Electricity and Magnetism Module 1
Student Guide

Concepts of this Module

- Electric Charge
- Coulomb's Law
- Addition of Electrostatic Forces

The Activities

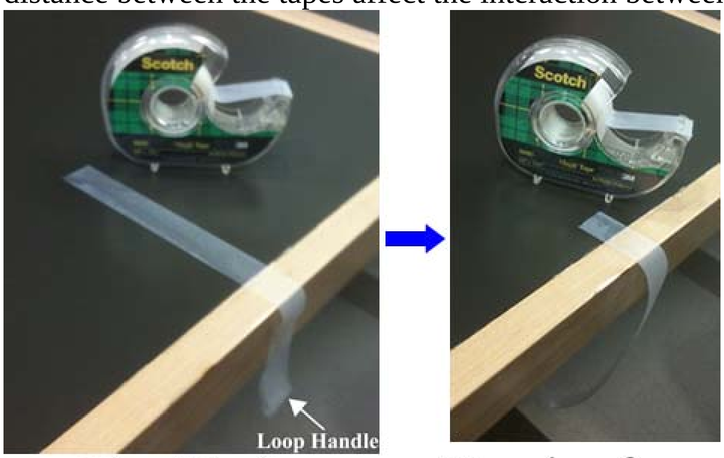
Background for Activities 1 - 3

Here are four hypotheses about electric charge:

> *Hypothesis 1*: The interaction between objects that have been rubbed or separated is due to a property of matter we call *charge*. There are two types of electric charge.
>
> *Hypothesis 2*: The strength of the interaction between electric charges increases as the distance between the charges decreases.
>
> *Hypothesis 3*: The strength of the interaction between electric charges increases as the quantity of charge increases and decreases as the quantity of charge decreases.
>
> *Hypothesis 4*: Excess charge moves readily on certain materials, known as conductors, and not on others, known as insulators. In general, metals are good conductors while glass, plastic, and rubber tend to be insulators.

Expt Activity 1

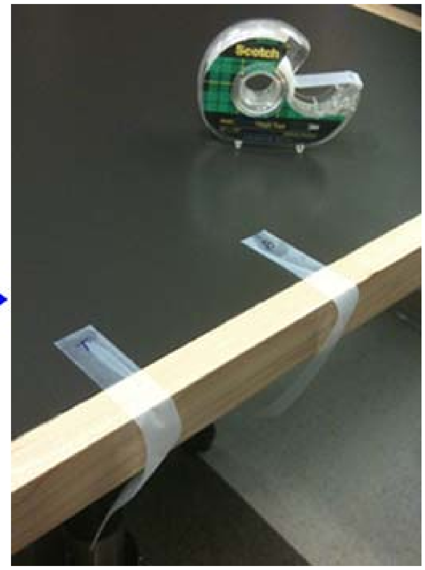
A. Press a length of sticky tape 10 – 20 cm long firmly on the table top or other unpainted surface, with a few cm hanging over the edge. Form a non-sticky handle by looping the tape hanging over the edge onto itself. Do this for a second length of sticky tape. Peel one of the tapes off the table and hang it from the edge of the tabletop or cupboard. Peel the second tape off the table and holding its handle bring it near the first tape. Try to keep your hand holding the second tape far away from the tapes that are hanging down. What happens? How does the distance between the tapes affect the interaction between them?



Fixed to the Tabletop **Hanging from the Tabletop**

B. Place two more strips of sticky tape on the surface as in Part A. Using a pencil or ball point pen, but not a rollerball pen, mark the tapes with *B* for bottom. Press another strip of tape on top of each of the *B* strips; label these strips *T* for top.[1] Pull one pair of strips off the surface, separate them, and hang them from the edge of the tabletop or cupboard at least 50 cm away from each other. Pull the second pair of strips off the surface and separate them. Describe the interaction between two top strips when they are brought toward one another. How does the strength of the interaction depend on the distance between the tapes? Caution: if the two tapes come into contact with each other the charges on them may change.

[1] The problem with roller ball pens is that the ink is water based and will smudge. Ball point pen ink is oil based and will not smudge nearly as much.



"T" is on top of "B"

In the lab notebook describe the interaction between two bottom strips when they are brought toward each other. How does the strength of the interaction depend on the distance between the tapes?

Describe the interaction between a top strip and a bottom strip when they are brought toward each other. How does the strength of the interaction depend on the distance between the tapes?

C. Rub the supplied plastic rod with the fur, hold the rod horizontally and bring it near but not touching the hanging bottom and top strips. Describe what you observe. Caution: if the tape touches the rod the charge on the tape can change. Again being careful not to touch the hanging strips, bring the *fur* near them. What do you observe?

   Rub the supplied glass rod with the polyester cloth, hold the rod horizontally and bring it near but not touching the hanging bottom and top strips. Describe what you observe.

   Note: if the humidity is relatively high you may not get much charging on the glass rod and polyester cloth. You are also supplied with a piece of Saran™ plastic wrap. Rubbing the glass with this is more difficult than rubbing the glass with the cloth because the plastic wrap is very sticky, but often gives a better charge. So if the glass / cloth is not working for you, try the glass / Saran wrap.

D. Do your observations in Parts A – C support the hypotheses? Which hypotheses are supported and which are not by your observations? Please explain in the lab notebook using complete sentences. You should not just state results that you may have learned about in class or from the textbook. Rather we wish you to devise a sound and logical set of reasons based on your observations.

E. Following Benjamin Franklin, we arbitrarily call the charge on the glass rod after being rubbed with polyester *positive* and the charge on the plastic rod after being rubbed by fur *negative*. For the sticky tape, what type of charge is on the top strip? What type of charge is on the bottom strip?

What type of charge is on the fur after rubbing the plastic rod? Devise and carry out an experiment to test your answer. Describe the experiment and the result in the lab notebook.

Predict what type of charge is on the polyester after rubbing the glass rod. Devise and carry out an experiment to test your prediction. Describe the experiment and the result in the lab notebook.

Please remove all the sticky tapes from the table top when you have completed this Activity.

Expt ***Activity 2***

Blow up the two balloons, tie them off, and tie each to the end of one of the supplied strings. Hang each balloon from the horizontal rod which is attached to the vertical rod that is clamped to the table. You will want each balloon to be as far as possible from the vertical rod, the edge of the tabletop, and any other objects. At the end of today's Practical you may keep the balloons.

Below you will also be using a small white ball of *pith*[2], which is hanging by a silk thread onto a small stand. You will also be supplied a dark gray ball hanging by a thread from a stand; these are pith balls that have been coated in Aluminum.

A. Rub the glass rod with the polyester, and slowly bring the rod near the Aluminum coated pith ball, letting the two touch. Describe what happens. Can you explain your observations? Do your observations confirm or reject any of the hypotheses described at the beginning of this document?

   Note: if the humidity is relatively high you may not get much charging on the glass rod and polyester cloth. You are also supplied with a piece of Saran™ plastic wrap. Rubbing the glass with this is more difficult than rubbing the glass with the cloth because the plastic wrap is very sticky, but often gives a better charge. So if the glass / cloth is not working for you, try the glass / Saran wrap.

B. What is the sign of the electric charge on the coated ball? Confirm your answer using the glass rod after rubbing with polyester and the plastic rod after rubbing with fur, being careful not to let the rods touch the ball.
C. Remove the electric charge on the Aluminum coated ball by touching it with the metal plate. Repeat Part A using the plastic rod after rubbing it with fur.

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[2] Pith is an insulator found in vascular plants.

D. Now what is the sign of the electric charge on the ball? Confirm your answer using both the plastic rod after rubbing it with fur and the glass rod after rubbing it with the polyester.
E. Rub the glass rod with the polyester, and slowly bring the rod near the uncoated pith ball, letting the two touch. Describe what happens. Can you explain your observations? Do your observations confirm or reject any of the hypotheses described at the beginning of this document?
F. What is the sign of the electric charge on the uncoated ball? Confirm your answer using both the plastic rod after rubbing it with polyester and the glass rod after rubbing it with the polyester. Are your results the same as for Part B? Explain.
G. Rub the two balloons with the fur. Bring the balloons closer together. Describe what happens. Do your observations confirm or reject any of the hypotheses described at the beginning of this document?
H. Determine whether the charges on the balloons are positive or negative.
I. As you showed in Activity 1, when you rub the fur with the plastic rod it becomes charged. Does the charging of the balloons depend on whether or not the fur is charged? Explain.

Expt *Activity 3*

Coulomb devised a clever trick for determining how the interaction between charges depends on the quantity of charge without knowing the actual amount of charge. Say one of the Aluminum coated balls has a charge Q, and the other Aluminum coated ball is uncharged. If the two balls touch, they will quickly exchange charge until both have a total charge $Q/2$ on them. If one of the balls is then discharged by touching it to a large piece of metal, the procedure can be repeated to get $Q/4$ on both balls.

A. As you saw in Activity 2 Part G, if two objects have the same type of charge when they are brought near each other they repel each other. How is the force that they exert on each other related to the angle that their supporting strings make with the vertical? Just a qualitative answer is sufficient, although you may derive the formula if you wish.
B. Using Coulomb's trick, charge the two Aluminum coated balls with a charge $Q/2$. Bring them close together. Describe what happens. Do your observations confirm or reject any of the hypotheses described at the beginning of this document?
C. Now put a charge $Q/4$ on the two Aluminum coated balls and bring them close together. Describe what happens. When the two charges are the same distance away from each other as in Part B, how does the force the charges exert on each other compare to your observations for Part B? Do your observations confirm or reject any of the hypotheses described at the beginning of this document?
D. Put a charge Q on one of the Aluminum coated balls and discharge the other Aluminum coated ball. Bring the two balls close to each other. Describe what happens. Can you explain your observation?

Activity 4

In the late eighteenth century Coulomb used a torsion balance and a great deal of patience of discover how the electric force between small spherical charged objects depends on the distance between the objects. A modern implementation of his apparatus is shown; using it also requires considerable patience.

It is also possible to do a similar determination using the charged balls that you may have used in Activity 3, and these experiments have also been done. However, in practice this method is even more difficult than Coulomb's. An animation which side-steps these difficulties by simulating the experiment is available at:

http://www.upscale.utoronto.ca/PVB/Harrison/Flash/EM/Coulomb/Coulomb.html

The above link is to a fixed size animation which works nicely if only one person it viewing it. For use in the Practical itself a version which can be resized to be larger so that the entire Team can see it is better. Here is a link to such a version:

http://www.upscale.utoronto.ca/PVB/Harrison/Flash/EM/Coulomb/Coulomb.swf

This version will only work if your browser is configured to display Flash animations directly without an html wrapper.

A. Open the animation and explore how it works.
B. Move the right hand charge with the slider to some distance between the support points of the strings, move it to a new position, and then return it to the same original distance. You will notice that the measured angle the strings make with the vertical usually has a slightly different value for the same distance. Under what circumstances would a *real* apparatus exhibit this behavior?
C. If you had the patience of Coulomb and repeated the process of Part B a large number of times and made a histogram of the measured angles, what would you predict the shape to be? How would you characterize the width of the shape?
D. Set the right hand charge to any position that you like and record the distance and the angle. Calculate the value of the electric force F exerted on the left hand charge by the right hand charge. What is the direction of that force?
E. What is the error in this experimental determination of the value of the force? Assume, reasonably, that the errors in the mass and length of the string are

negligible. You may find one or more of the following error relations useful:

$$\Delta \sin(\theta) = \left| \cos(\theta)\Delta\theta \right|$$

$$\Delta \cos(\theta) = \left| \sin(\theta)\Delta\theta \right|$$

$$\Delta \tan(\theta) = \left| \frac{\Delta\theta}{\cos^2(\theta)} \right|$$

Note: in the above equations the error in the angle must be expressed in radians.

F. For this same position of the left hand charge calculate the distance *r* between the centers of the two 1 gram masses.
G. Calculate the error in this measurement of *r*.
H. We took 10 datapoints from the animation, calculated *r* and *F* and their errors, and placed the result in a dataset named `CoulombDistForce`.[3] A copy is located in the following area:

    `public:Modules/E&M/Module01/Data`

    Explore this data with the *ViewDataset* program which is on the desktop of your computer and/or a spreadsheet program such as *Excel*. As always, the datasets are tab separated, with the first row a title, the second row the names of the variables, and the rest of the rows the actual data. How could you use a collection of force-distance, *F* versus *r*, data for different values of the distance to determine how the force depends on the distance? How many different ways can you and your partners think of? Which do you think might be best?
I. Here is a method which you may have thought of in Part H. Imagine that the force *F* varies in an unknown way with the distance *r*:

$$F = \frac{c}{r^n} \tag{1}$$

You wish to determine *n* from data of *F* versus *r*. A good way to do this is to fit the data to Eqn. 1. However, *n* does not have a linear relation to *F* and *r*, so a non-linear fitter has to be used. We have non-linear fitters, but using them is not as simple as the *PolynomialFit* program which you may have used in other Modules.

But, if we take the logarithm of both sides of Eqn. 1, we get:

$$\ln(F) = (-n)\ln(r) + \ln(c) \tag{2}$$

Recall that the generic equation of a straight line is:

$$y = mx + b$$

[3]Not having Coulomb-like patience, I did not do the error calculations by hand. Instead I used some error propagation routines with *Mathematica* software.

So if we take the logarithms of F and r and fit this data to a straight line:

Slope = ($-n$) Intercept = $\ln(c)$

Use this method using *PolynomialFit* which is on the desktop of your computer to determine n in Equation 1. The following file, located in the same directory as the one you looked at in Part H, contains data of the logarithm of the force F versus the logarithm of the distance r:

`CoulombLnDistLnForce`

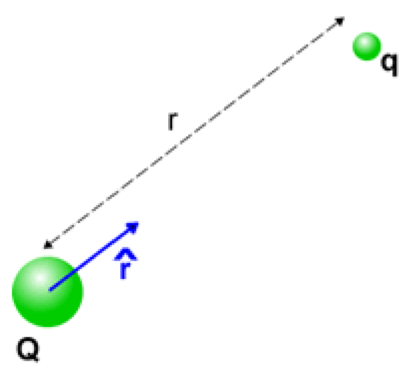
J. There is another file which you may wish to use to explore the relation between the force and the distance, located in the same directory as the other two data files.

`CoulbDist2Force`: F versus r^2

How can you use this data to verify that the data are consistent with Equation 1?

Course Concepts *Activity 5*

We commonly say that there are two types of electric charges, *positive* and *negative*. Imagine two charges Q and q are separated by a distance r as shown. We construct a unit vector $\hat{r}$ pointing from Q to q. Then the force exerted on q by Q is given by Coulomb's Law:



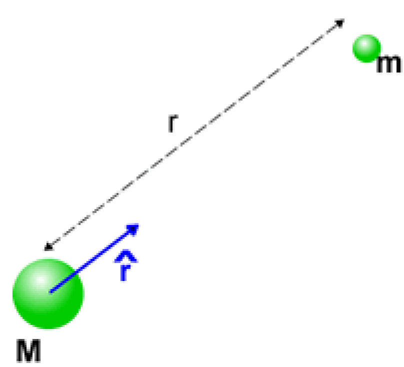
$$\vec{F}_{\text{on q}} = c_E \frac{1}{4\pi\varepsilon_0} \frac{qQ}{r^2} \hat{r}$$

Here c_E is either +1 or -1.

A. Which value of c_E correctly expresses the direction of the force exerted on q by Q for all four combinations of the two charges being positive or negative? You may find it useful to build a table of the four possible sign combinations and the direction of the force on q for each combination.

For two masses, the gravitational interaction is given by Newton's Law of Gravitation, which we write as:

$$\vec{F}_{\text{on m}} = c_G G \frac{mM}{r^2} \hat{r}$$



where c_G is similarly either +1 or -1.

B. Which value of c_G correctly expresses the direction of the force exerted on *m* by *M*?

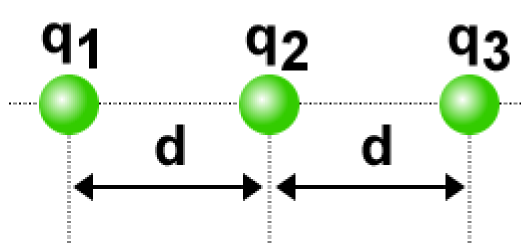
Course Concepts *Activity 6*

There is another model of electricity, due to Benjamin Franklin and William Watson in the 18th century, called the *one fluid theory*. In this model all objects contain some amount Q or q of electric "fluid". Portions of the fluid repel each other, and portions of fluid are attracted by matter that does not have fluid.

There is a "natural" quantity of this electric fluid, Q_0 or q_0. When an object has more fluid than this natural amount we say that it has a positive amount of fluid, and when it has less fluid than this we say that it has a negative amount.

A. Object 1 has a natural quantity of electric fluid Q_0 and has an amount Q of fluid. Object 2 has a natural quantity of electric fluid q_0 and contains q fluid. The two objects are separated by a distance *r*. Write down a form of Coulomb's Law for the electric force that is exerted on object 2 by object 1.
B. Imagine that instead of thinking about an electric *fluid* we think about the total number of electrons contained in some object. Is there a "natural" quantity of electrons in the object? If so, what might it be related to?
C. We now have two different models of electricity, the usual one of positive and negative charges and the *one fluid* one of Franklin and Watson. Both seem to explain all the data. What are all the differences you can think of between these two models?

Course Concepts *Activity 7*



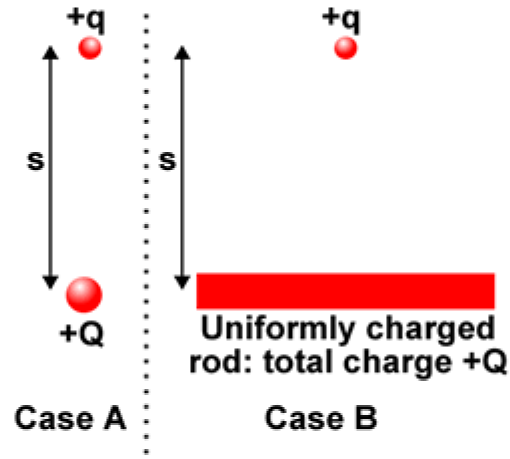
In the figure three charged particles lie on a straight line and are separated by distances **d**. Charges q_1 and q_2 are held at fixed positions.

Charge q_3 is free to move but happens to be in equilibrium (i.e. no net electrostatic force acts on it).

Charge q_2 has the value Q.

What value must the charge q_1 have?

Course Concepts *Activity 8*



In Case A a point charge **+q** is a distance **s** from the center of a small ball with charge **+Q**.

In Case B the point charge **+q** is a distance **s** from the center of a rod which is uniformly charged with a total charge **+Q**.

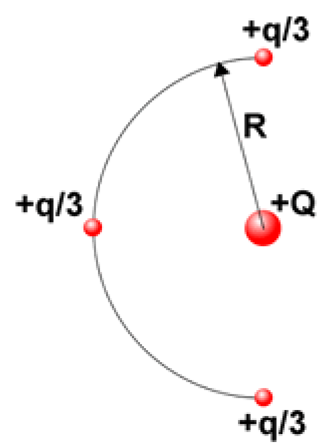
Consider the following student dialog:

Student 1: "The charged rod and the charged ball have the same charge **+Q** and are the same distance from the point charge **+q**. So the force on **+q** will be the same in both cases."

Student 2: "No, in Case B there are charges spread all over the rod. The charge directly below the point charge will exert the same force on **+q** as the ball in Case A. The rest of the charge on the rod will make the force in Case B bigger."

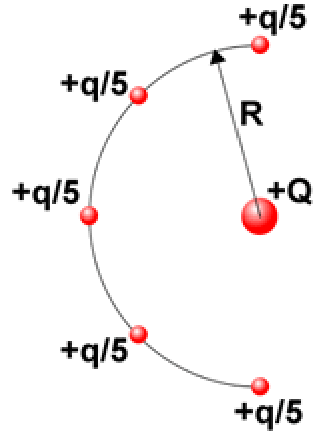
Neither student is correct. What are the errors made by each student? What is a correct description of how the forces compare? Explain.

Course Concepts *Activity 9*



A. A point charge **+Q** is located a distance **R** away from three identical point charges, each of charge **+q/3**, equally distributed along a semicircular arc of radius **R** as shown. What is the total force, magnitude and direction, exerted on **+Q**?

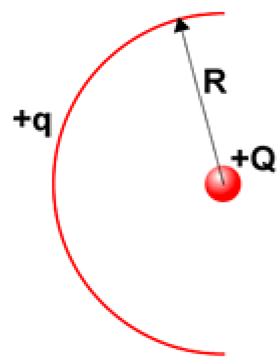
B. A point charge **+Q** is located a distance **R** away from five identical point charges, each of charge **+q/5**, equally distributed along a semicircular arc of radius **R** as shown. What is the total force, magnitude and direction, exerted on **+Q**?



C. A point charge **+Q** is located a distance **R** away from a semicircular arc that is uniformly charged with a total charge of **+q** as shown. The charge per arc length λ along the semicircle is:

$$\lambda = \frac{+q}{\pi R}$$

What is the total force, magnitude and direction, exerted on **+Q**?



Course Concepts *Activity 10*

We commonly call forces such as you exert with your hand on a door to close it a *contact force*. But physicists say that there are exactly four types of interactions that can occur:

1. Gravitational
2. Electromagnetic
3. Weak
4. Strong or Nuclear

Do contact forces fit into this classification? If yes, how? If no, should they be added to this list as a fifth type of interaction?

This Guide was written in October 2007 by David M. Harrison, Dept. of Physics, Univ. of Toronto. Activities 1- 3 are based on Priscilla W. Laws et al., **Workshop Activity Guide**, Module 3, Unit 19, (John Wiley, 2004), pg. 531-533. Activity 7 is from Edward F. Redish, Rachel E. Scherr and Jonathan Tuminaro, "Reverse-Engineering the Solution of a 'Simple' Physics Problem", The Physics Teacher **44**, 293 (2006).

Activity 8 is from Lillian C. McDermott et al. **Tutorials in Introductory Physics** (Prentice Hall, 2002), pg 75. Last revision: Marach 5, 2011.