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Unit 6: Charge and Electric Forces

In this unit we will become familiar with the notion of electric charge. In particular, we will see that it was the quantity that was flowing in the electric circuits we have used, it is the quantity that was stored in capacitors, and that it can cause electric forces *and* experience electric forces. These forces are responsible for a variety of familiar phenomena, such as electric current flow, "static cling," lightning, and electric shocks and sparks. More remarkably, it also turns out to be responsible for the structure of matter and all chemical processes, once it is coupled with quantum mechanics. A detailed study of this is beyond a course such as this, but it is truly amazing that the same simple force law we will study in the next few weeks is responsible for the incredibly diverse and complicated world of chemistry.

Session 1: Observing Charge, Current, and Force

We were unable to actually see electric current; we needed tools to infer that new kind of flow. To be specific, we used light bulbs, current meters, and then Ohm's law ($V = IR$) with a voltmeter to observe current flow. In this session, we will make some qualitative observations of charge to relate it to the current flow we saw before. We will make indirect observations of charges, but direct observations of the electric forces that we had speculated about in previous activity guides. We also will develop some skills with using the computers to record electrical properties of a circuit (voltage across any particular element) as a function of time, which we'll use in subsequent sessions.

Guidebook Entry VI.1: Opposites Attract!

When we introduced the capacitor, we made arguments about the capacitor being a good storage vessel for charge because we stored the positive charge on one plate, the negative charge on the other, and each type of charge, while repelled by the neighboring like charges also was attracted by the opposite charge on the other plate.

If we accept the notion of two types of charge, and that they are stored separately on the two plates, what direction should the force be on one of the plates? Use a sketch to assist your answer, and assume two circular, parallel plates for your capacitor.

Let's imagine that each plate has a charge Q on it, and that the force between the two plates is F. Now we double the charge to 2Q on only one plate. If each charge *unit* attracts each other charge unit equally, how should the force change?

Now, what happens if we double the charge on *each* plate--what is the force now?

How then do you predict the force depends on the charge Q on the plates of a capacitor? Check with your instructor after you have decided on an answer.

If the charge stored is proportional to the voltage, how should the force depend on the voltage?

We have a device that allows you to observe this force: a sensitive electronic balance. The balance, which actually measures force, is calibrated in mass units. This activity involves equipment that we have only one copy of, and uses high voltages, ***so you must do this with an instructor***.

First, observe and describe the set-up. What do you predict will happen to the reading of the balance when the voltage is turned on?

Observe what happens when the power is turned on. Was it what you predicted? Make sure to note signs and directions.

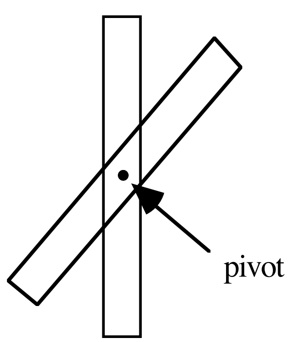
Now measure the force as a function of the applied voltage. Graph your results. Is it what you predicted above? How can you check to see that it has the correct functional dependence?

Guidebook Entry VI.2: Likes Repel!

In this section, you will experiment with electroscopes, fur and a plastic rod, and a "Wimshurst Machine." Equipment is limited, so take turns with other groups or work together.

We also suggested that like charges repel one another. Imagine that we have four like charges free to move on a square sheet of metal. What is the most stable (lowest energy) configuration of the four charges (sketch and explain below)?

Now imagine that we are placing the four charges on two metal rods that are connected with a pivot in the center, much like a pair of scissors. The repulsive force will now not only cause the charges to move, but the metal rods as well. What is the most stable configuration here?



We have two types of devices that sense charge by moving in response to repulsive electric forces. Both are called electroscopes. The first is a cross-like object (like the figure above) that is balanced such that gravity tends to make the rods line up, but the repulsive force makes them spread apart. The second uses a thin gold foil that spreads out in a similar way when charged. *Try each experiment below with the more rugged cross-type electroscope* ***first****. Use the fragile, sensitve gold-foil electroscope only when you can't get a response from the rugged electroscope.*

Observe the electroscope when it is charged with a power supply. Sketch what happens below.

Develop static charge with a rubber rod and cat's fur. Transfer this to the electroscope, and describe what you see. Is it plausible that this static electric charge is the same as the moving charge that comes out of batteries and power supplies?

Use the Wimshurst machine to develop some sparks. (Be careful not to touch metal parts, since you can get a nasty shock.) Then separate the poles of the machine, and touch one pole to the electroscope. Describe what you see. Is it plausible that sparks are again another feature of this same electric charge?

Charge up the poles on the Wimshurst machine. Touch one of the small pith (or aluminum foil) balls to one of the poles. Which pole is the pith or foil ball now attracted to? Which one is it repelled from? Can you explain this?

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Session 2: Electric Forces and Fields

Now we will return to electric forces. Ideally we would like to observe the force between two point-like charged objects, but it is very difficult to confine much charge to a very small region (in the words of capacitance, the capacitance of a sphere goes to zero as the sphere's radius goes to zero). We will instead look at the force between a moderate sized object (a conducting sphere of a few centimeters diameter) and a small object (a small pith ball with conducting paint on the outside). In this case, it turns out to be a good approximation that the force behaves as if the charge of each object was just located at the **center** of the respective object. We will therefore obtain only roughly correct results, but we will supply you with the correct relationships, which are some of the most accurately known laws in nature.

Guidebook Entry VI.9: Force versus Position, Qualitative Description

First, let's return to an observation that you made last class. Use the Wimshurst machine to charge an isolated metal sphere. Then, hanging a pith ball on a string, touch it to the charged sphere. Sketch what you see when you bring the ball close to the sphere. (If the weather makes it hard to keep a charge on the sphere, use one of the terminals of the Wimshurst machine instead.)

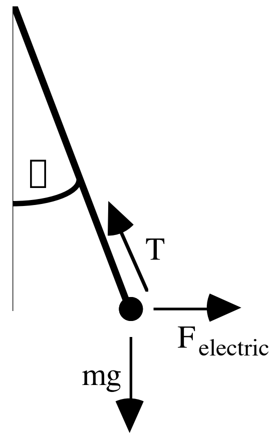
Describe in your own words why you see what you sketched above.

Does the effect seem to get larger or smaller as you bring the ball closer to the sphere? How might you explain this?

You should have noticed that the pith ball, when charged with the same sign of charge as the sphere, did not hang straight down, but rather, hung at an angle. This is a result of the electric (also called electrostatic, or static, or Coulomb) force. We will use this effect to help us make quantitative measurements of the force law as a function of distance.

Guidebook Entry VI.10: Force and Angle of Supporting String

Consider a ball hung from a string as shown below:



The string pulls along its length with a tension force T, and gravity pulls down with a force mg. We consider the situation in which the ball does not accelerate, so these two forces, when added as vectors, must exactly balance the electric force.

Recalling that we must balance these forces by their x and y components separately, how are T and mg related?

Using a similar method, how are $F_{electric}$ and T related?

Combine the last two expressions to eliminate T, and find an expression that relates $F_{electric}$ to mg (which we know is constant) and the angle θ.

Why did we bother with that calculation? We can now use the angle as a measure of the electric force. While it is true that we need to know the mass of the ball to know the force exactly, this is not important, because we also don't know how much charge is on the sphere, or on the ball. What we *will* be able to discover, however, is *how the force depends on the spacing* between the center of the sphere and the center of the ball. We have already seen (with the parallel plate capacitor on the electronic balance) that the force appears to be proportional to the charge q on one object times the charge Q on the other object ($F \propto qQ$). With the additional result below, you will know, within some scaling constant, the complete law of electric force.

You may have already observed, however, that the charge placed on a capacitor, or any charged object, does not stay there for very long. It can be neutralized by charged dust in the air, by cosmic radiation, or by electric currents through conductors (like you) which may touch the charged object. As a result, there is not a very long time window within which one can make a measurement that depends on the charge on the sphere and on the ball staying constant! To get around this, we will use a video camera to take pictures of the experiment, and digitize these images, so that you may analyze them at your leisure at your own workstation. The Quadra computer is connected to the video camera; after digitizing your experiment, make sure you save it in the Workshop Video folder. You can then gain access to this through the network on any of the machines in the lab. Be forewarned--if the weather is nice, nothing will charge well, so you may have to resort to analyzing a pre-recorded video called Electrostatic Repulsion.

Guidebook Entry VI.11: Force versus Radius

You probably noticed in your earlier observations that the ball tended to swing around a great deal; it was hard to move it smoothly in to the sphere. To get around this, we have made a two-string (bifilar) pendulum with the ball. This way, with care, the ball will stay just where you want it.

In the past, we have actually had students make a movie of the repulsive force experienced by a charged ball. Because of the often humid early fall weather, and the cumbersome nature of the video files, we have chosen not to do this, but rather have you analyze a video from a past year. However, it is important for you to try the experiment yourself so you understand what it is you are analyzing.

During the recording, we moved the ball from very close to the sphere, to reasonably far away (but still within video range). You should try this, and describe below, perhaps with sketches, what the ball does.

Start up the video file Electrostatic Repulsion by double clicking on it The buttons at the bottom allow you to step one frame at a time through the images. The lines on the white board in the video are vertical (notice the camera's distortion), and spaced 10 cm apart. Use a marking pen to mark the relevant locations on the screen, and determine the angle of deflection as a function of how close the ball is to the **center** of the sphere (which is labeled as r below). Record your results below (or paste your Excel data), using the space to the left to record whatever other original data you use to determine the deflection angle θ.

	θ	r

What we really want is a graph of Force versus r. Use your relationship derived previously to translate those angles into force.

Your data should show a force that is large when r is small, and small when r is large. If the force law were described by an equation like

$$F = kr^n$$

where k and n are constants, would you expect n to be positive or negative?

How about k; how would you expect it to depend on the signs of the two charges?

Use the power law fit in Excel (select your data on your graph, choose Trendline from the Insert menu, then select Power Law, and choose the option to show equation on graph) to find out what n value is the best fit to your data. Give your result below.

The actual form of the electric force law (or Coulomb's law) is

$$F = q_1 q_2 /(4\pi\varepsilon_0 r^2)$$

where ε_0 is a constant equal to 8.85 x 10^{-12} C^2/Nm^2. Are your data roughly consistent with this? In particular, how does n here compare with your result, and does this form give the right effects for all possible combinations of positive and negative charges?

Since the pith ball is much smaller than the sphere, you might guess that it has much less net charge than the sphere. This is indeed true. Because of this, the pith ball does not have much effect on the charges on the sphere; while it does exert an equal and opposite force on the sphere, because of their relative sizes, this is largely unobservable for the sphere. With this in mind, we develop the concept of the electric field, which tells us how much force the pith ball would experience at any point in space. Much like the velocity field that we drew for the fluid flowing between the parallel plates (the experiment with the hypodermic full of dye), this is a vector function, which we need to sketch with varying size arrows to convey the relevant information.

Guidebook Entry VI.12: Force around a Sphere and the Electric Field

Draw a sketch of the sphere, and the pith ball located in several possible locations. At each position, draw an arrow that qualitatively indicates the size and direction of the force that the ball would feel if it were there.

How would the force change if the charge of the pith ball doubled and that of the sphere stayed the same? What if the ball's charge was cut in half?

The electric force diagram is often a useful mechanism for describing the full range of electric interactions that one might experience in such a situation. Would you need to draw a complete new diagram to describe what would happen if the charge of the ball was doubled? What if the charge had an opposite sign? Explain your answers? Check with your partners and an instructor after you've thought about this a bit.

The electric field allows a convenient way of drawing only a single diagram to describe all possible interactions with a fixed external field (like that due to the larger charged sphere). The electric field is simply the force that a test charge (like the pith ball) would feel (at that particular location) divided by the charge on the ball. Notice that the force is just a single vector, but the field is a vector *function*. Draw a sketch of the electric field for a positively charged sphere and a negatively charged sphere. Discuss this with your partners and an instructor.