Chapter 20

Electric charge

Fundamental Concepts

- We have a model for how charge acts. The model tells us there are two types of charge, and that charges of similar type repel and charges of different type attract.

- We call the types of charge "positive" and "negative"

- In metals, the valence electrons are free to move around. We call materials where the charges move "conductors."

- Materials where the valence electrons cannot move are called "insulators."

- In insulators, the atoms can "polarize."

20.1 Charge

Let's summarize what we tried to learn last time:

Model for Charge
Frictional forces can add or remove charge from an object
There are two, and only two kinds of charge
Two objects with the same kind of charge repel each other
To objects with different kinds of charge attract each other
The force between two charged objects is long ranged
The force between two charged objects decreases with distance
Uncharged objects have an equal mix of both kinds of charge
There are two types of materials, conductors (in which charges can move) and insulators (in which charges are fixed in place)
Charge can be transferred from one object to another by contact between the two objects

A serious shortcoming of this model is that it does not tell us what charge is. This is a shortcoming we will have to live with. We don't know what charge is any more than we can say exactly what mass or energy are. Charge is fundamental, as far as we can tell. We can't find a way to change charge into something else or to change something else into charge. For fundamental particles (like protons and electrons) either a particle has charge, or it does not.

20.1.1 Conservation of charge

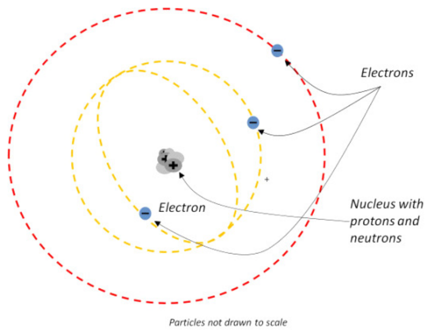
In some ways, this is really great! We have a new quantity that does not ever change. We can say that charge is conserved in the universe. Like energy, we can move charge around, but we don't create or destroy it. When we rubbed the plastic rods with rabbit fur or wool, we were removing charge that was already there in the atoms of the fur. If you take PH279 you might find that there are some caveats to this rule. We can make positron and electron pairs from high energy gamma rays. But when we do this we must always make a pair; one positive, and one negative. So the net charge remains unaffected.

20.2 Insulators and Conductors

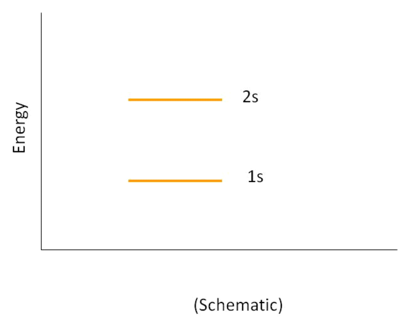
Let's return to charges and atoms. We have an intuitive feeling for what is a conductor and what is an insulator, but let's see why conductors act the way they do.

20.2.1 Potential Diagrams for Molecules

Back in high school or in a collage chemistry class you learned that electrons move around an atom.



In the figure there are two energy states represented. You may even remember the names of these energy states. The orange-yellow lines show one "orbital distance" for the electrons near the nucleus. The red line shows another electron at a larger orbital distance. The inner orbital is a $1s$ state and the outer orbital is a $2s$ state. If these were satellites orbiting the earth, you would recognize that the two orbits have different amounts of potential energy. This is also true for electrons in orbitals. If we plot the potential energy for each state we get something that looks like this

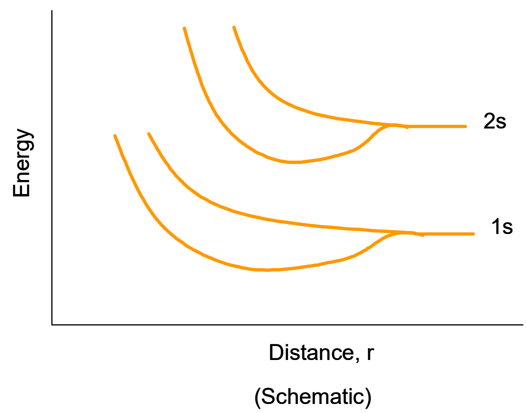


You can think of this as potential energy "shelves" where we can put electrons. If you were a advanced high school student, you learned that on the first two shelves you can only fit two electrons each. The higher shelves can take six, and so forth. But that won't concern us in this class.

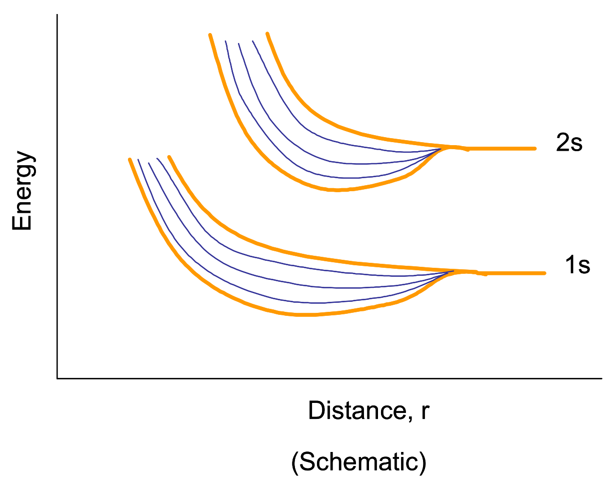
20.2.2 Building a solid

So far I have really only talked about single atoms. What happens when we bind atoms together? Let's take two identical atoms. When they are far apart, they act as independent systems. But when they get closer, they start acting like one quantum mechanical system. What does that mean for the electrons in the atoms?

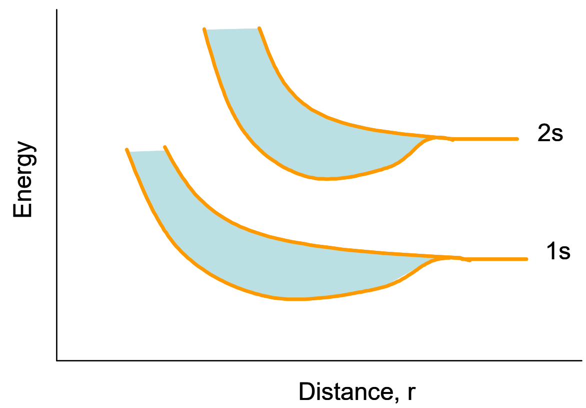
Electrons are funny things. They won't occupy the exactly the same energy state. I can only have two electrons in a $1s$ state, but as I bring two atoms near each other I will have four! How does the compound solve this problem? The energy "shelves" split into more shelves. As the atoms get closer, we see something like this



At some distance, r, the states split. So each electron is now in a different state. Suppose we bring 5 atoms together.



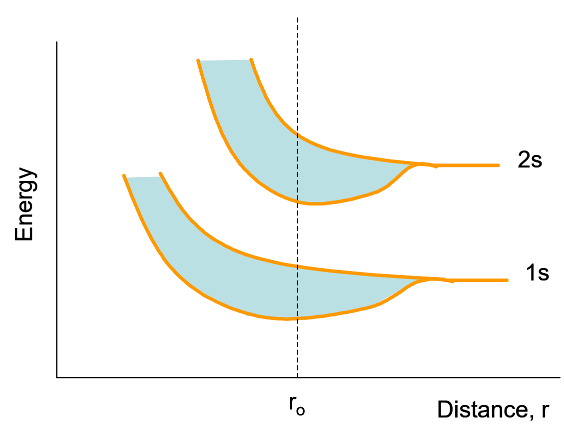
I get additional splitting of states. Now I have five different $1s$ states, enough for 5 atoms worth of $1s$ electrons. But solids have more than five atoms. Let's bring many atoms together.



(Schematic)

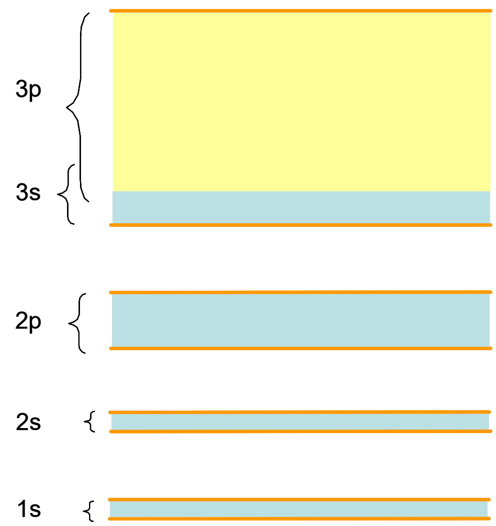
Now there are so many states that we just have a blue blur in between the original two split states. We have created a nearly continuous set of states in two bands. Each electron has a different energy, but those energy differences might be tiny fractions of a Joule. The former two states have almost become continuous bands of allowed energy states.

The atoms won't allow themselves to be too close. They will reach an equilibrium distance, r_o where they will want to stay.



(Schematic)

Since this is where the atoms usually are. We will not draw the whole diagram anymore. We will instead just draw bands at r_o.(along the dotted line). Here is an example.



This means we have *bands* of energies that are allowed, that electrons can use, and *gaps* of energy where no electron can exist.

20.3 Conduction in solids

Notice that in our last picture, the $3s$ and $3p$ bands have grown so much that they overlap. The situation with solids is complicated. Notice also that the lower states are blue. We will let blue mean that they are filled with electrons taking up every available energy state. The upper states are only partially filled. Yellow will mean the energy states are empty. We will call the highest completely filled band the *valance band* and the next higher empty band the *conduction* band.

We have three different conditions possible.

20.3.1 Metals

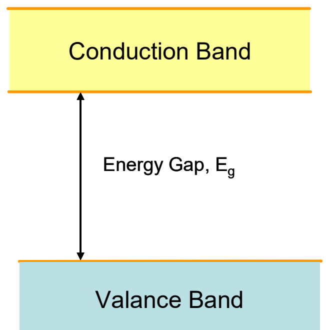
In a metal, the highest occupied band is only partially filled

the electrons in this band require only very little energy to jump to the next state up since they are in the same band and the allowed energies are very closely spaced. Remember that movement requires energy. So if I connect a battery to provide energy, the electrons must be allowed to gain the extra energy, kinetic energy in this case, or they will not move. But in the case of a metal, there are easily accessible energy states, and the electrons flow through the metal.

We can say that the outer electrons are shared by all the atoms of the entire metal, so the electrons are easy to move for metals.

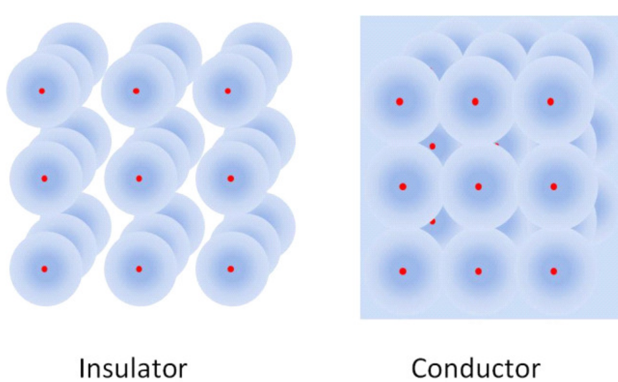
20.3.2 Insulators

A second condition is to have a full valance band and an empty conduction band. The bands are separated by an energy gap of energy E_g.



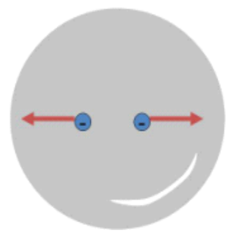
In this case, it would take a whopping big battery to make the electrons move. The battery would have to supply all of the gap energy plus a little more to get the electron to move. You might envision this as if there were an electrical "glue" that keeps the electrons in place. Before they can move, you have to free them from the "glue." It takes an amount of energy, E_g, to free the electrons before they are able to accept kinetic energy. If we do connect a very large battery, say, 33000 V, then we can get electrons to jump the gap to a higher energy "shelf." But high voltages are not normal conditions, so this is not usually the case. A material that has a large energy gap between it's valance band and an empty conduction band is called an insulator.

A mental picture for this might be as shown in the next figure.



The insulator atoms keep their valence electrons bound to the nuclei of the atoms. But for a conductor, the valence electrons are free to travel from atom to atom.

In an isolated conductor, normally the charge is balanced, so the electrons may move but generally they stay near a nucleus. But if a conductor has extra electrons, the electrons that can move will move because they repel each other. So any extra charge will be on the surface of the conductor.



This happens very quickly, generally we do find the extra charge distributed on the outside of a conductor.

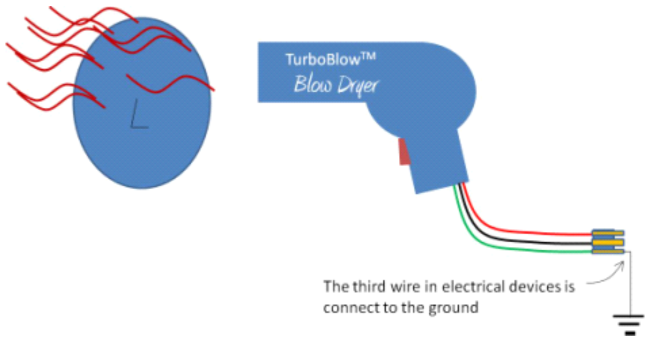
20.3.3 Semiconductors

The third choice is that there is a band gap, but the band gap is small. In this case, some electrons will gain enough thermal energy to cross the gap. Then these electrons will be in the conduction band. Devices that work this way are called semiconductors. We won't deal with semiconductors much in this class, but you probably used many of them in ME210. Diodes, and transistors are made from semiconductors.

20.3.4 Charging and discharging conductors

Conductors can't usually be charged by rubbing. The electrons in the conductor may move when rubbed, but then they are free to move around in the conductor, so they don't leave. But if we rub an insulator, the electrons are not free to travel in the insulator material, so we can break them free. Once this happens, we can take our charged insulator and place it in contact with a conductor. The charge can flow from the insulator to the conductor (and arrange itself on the conductor surface). Once the charge has moved to the exterior, it will reach what we call *electrostatic equilibrium*. All of the repelling electrical forces are in balance, so the charges come to rest with respect to the conductor.

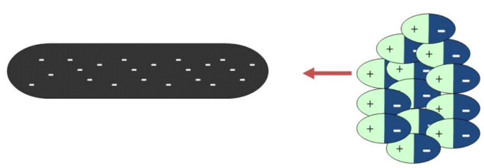
We can remove the extra charge by creating a path for the charge to follow. Consider charging a balloon by rubbing it on your hair. Then you connect a wire to the balloon that is also connected to a metal water pipe. The charge can flow through the metal conducing wire. If there is a large body that can attract extra charge, the charge will flow. The Earth is such a large body that can attract the extra charge. The charge will flow through the wire and pipe and go into the ground.



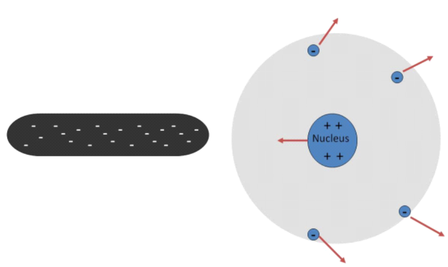
You may have heard of electrical grounds. This literally means tying your device to the Earth through a wire. Since you are made mostly of water that contains positive ions, you are also a conductor. So if we touch a charged object, we will most likely discharge the object. This is also why we must be careful with charge. Large amounts of charge flowing through us leads to death or injury.

If an object is *grounded*, it cannot build up extra charge. This is good for appliances and houses, and people.

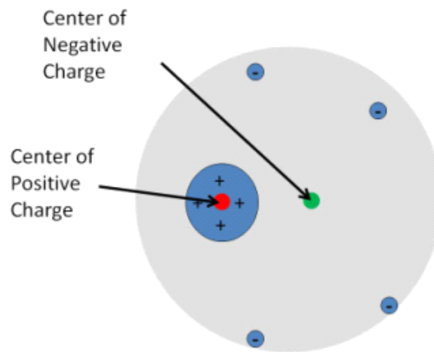
We talked last time about insulator atoms being polarized.



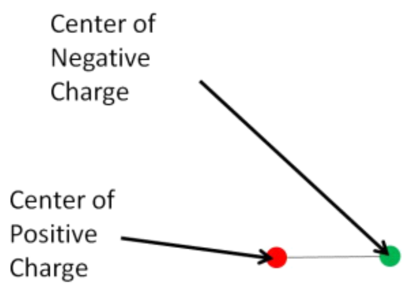
Remember that for each atom the electrons are displaced relative to the nucleus.



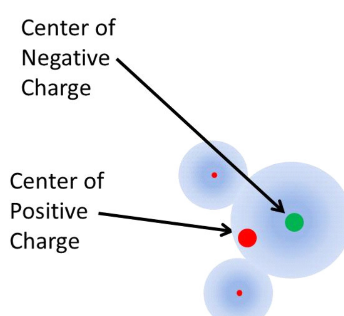
We can define a *center of charge* much like we defined a center of mass. In the case in the figure, we can define a negative center of charge and a positive center of charge.



Notice that the negative and positive center of charge are not in the same place when the atom is polarized. We have a name for a pair of positive and negative charges that are separated by a distance, but that are still bound together. We call it an *electric dipole.* Often we just draw the centers of charge joined by a line.



Using this we can explain why humidity affects our last lecture experiments so much. The water molecule has two hydrogen atoms and one oxygen atom. The covalent bond between the oxygen and hydrogen atoms forms when the oxygen "shares" the hydrogen's electrons. The electrons from the hydrogen atoms spend their time with the oxygen atom making one side of the molecule more positive and the other side more negative.



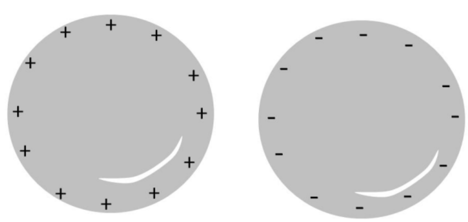
Thus if you have a charged balloon on a humid day, one side of the water molecules in the air will be attracted to the extra charge on the balloon. The extra charge will attach to the water molecules, and float away with them. This will discharge the balloon.

20.4 Note on drawing charge diagrams

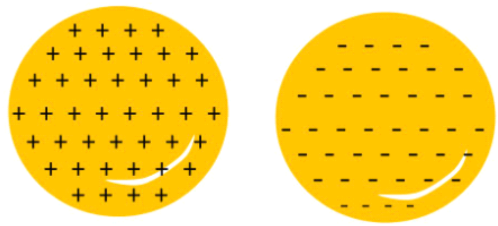
We will have to draw diagrams in our problem solutions. Normally we won't draw atoms, so we will be drawing large objects with or without extra charge. We know that all materials have positive nuclei and negative electrons. When these are balanced, there is an electron for every proton, so if we add up the charges we get zero net charge. These charges don't contribute to net forces because for every attraction there is a repulsion of equal magnitude.

So we won't draw all of these charges, but we should remember they are there. We usually draw a cross section, so here is the cross section of a round, conducting ball.

But if we have extra charge, we should draw it. We will just add plus signs or minus signs. We won't draw little circles to show the electrons (we can't draw them to scale, they are phenomenally small). Here is an example of two round objects, one positive and one negative



If the objects are not conductors, the extra charge may be spread out. We draw the charge throughout the cross section of the object.



Note that if you transfer charge, from one object to another, you should try to keep the same total number of "+"' or "-" signs to show the charge is conserved.

Basic Equations

None so far.