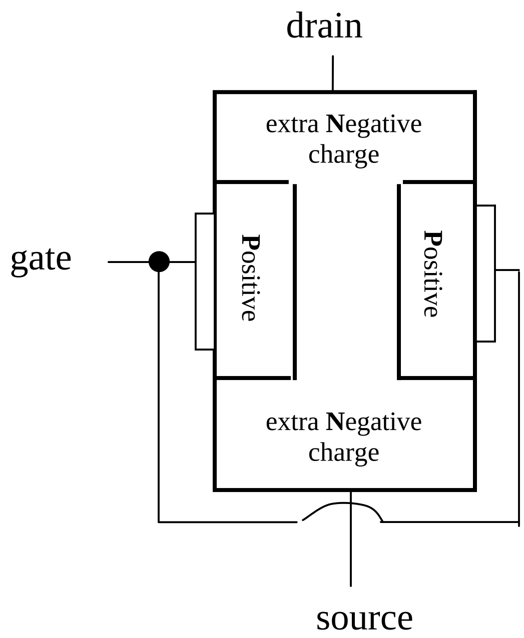


Figure 2. 15: Planar epitaxial transistor[9]

A Few More Tidbits About these Designs





1. The BJT design has evolved into "Bipolar" technology

1. FET's tend to "leak" current from their source to their drain. A thin oxide on top of the gate stops this (and made small integrated circuits possible).

2. The FET's have evolved into "CMOS" technology.

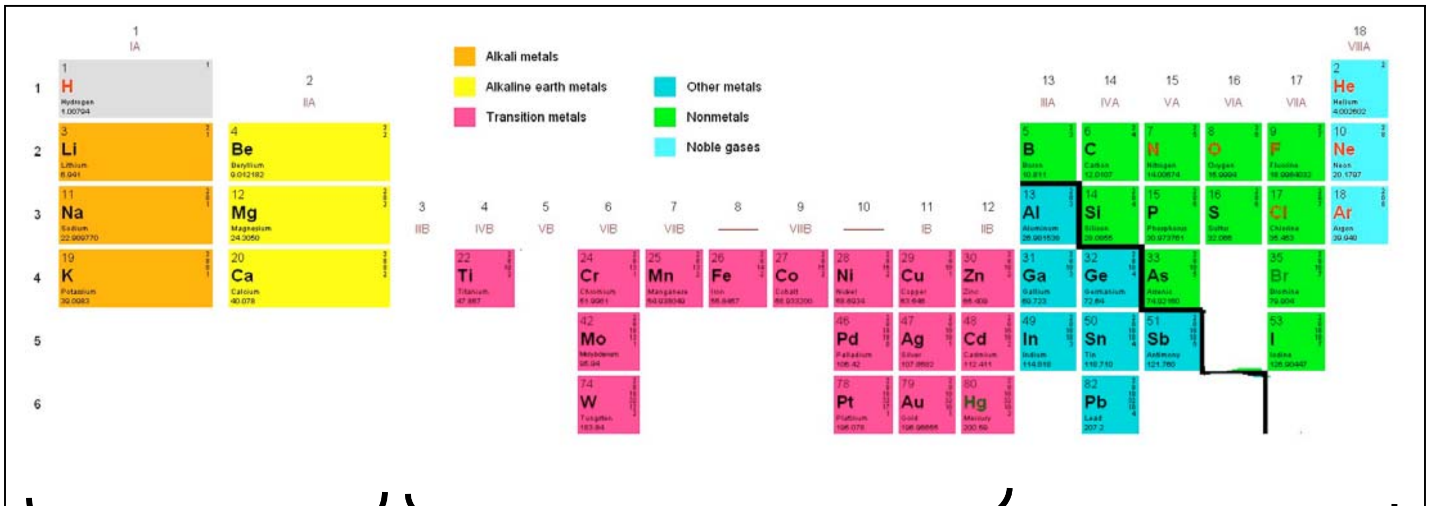
(II) MORE DETAILED: Doping 101

Back to Chemistry -- The Periodic Chart

To understand which elements we use for "doping" (adding a little extra positive or negative charge to regions of the perfect crystal) you must understand three things about the elements in the periodic chart:

1. The **row** determines the size of the atom

Electrons are closer to nucleus
=
stronger bonding, stronger reactions



Electrons are further from nucleus
=
weaker bonding, weaker reactions

Most Positive - chases after negatives

Wishy-washy - goes after negatives or positives

Most Negative - chases after positives

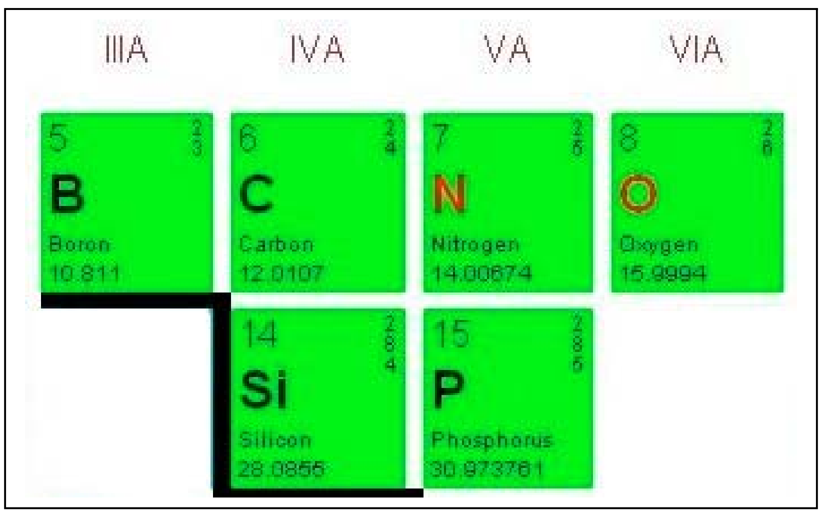
\+ -

2. The **column** determines the number of electrons in the outer orbit

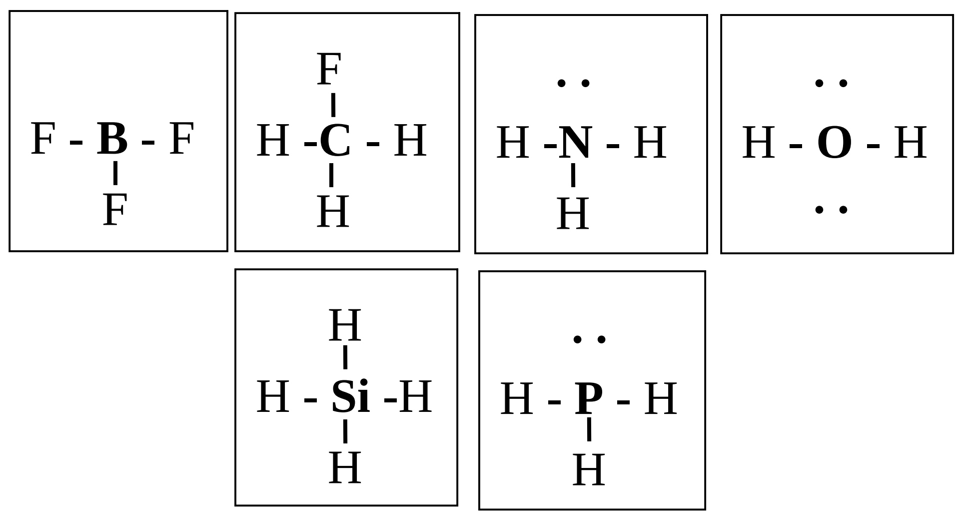
- Remember: only outer orbit electrons matter
- This is important if we want to add a little positive or negative charge to the perfect crystal. We have to look at the periodic chart to be able to pick out which type of atoms to add

3b. Atoms heavier than Boron want EIGHT electrons in their outer orbit (Boron wants six in its outer orbit)

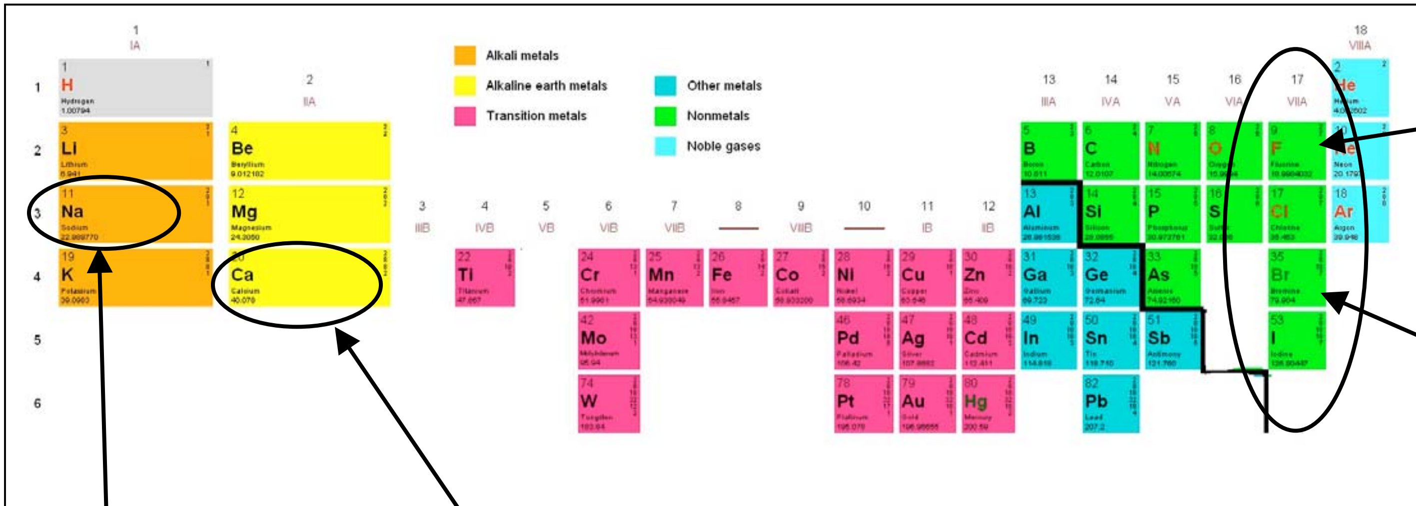
Question 1: Given that each line represents two electrons, which of the following molecules are stable?



III IV V VI



Question 2: Given that both HF and HBr break up in water (into H^+ F^- and H^+ Br^-), which one is worse to get on your skin and why?



Group 7 (the Halogens) means 7 electrons in the outer orbit

One more electron and the halogen atom is stable.

Halogens are fiercely determined to get that extra electron.

Q: Which halogen would be the fiercest?

Na+ is in the salt on your skin

Ca++ is in your bones

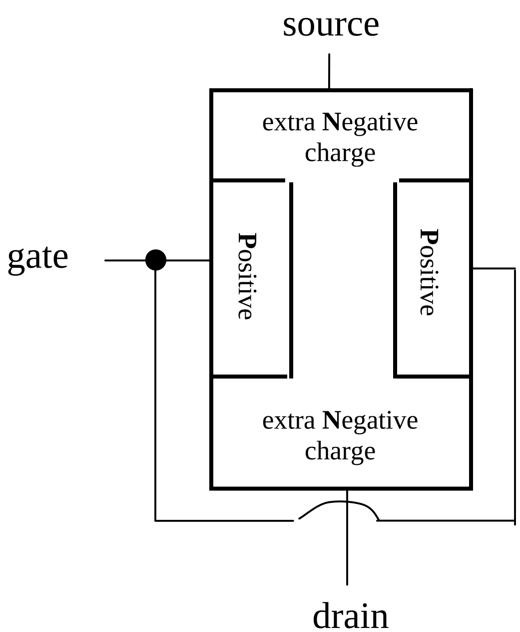
The body is ~90% water. HF and HBr will break up on your skin

Question 3: *Given that the below break apart in a plasma, which would be the stronger etchant?*

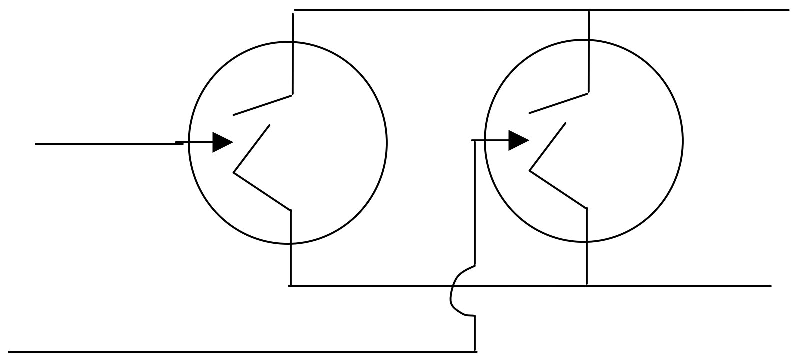
H	F	H
H - C- F	H - C - F	H - C - Cl
H	F	H

What does all this have to do with Transistors?

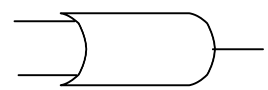
It turns out a little bit of doping (extra positive or negative charge inserted into the perfect crystal) to the structures below, enables them to be amplifiers and switches



gives:



gives:



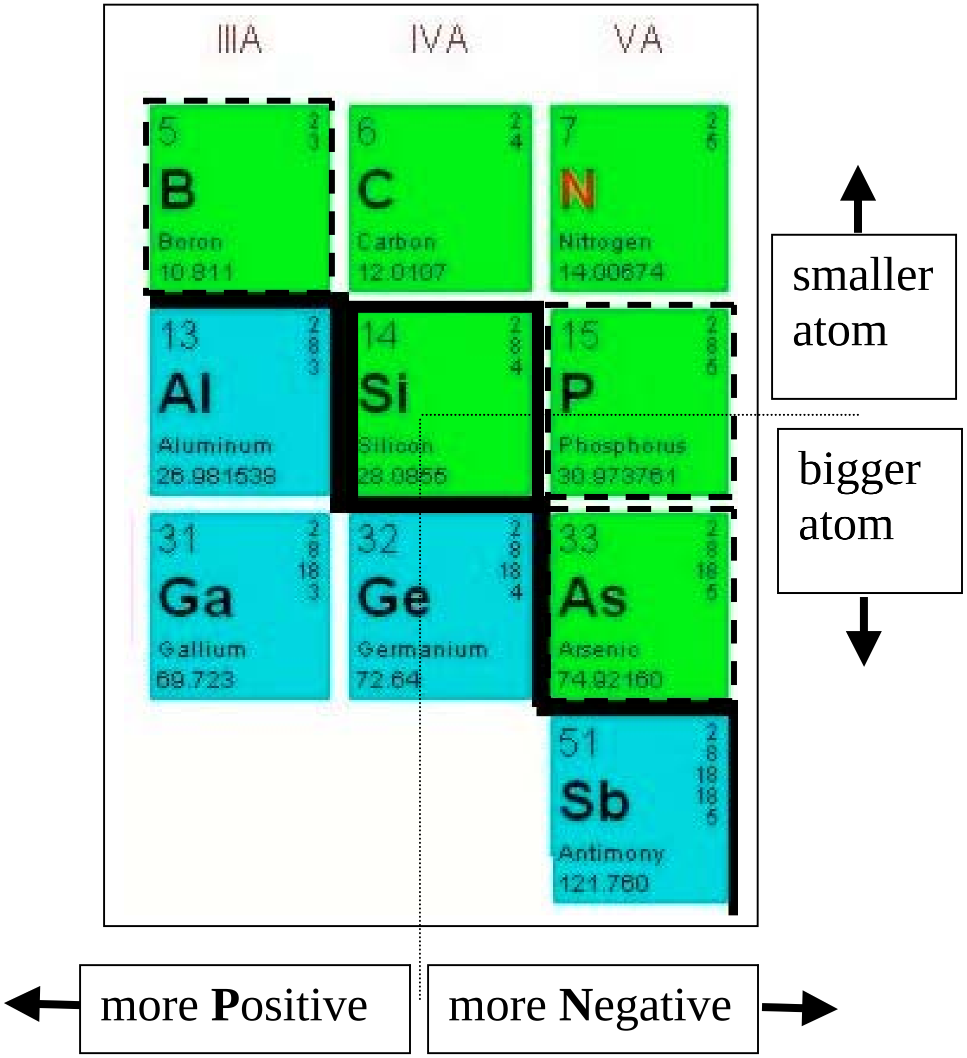
We use Silicon (Si) as our perfect crystal

Our extra **P**ositive charge is Boron (B)

- We use BF_3 because it is a gas, and gasses go through the implanter easier.

Our extra **N**egative charge is Phosphorous (P) or Arsenic (As).

- We use Phosphine (PH_3) and Arsene (AsH_3) because they're gasses
- The Florines and Hydrogens don't wind up in the perfect crystal



Silicon has about 5 x 10^{22} atoms per cm^3

We implant doses of 1 x 10^{12} to 1 x 10^{14} of our extra **P**ositive charge and extra **N**egative charge atoms.

- If we implant 100 angstroms ($=1 \times 10^{-6}$ cm) deep, then 5×10^{22} Si atoms/cm^3 x 1×10^{-6}cm deep = 5×10^{16} Si atoms/cm^2

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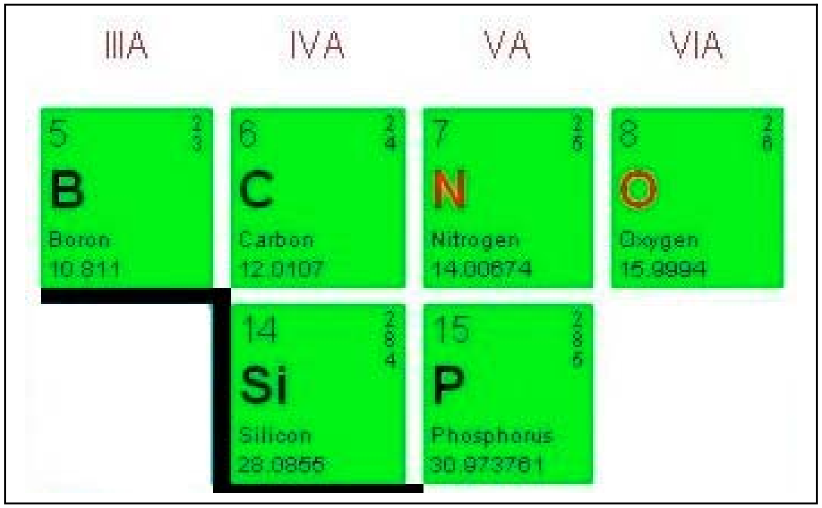
Stable Covalent Bonding:



III	IV	V	VI
BF_3: F - B - F, with F bonded below B	CH_3F: H - C - H, with F above and H below C	NH_3: H - N - H, with H below N (one lone pair)	H_2O: H - O - H (two lone pairs)
	SiH_4: H - Si - H, with H above and H below Si	PH_3: H - P - H, with H below P (one lone pair)	

Highly reactive extra **P**ositive charge

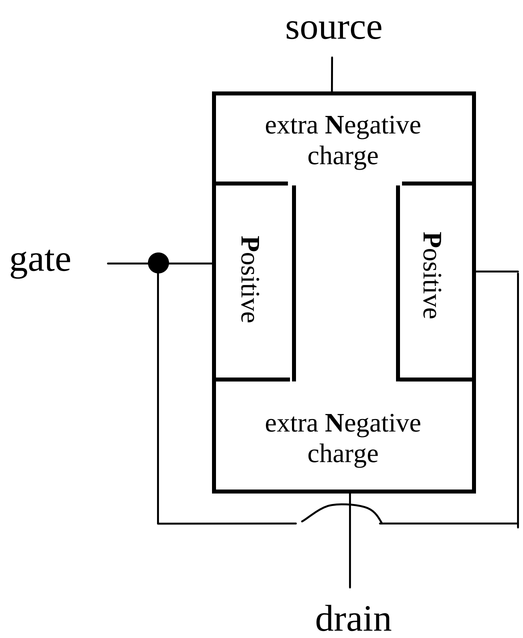
```
    |     |     |     |     |
 - Si  - Si  - Si+ - Si  - Si  -
    |     |     e     |     |
 - Si  - Si  -  B  - Si  - Si  -
    |     |     |     |     |
 - Si  - Si  - Si  - Si  - Si  -
```

Highly reactive extra **N**egative charge

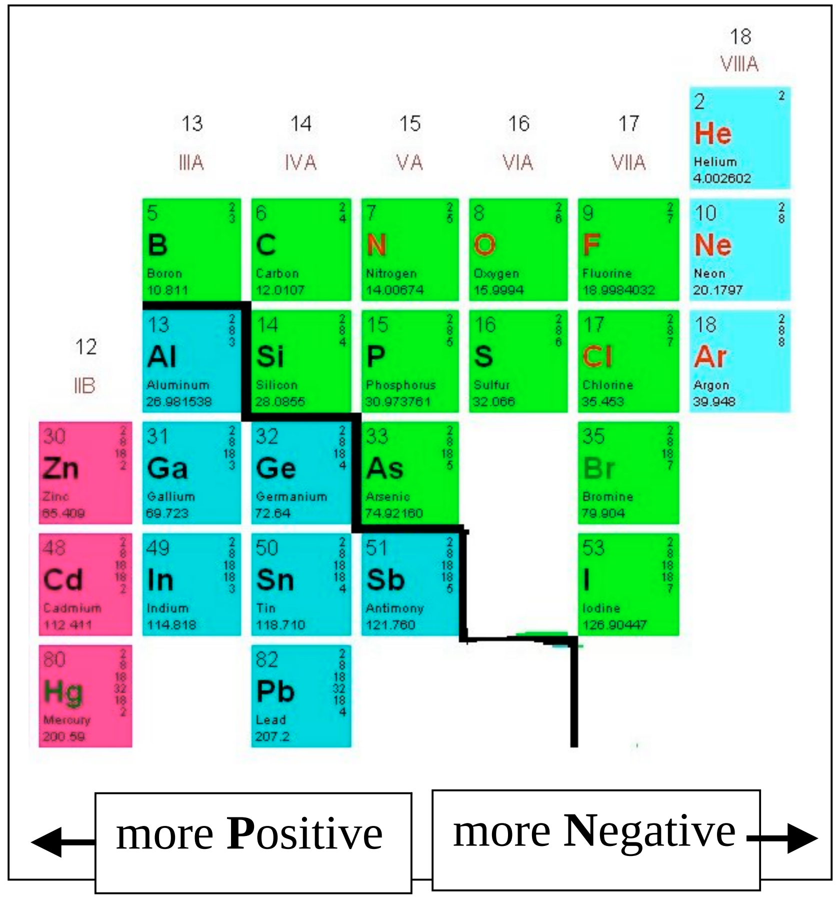
```
    |     |     |     |     |
 - Si  - Si  - Si  - Si  - Si  -
    |     |     |e    |     |
 - Si  - Si  -  P-  - Si  - Si  -
    |     |     |     |     |
 - Si  - Si  - Si  - Si  - Si  -
```

Early semiconductor developments used germanium (Ge) as the semiconductor material. What do you think it was doped with?

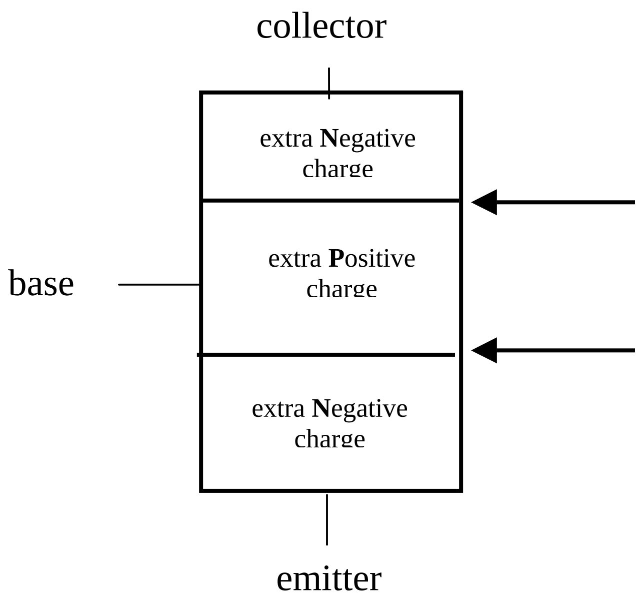
(Due to its ease of processing and more stable temperature characteristics, silicon became the semiconductor of choice).



For doping, you want an element whose outer shell electrons are about the same distance from the nucleus as the perfect crystal's, with one electron more and one electron less.

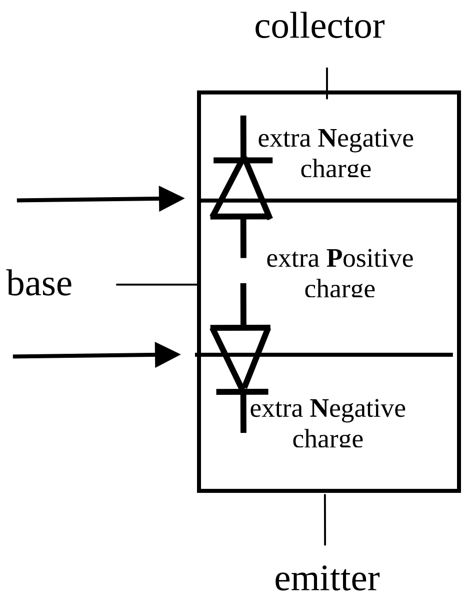


(III) NITTY-GRITTY: Diodes and the PN Junction



It turns out that every time we a boundary between extra **P**ositive charge and extra **N**egative charge, we have :

1) a "PN" junction
2) a diode



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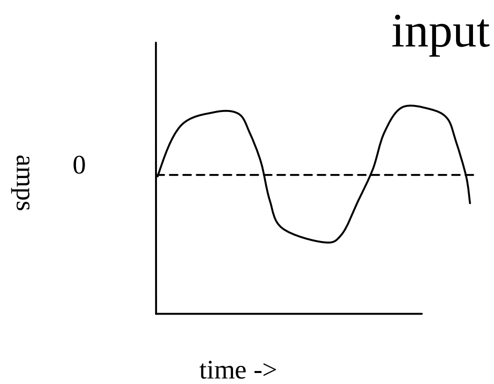
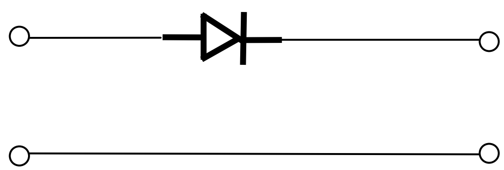
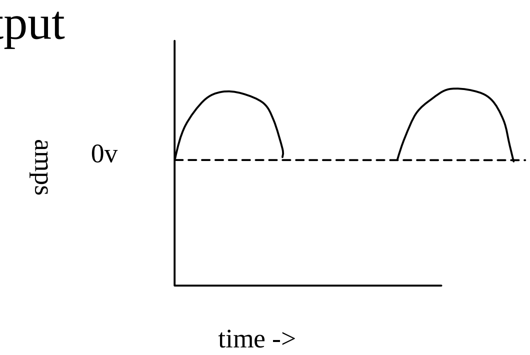
A diode only allows current to flow in one direction; e.g.:

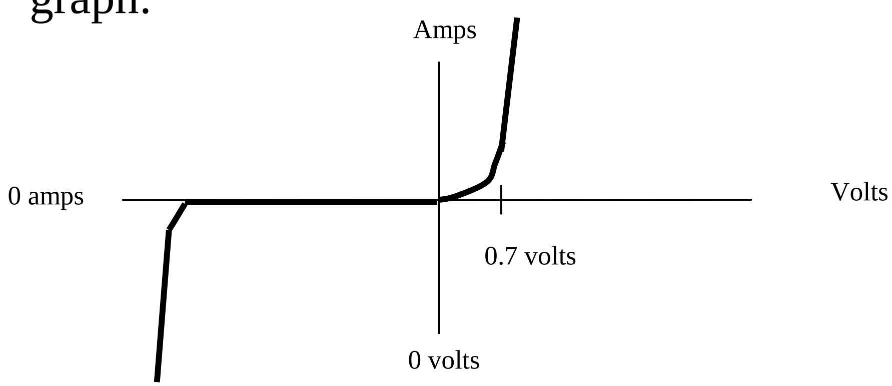


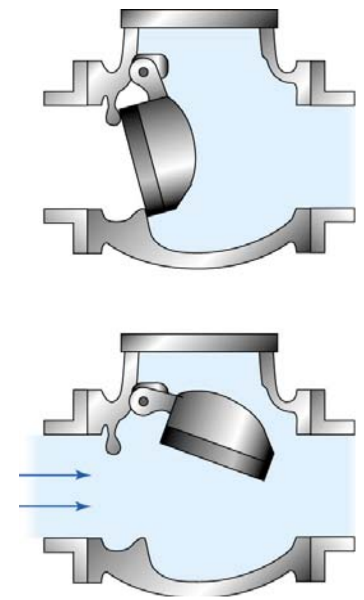




Diodes (along with capacitors) can be used to turn “AC” (alternating current) into “DC” (direct current)

Another way of representing the above is with a “volt-ampere graph:

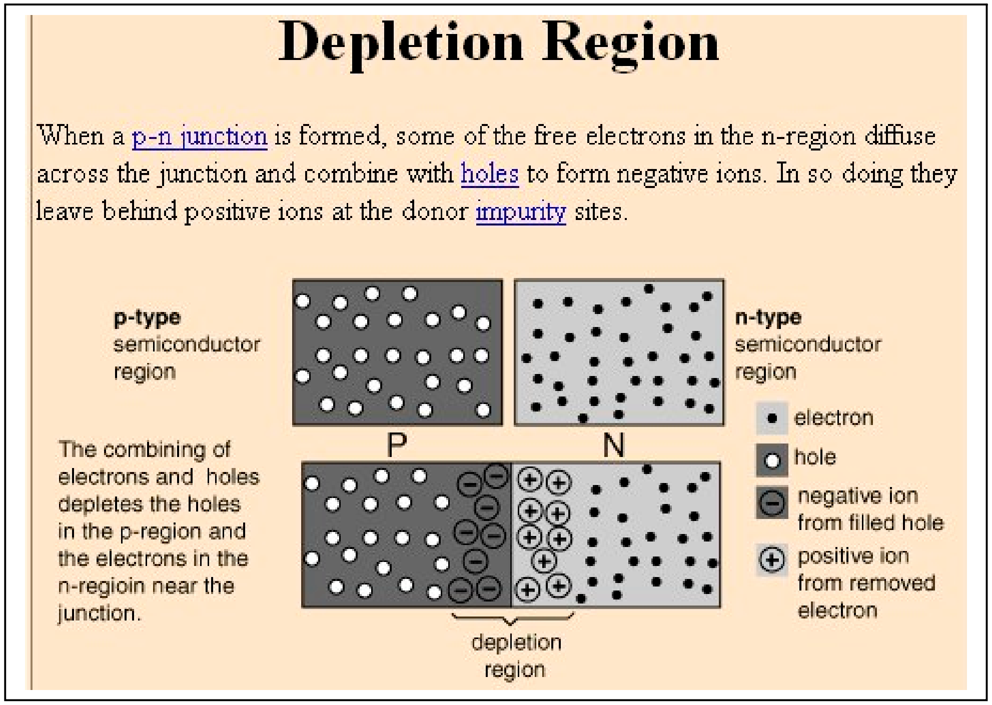




Mechanical check valve diode analogy

CYPRESS

How Does this Work?



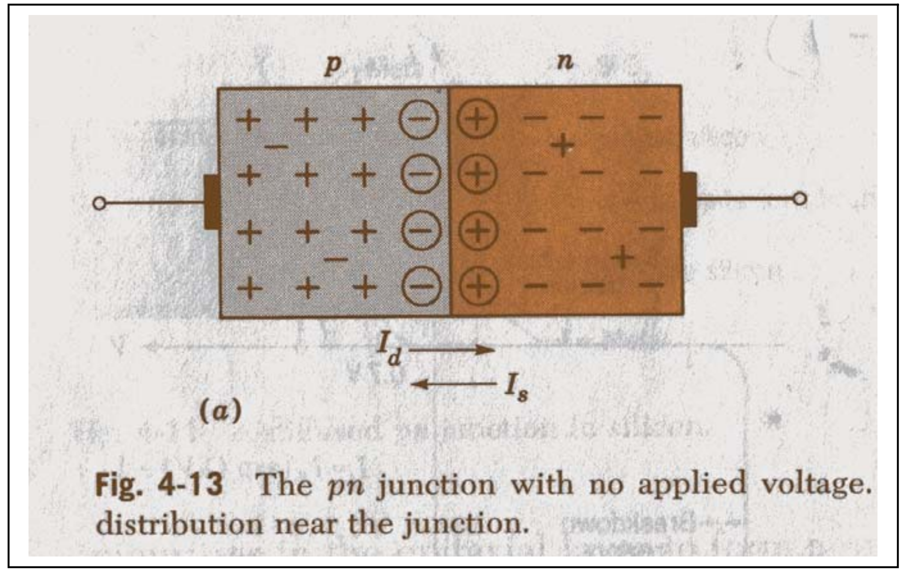
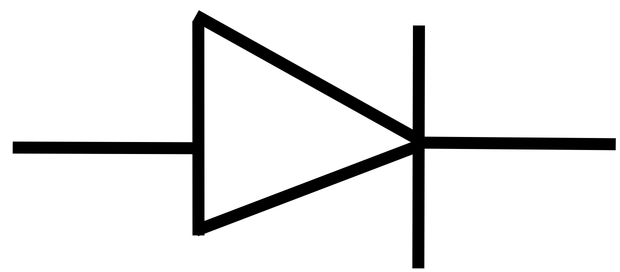
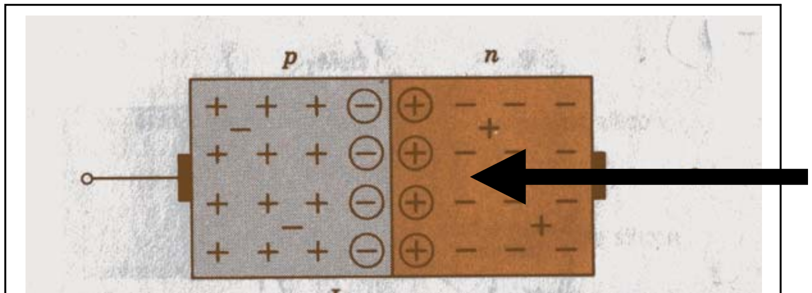


Fig. 4-13 The *pn* junction with no applied voltage. distribution near the junction.

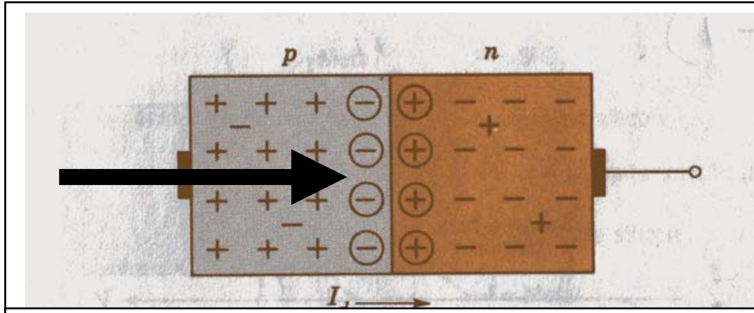


Forward Bias:



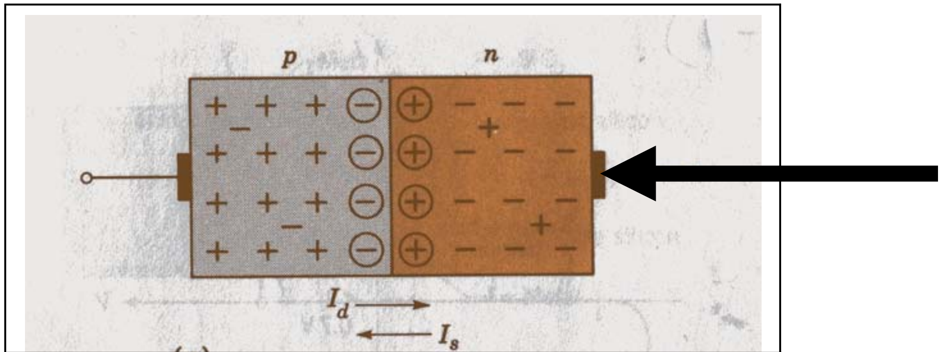
More negative electrons build up and enable "push through" the space charge region. Their "momentum" (of now being in the "conduction band") keeps them going through the positive region. Current flows.

Reverse Bias:

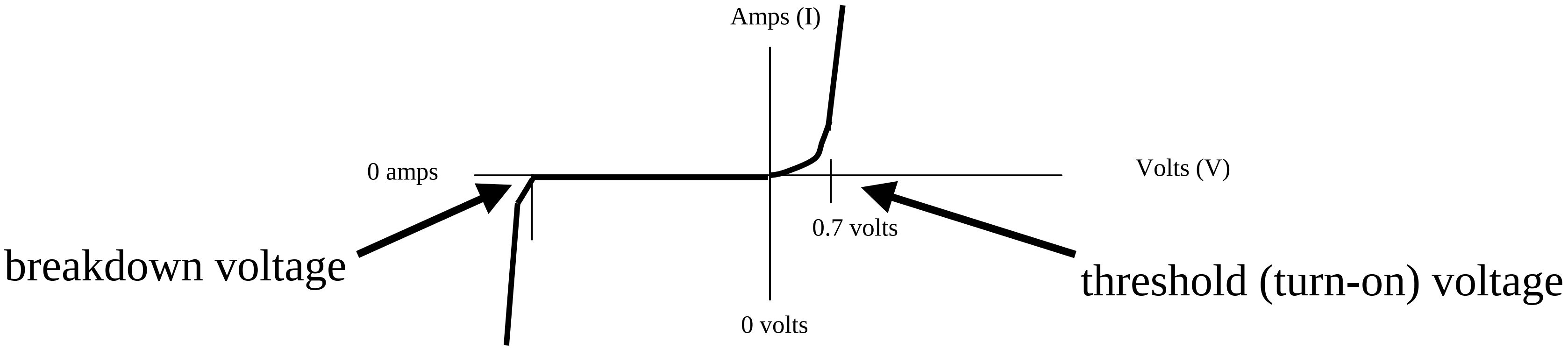


The SAME number of negative electrons, when pushed through on this side, just get neutralized (soaked up) by the positive charge (holes). They can't get out of the starting blocks=No "momentum" nothing flows.

Comparing Forward Bias to the IV Graph



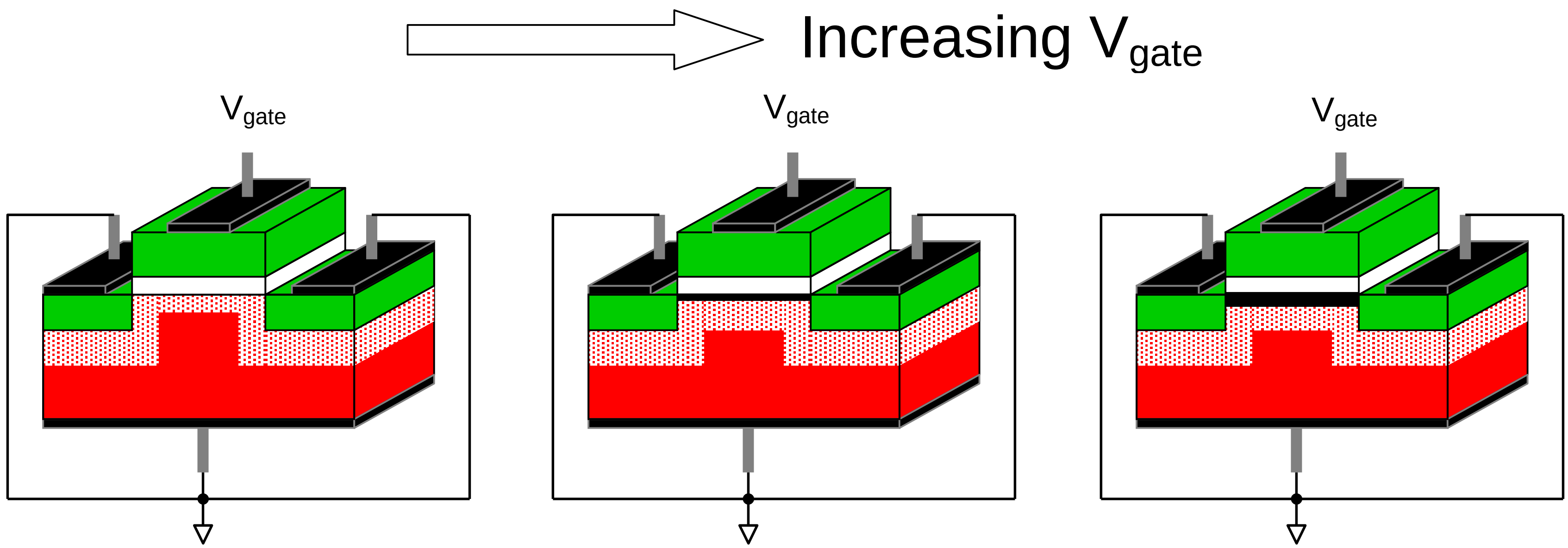
More negative electrons build up and enable "push through" the space charge region. Their "momentum" (of now being in the "conduction band") keeps them going through the positive region. Current flows.



CYPRESS

Next Week (Shane's Lecture):

How the MOSFET's we make turn on and off putting a field next to the charge depletion region:



In Conclusion: You should now know the **concepts**:

1. Big Picture:

    What transistors do in analog and digital circuits, and how they are designed.

2. More detailed:

    How the periodic chart relates to our selection of dopant for our "perfect crystal".

3. Nitty Gritty Details:

    What a PN junction is and how it works

For More Information - Take Some Courses!

Basics for Everything:

1. Potential and kinetic energy - Physics I

Electrical:

2. Ohms law and circuits: Physics II, Passive Circuits
3. Transistors and PN junctions: Active Circuits.
4. How computers work: Digital Electronics

Chemical:

5. The periodic chart, how atoms and molecules combine and break down, the different kinds of bonds, chemical equilibrium: General Chemistry I and II. Organic Chemistry I and II

Computer Science:

6. The limits of machine intelligence: Automata Theory
    - or browse the book “Goedel Escher Bach, an Eternal Golden Braid”