Chapter 21: The Electric Force

Electric Charges and Coulomb's Law

Since we now understand gravity, it is time to apply this new found knowledge to the second of the four forces; the electromagnetic. The electromagnetic (EM) force manifests itself in two fashions; as the electric force in some circumstances and as the magnetic force in others (occasionally it will be both simultaneously). As the electric force, which we will discuss first, it is the most important force in the universe (a debatable statement). It is true that each force is necessary for the universe to exist at all, however, when I refer to the em force as the most important, I am saying this because it is the force that most directly affects our lives. The em force is responsible for all chemical reactions (including our own digestion), it is responsible for giving matter its solidity, and for holding the electrons in their orbits.

If the student will permit, I would like to take a side track and discuss how the em force affects our perceptions of matter itself. Firstly, consider trying to touch an object. Are you really in contact with that object? The answer is no. When you touch something, you are actually bringing the atoms in your hand close to the atoms in that object. Around the atoms swirl electrons. As the electrons in your hand get close to the electrons in the object, they repel. When you hold your pencil, there is still space between your fingers and the pencil. If you try to push harder, the electrons get closer and push apart harder. You can never make contact. You are not really in contact with the chair you are sitting in. You are actually floating on a thin vacuum layer between your atoms and the atoms in the chair. Dr. Richard Feynman, a famous modern day physicist, was once asked if scientists would ever invent an anti-gravity machine. He said there is one, called the electromagnetic force which causes everything to float on everything else. The second point I wish to make is about the illusion of solidity. We know that the nucleus is a very, very tiny percentage of the atom, and the electrons are even smaller. Thus most of the atom is empty space. In fact, if we were to take all the empty space out of the earth, it would only be about 6 miles wide. Why then do objects look solid? The answer lies in the electromagnetic force. We see things as solid because of the way light (which is an electromagnetic phenomena) interacts with the electrons on the outside of the material. Matter is not solid, it just looks that way. I give you these examples to think about because they show how important the em force is to us in the world around us. They also show that the effects of the em force are numerous but not obvious to the untrained eye. Besides those reasons, they also show us that there are marvels unbelievable in nature if we only know how to look for them.

But let us begin at the beginning. The electrical force is the force of attraction or repulsion between two charged objects. The charge of an object is a physical property that describes how the object reacts to the electric force. Charge is very similar to gravitational mass, in fact charge is the "electrical mass" of an object (we really don't know what it is, but we can measure its effect and give it a name and that makes us think we are smart). All matter has charge, although it is possible to have a charge of zero. You have probably learned that electric charges are either positive or negative (a description that was devised by none other than Benjamin Franklin), and that protons have a charge of +1 while electrons have a charge of -1. The SI unit for measuring charge is the Coulomb (C) and its actual definition is rather confusing. A Coulomb is not a fundamental unit, it is actually a derived unit. At this point in time the student would not be able to understand the derivation, since it involves units that have not yet been introduced. One Coulomb is a <u>very</u> large amount of charge, and so a smaller unit is often used. This other unit is called an elementary charge, usually abbreviated with an e. The conversion between the two is very important and will be used often.

$$1 \text{ e} = 1.60 \times 10^{-19} \text{ C.}$$

The elementary charge is the charge on one proton or the negative of the charge on one electron. We can see from the above conversion that an elementary charge is very small in relation to a Coulomb.

You probably also remember that it is charge difference in an object that matters, not the number of charges. What this means is the difference between the positive and negative charges in an object determines its overall charge. An object with 50 positive charges and 45 negative charges is the same as an object with five positives and no negatives.

Another reason why the elementary charge is so important is that charge appears to be quantized. When something is quantized, it means that it exists in discrete bundles. The fact that charge is quantized means that we can find an object with a charge of 5e or 30001e, but never with 2.6e or 0.4e. Charge must exist in integer multiples of the elementary charge (as another example of a similar system that is quantized, consider money: the smallest (quantized) unit is a penny). Since the elementary charge is so small, however, it would almost appear as if any value of charge were possible. The quantization of charge only holds to the particle level (electrons, neutrons and protons). Inside the protons and neutrons are what are called quarks which seem to have fractional charge (2/3, or 1/3 of an e).

Another important aspect about charges is that in any physical situation, charge must be conserved (just as mass, energy and momentum). Charges can then be neither created nor destroyed, which is almost a matter of common sense. If you charge an object (like shuffling your feet across the carpet) you do not create charges, you simply rearrange them. In nature, the conservation of charge can be seen in the strange happenings of particle and nuclear physics. For example, it is possible for a gamma ray (a particle of light) to spontaneously turn into an electron and an anti-electron. Notice how charge is conserved. The gamma had no charge and the electron and anti-electron cancel each other out (-e and +e charges, respectively). It would be impossible for a gamma to change into two electrons, since that would violate the conservation of electric charge. Another example is the nuclear reaction of beta-decay mentioned earlier. In β^- decay, an element moves up one atomic number while keeping its mass number the same (ex: Tc-100 can change into Ru-100). For this to happen, a neutron must disappear and a proton must take its place. However, conservation of charge prohibits this unless an electron (or other negative particle) is also formed. In β^- decay, an electron (also called a beta particle) comes flying out of the nucleus.

Electric charges attract and repel each other just as two masses attract each other due to gravity. However, instead of the mass determining the strength of the force, the charges of the two objects determine the strength and direction of the force. It is important to note that charge and mass are parallel concepts. In fact, the charge could be called the "electrical" mass of the object, or the (gravitational) mass could be called the gravitational charge of the object. The electrical force is determined quantitatively by using a law that resembles NULG:

$$F_E = Cq_1q_2/r^2$$

Where F_E is the electric force, q_1 and q_2 are the charges of the two objects in question and r is the distance between the two charges. The above formula is the "modern" version of what is called Coulomb's Law, named after Charles Coulomb. Coulomb devised this law by using a "torsion balance" which was almost identical to Cavendish's experiment to measure G, except that this time charged objects were used. Historically, Coulomb's Law was written as:

$$F_E = \frac{1}{4\pi\varepsilon_o}\frac{q_1q_2}{r^2}$$

Comparing the two versions, we see that:

$$C = \frac{1}{4\pi\varepsilon_o} = 8.99 \times 10^9 \text{ N.m}^2/\text{C}^2$$

Where

ε_o = the permativity of free space

$\varepsilon_o = 8.85 \times 10^{-12}$ C^2/N.m^2

Obviously, the two versions of the equation are equivalent, however, some books and some professors use the older version. The reason for this is that while the new version looks very much like NULG and is easier to remember, the older version fits in more nicely with some advanced concepts that link electricity and magnetism. The constant factor (ε_o), is an electrical property of a vacuum. The beginning student need not concern themselves with its actual meaning.

Coulomb's law is used in precisely the same manner as NULG, so let us begin some problems to practice using it. As you will see, these problems require that you remember some basic concepts from chemistry.

EX A.) In an average lightning flash, about 10 C of charge are exchanged between the ground and the clouds. How many electrons are exchanged?

EX B.) Compare the number of electrons in the lightning flash with the number of electrons in a human hair. Assume the hair to have a mass of $1x10^{-4}$ g and to be composed primarily of carbon.

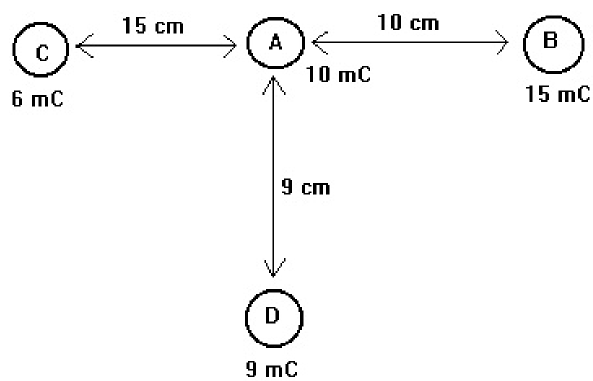
Besides giving you practice, this past example (although a crude approximation) should give you some inkling about the phenomenal number of charges present in everyday objects.

EX C.) Imagine you could take all the electrons from the hair in the last example and pull them all to one end of the hair. If all the remaining positive charges were pulled to the other end, what force would be needed to hold these two charge bundles apart? Assume the hair to be 12 cm long.

Although what was asked in the above problem is ridiculous and impossible, it was meant to demonstrate the incredible about of force, power and energy that is locked up in normal, everyday objects. The electrical force is present everywhere, it is just unusual for us to notice its effect if we don't look carefully.

The next example demonstrates that when many electrical forces are present, we need to recall the vector nature of forces.

EX D.) Calculate the net force experienced by charge A in the set up below.



Basic Electrical Knowledge Regarding Materials

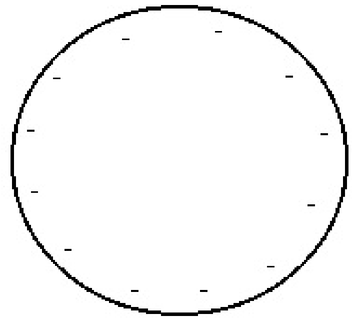
Before we move on to discussing the electric field, there are a number of interesting and basic concepts regarding the behavior of charges and charged objects that the student should be familiar with. The topics are generally covered in introductory science courses, but it might be helpful to quickly refresh your memory regarding these concepts.

Materials are generally classified as conductors or insulators (although there is no distinct line between the two, rather there is a continuous spectrum of materials running from extreme conductors to extreme insulators, with most materials falling somewhere in between). A conductor is a material that allows charged particles to move freely inside of it and an insulator is a material that hinders the free movement of charged particles. When we discuss moving charges in a material, we usually discuss electrons, since it is rare to have a free proton floating around a material. Thus conductors and insulators are often described in terms of how they allow electrons to move.

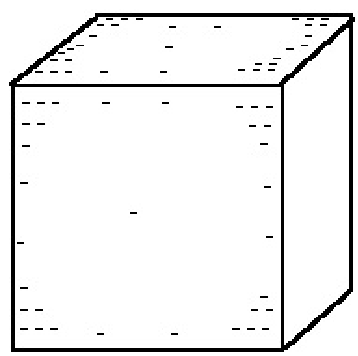
Since conductors allow charges to move easily, once we put a charge in a conductor, it will simply float around until it reaches an equilibrium point. Because of this, charges can easily leave a conductor if conditions permit. Once a conductor is charged, for example, the charge can leak off into the air. For this reason, conductors loose their charges easily while insulators tend to hold their charges for longer period of time. A good example of these principles is the case of a typical, electrical wire in your home. The inside is metal, allowing charges to flow freely and quickly, while the outside is plastic, which does allow some charge to flow through, but so slowly and in such a restricted manner that it would never pose a danger to someone or something in contact with the outside.

The terms conductor and insulator have nothing to do with the ability to <u>have</u> a charge, only with the behavior of the charge once it is on the material. A common misconception is that insulators cannot be charged. It is possible to have an electrically charged piece of rubber. However, because the charges do not move freely, it is more difficult to charge the rubber than it would be to charge, say aluminum. Once a charge is on the rubber, it would retain that charge better than a metal since the charges would have difficulty leaking off. This can be seen in many of the common electrical demonstrations done in a physics class. When a teacher wants to demonstrate charges, they often use a rubber or glass rod, so the charges do not leak off before the demo is over. When using a metal object, the object is often kept continually charged (as in the case of a Van DeGraff generator) or is given a very large charge so that if some leaks off, the demonstration will still work. The humidity in the room is often a big factor in the amount of time an object will retain a charge, since humid air is a good conductor, thus the charges can easily enter the air on a humid day. Humidity has been the cause of many failed demos in a physics class.

Because conductors allow for free passage of charges, on good conductors we get an interesting effect. <u>When a charge is placed on a conductor, it will move so that all the charges reside on the outer surfaces.</u> Consider pumping millions of electrons into a solid metal sphere. They will all repel each other and try to get as far away from each other as they can, as shown below.



On a regular, symmetric sphere, the charges will spread out evenly on the surface (and will even be pushed off if possible, as they try to get away from each other). However, on other objects, such as a metal cube, their attempt to get away from each other will result in a non-uniform distribution of charges on the surface. It turns out that charges will migrate to the furthers extremities and get as far away from the center as possible. This means that charges will generally conglomerate at points, with fewer charges in other areas. The diagram below illustrates this, but charges were not drawn on the side for clarity.



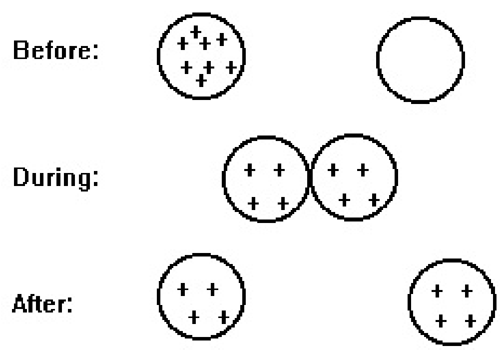
When students first see this diagram, they often wonder why the charges would gather so close together at the corners. The reason is that although this puts them very close to each other, it allows them to get as far away as possible from as many other charges as possible. The student should keep this behavior in mind in later discussions of lightning and electric fields.

Before we move on, it should be mentioned that although we have been talking about putting a negative charge on these objects, it is also possible to have the same effect with a positive charge. Generally, charging an object positively requires not putting positive charges on the object, but rather removing a certain amount of negative charges. Thus, in the example of the sphere, if we remove negatives we leave positive "holes" and the electrons in the material will rush to fill these holes, leaving gaps elsewhere. In the sphere, electrons will rush from the surface to fill in the gaps in the middle, leaving a uniform positive charge on the surface.

We have been talking about charged objects during this chapter, but have yet to discuss how an object can become charged. It is important to remember that all objects have charges (the electrons and protons in their atoms), however if the number of positive and negative charges are the same, the object is neutral. This is the normal state of most objects. When we discuss charging an object, we are really discussing creating a charge imbalance between its positive and negative charges. Obviously, a positively charged object has more positive than negative charges and visa-versa. Creating this imbalance is (in general) a matter of either taking electrons away from an object (leaving it positive) or adding extra electrons (and making it negative). There are three ways of charging an object: friction, conduction and induction.

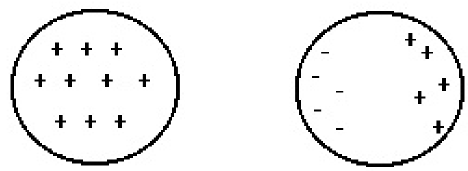
Charging by friction is what occurs when two objects are rubbed together. It is possible, depending on the materials and their ability to lose or gain electrons, to rub two objects together and have the electrons from one be transferred to the other. This is the explanation for that annoying shock you receive after you shuffle your feet across a carpet.

Conduction refers to the process of charging an initially neutral object by bringing another charged object in contact with it (or close enough for the charges to "jump" from one to the other). Since the charges are repelling each other on the charged object, they will move to the neutral object to escape each others forces. Once there, they will establish a new equilibrium. The diagram below shows a before and after sequence of charging by conduction.



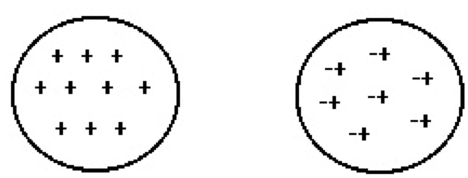
Of importance to note is that after the two objects are separated, both are still charged. Also, conduction applies to any situation where there is a transfer of charges. It is not necessary to actually have the two objects contact each other, they simply need to be brought close enough together so that the charges can leave one object and "jump" on to the other.

As a charged object is brought close to a neutral object, the charges affect the electrons in the uncharged object even before conduction occurs. If objects are brought close, but not close enough for the charges to make the jump from one to the other, it is called induction. Let us consider inducing a charge in a conductor and in an insulator separately. If we bring a charged object near an uncharged conductor, we will get a situation as shown below:



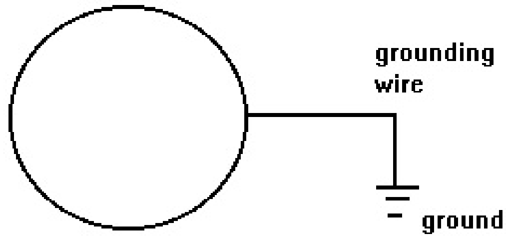
Here, the positive charges have "chased" the positive in the other object over to the far side, while attracting the negatives to the side closest to the charged object. Thus, while the second object actually has no charge (it is still neutral), each end of it appears to have a different charge. It is said that this object is <u>polarized</u> (a situation where one end of the object is predominately positive and the other end predominately negative). If the charged object is removed, the polarization disappears.

Although a similar situation occurs in an insulator, the charges are not free to move around as much. What happens then is that each atom becomes polarized in its own spot. This results in a polarization that is much weaker than that of a conductor. The diagram below shows the situation.

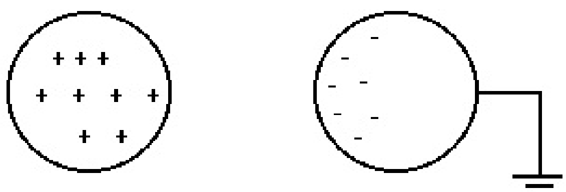


Once again, the change is only temporary.

There is yet another type of induction, usually associated with conducting materials. This involves grounding an object. Grounding is an electrical term that involves attaching a wire to an object that connects it to the earth. The actual definition of <u>grounding</u>, however, it connecting the object to a source or sink of electrons. A source is an unlimited supply of electrons that neither has an effect on nor is affected by the object. A sink is a place that can accept an unlimited supply of electrons with out being affected. In other word, grounding an object allows the object to "pull up" as many electrons as it needs or dispose of as many as it wants. The symbol for grounding an object is shown below:



Consider what happens if you attempt to induce a charge in a grounded object. You will get a situation as shown below.



The extra negatives were pulled up out of the ground because of the attraction of the positive charges (or alternately, the positive were "chased" out of the object and down the ground wire). Notice now that the grounded object is charged, not just polarized. Consider what would occur if the charged object was moved away.

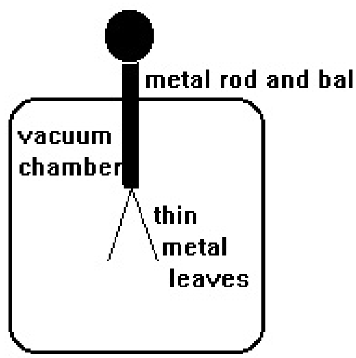
Also take a moment to consider what would happen if the ground wire was disconnected before the charged object was moved away. The student should take a moment to see if they can explain what would happen if the original charged object was negative.

So we see that each of the three methods of charging an object is different. The chart below summarizes the differences.

Method of Charging	Start with...	End with...

Friction	two uncharged objects	two oppositely charged objects
Conduction	one charged, one uncharged object	two similarly charged objects
Induction (cutting ground)	one charged, one uncharged object	two oppositely charged objects

A good exercise to review these concepts is to discuss the electroscope. The electroscope is a device that has a metal rod suspended into a vacuum chamber where two very thin and very light metal strips (called leaves) are suspended. On top of the rod is placed a metal ball. This object is used to determine or measure the charge on an object, by observing its behavior when the object in question is brought near or in contact with it. It is also used to detect certain types of radioactivity, since charged particles (like β-particles) are often given off. Below is a diagram and a few questions about the behavior of the electroscope in certain situations.

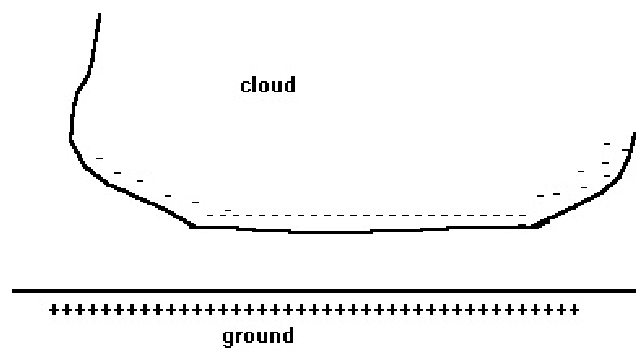


EX. F.) What happens to the electroscope if...

a.) The ball is touched by a positive object?
b.) A positively charged object is brought near the ball and then moved away?
c.) The ball is touched by a positive object and then a negative object is brought near?
d.) The ball is touched by a negative object and then a positive object is brought near?
e.) The ball is touched by a negative object and then grounded?
f.) The ball is grounded, a positive object is brought near, the ground is broken and the positive object is taken away?

There are some other "real world" examples that are worth discussing before we close out the chapter. In the past, you may have noticed that some tractor-trailer trucks carrying flammable cargos will have chains dragging along the road a few feet behind them. The reason for this is to ground the truck in case of static build-up from rolling along the highway. By dragging the chains, the charge is allowed to gradually leak from the truck instead of building up and causing a spark that might ignite the cargo. The practice is fairly rare today, since they have begun to manufacture truck tires that allow the charges to flow through more easily. However, tire manufacturers very recently have made new tires that last much longer than their predecessors. These tires are made of new combinations of rubbers and engineers have discovered that a longer lasting tire does not allow charges to flow as easily as one that wears out quickly. Thus we may see chains added again in the near future.

Another example of these concepts is the phenomena of lightning. Some aspects of lightning are well understood, but many pieces of the explanation simply are not complete. Lightning begins when clouds become polarized (why they do so is still not understood) and we end up with negative charges along the bases of the clouds. This highly charged base can then induce a charge in the ground below.



As the charge in the cloud builds, the attraction between the ground and the cloud increases. Finally the pull gets strong enough for charges from the ground to begin to rise up and charges from the cloud to begin to descend. When these two "streamers" meet, lightning occurs. The electrons rush from the cloud down to the ground, superheating the air and causing it to form a brief plasma, which glows (the lightning). The hot air rushing out from the bolt causes the clap of thunder. This explanation should tell you why lightning tends to hit the highest object and why your hair will stand on end just prior to a lightning strike in your immediate area. It should also explain why lightning rods work so well.

Remember back to our discussion of charges in conductors? We said that charges gather at extremities, such as points and can leak easily from there. Thus a long, thin metal rod pointed skyward will be the most likely place for an upwards streamer to begin.

Let us close this section with one final example from your childhood.

EX TREE.) Explain why a balloon, after being rubbed on your hair will stick to the wall and then fall off after a certain amount of time.

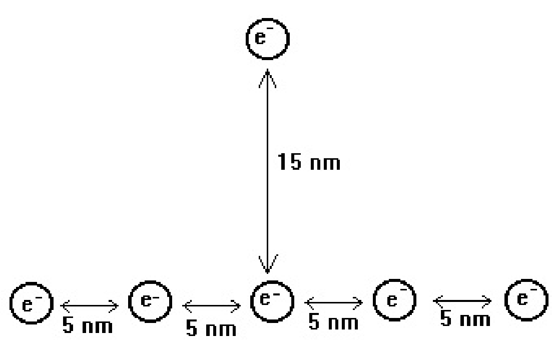
Assignment #21

1.) Suppose you had two charges arranged 2 cm apart. If the one of the left had a charge of 3 C and the one on the right had a charge of 5 C, at what point between them would the combined electric force on a third particle be zero? Now suppose the 5 C charge was negative, where (exactly) would the zero point be now?

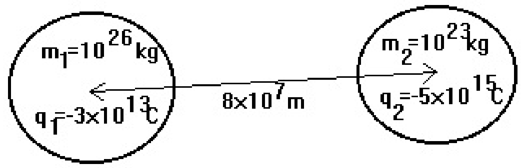
2.) Imagine that the charge on an electron was not equal in magnitude to the charge on a proton. This would, of course, cause some serious problems in real life. However, imagine that the proton had a charge that was 0.00001% higher than the charge on an electron. (A.) What would the force be between the proton and electron in an atom of hydrogen? Suppose the atom was somehow held together. This would cause every object to be slightly positive. What would the repulsive force be between two pennies placed 5 m apart? Some necessary information: gaw for Cu=63.5 g/mole, atomic number=29, mass of penny=3.11 g.(HR126)

3.) Suppose an evil villian came up with a plan for pushing the moon out of its orbit. He (or she) decided to take regular water and remove all the electrons. He (or she) would then place half of the electrons on the moon and half on the earth so the two planets would repel each other. How much water would he (or she) need? Answer in kilograms and volume (i.e. a cube X m on each side). The gram molecular weight of water is 18 g/mole.

4.) Consider the set-up below. Calculate the net force on the single charge above the line of charges if all the particles are electrons. Consider symmetry, it may save you some time. (EL17*)



5.) Imagine the two planets below. If the planets not only have mass, but are also charged, what is the force between them?



7.) Decipher: “The stylus is more potent than the claymore.” (DNCTHWG)

Activity #20 - The Electroscope

In this activity, you will use an electroscope (as discussed in the chapter) to investigate different electrical phenomena. For each different investigation, you should go beyond what is written and attempt to compare the charges produced in one instance with charges produced in another (for both strength and sign).

Hints: If the electroscope is too highly charged, instead of touching it directly, charge an isolated conducting sphere and touch the sphere to the electroscope. When grounding the object, use a wire connected either to a metal plumbing fixture or to the third slot in a three prong outlet.

Procedure:

1.) Bring the electroscope near the Van DeGraff generator as instructed by your teacher. Observe the effects.

2.) Bring the electroscope in contact with the Van DeGraff generator (please don't be surprised and drop the electroscope when the sparks fly).

3.) Ground the electroscope, bring it near the Van DeGraff and then remove the ground wire.

4.) With the electroscope charged, wave a magnet around the casing and observe the effects.

4.) Discharge the electroscope (by grounding it) and touch it with the magnet.

5.) Using a 9 V battery, touch one terminal to the electroscope. Discharge the electroscope and touch the other terminal to the electroscope. Observe the effects and discharge the electroscope.

6.) With a piece of fur, rub a plastic rod about thirty times. Touch it to the electroscope. Observe and discharge.

7.) With a piece of silk, rub a glass rod thirty times. Touch it to the electroscope, observe and discharge.

8.) Compare the effects on the electroscope between the charged plastic and glass rods by charging it first with one and then the other without discharging it in between. Discharge when finished.

9.) Get a low-level radioactive source from your instructor and touch it to the electroscope, holding it in place for a few minutes. Repeat with the other sources provided.

Draw conclusions about each situation. Remember: an electroscope determines if a charge is present and gives some clues about the strength of the charge.