Experiment manual – electrostatics

03.01.11 Ex 4410.00

1 Electrostatic Charge

Background

The property of electric charge was discovered by the ancient Greeks ca. 600 BC. If amber was rubbed against wool, the amber attracted other objects. Indeed the word electricity is in fact derived from the Greek word for amber, “elektron”.

Attraction and repulsion

Select two perspex rods and mount one of them on a rotating stand with a base as shown in Figure 1. Rub the mounted perspex rod with cat fur. Now rub the other perspex rod with fur as well. The fur will loose electrons to the rods, so that the fur becomes positively charged, and the rods become negatively charged. Approach the rotating rod with the second rod, and observe how they repel one another.

Figure 1: A perspex rod (4380.00) mounted on a stand (4395.00) is shown with a second rod nearby. Both rods have received a net negative charge by rubbing them with a piece of fur (4390.20).

Note that charge is not created in this experiment. It is simply redistributed by moving negative charge from one body (the fur) to another (the perspex rod). Note also that the rods repel one another, because they have the same charge (both negative).
If you quickly charge the rotating rod with the fur and then approach it with the positively charged fur, you should observe attraction.

Laws of attraction and repulsion:

Like charged bodies repel one another. Opposite charged bodies attract one another.

The following experiment provides a good illustration of the repulsion between like charges. Use the pith ball support with a hook and a pair of pith balls connected by a string. Hang the pith balls from the hook so that they touch one another as shown in Figure 2.

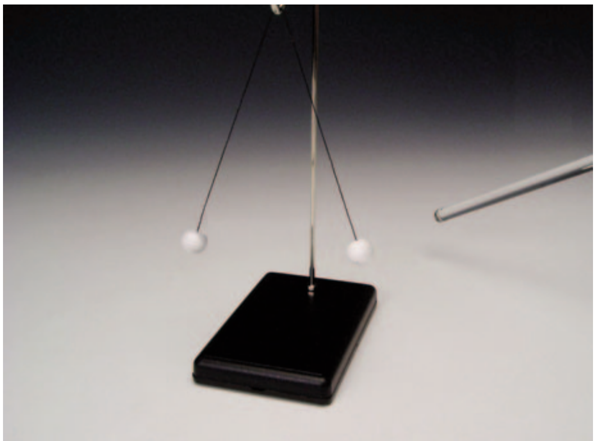

Figure 2: A pair of pith balls (4400.00) mounted on a stand (4407.00) is shown. Use cat’s fur (4390.20) and a perspex rod (4380.00) to charge the pith balls.

When the pith balls are touched by a negatively charged perspex rod, both pith balls become negatively charged. The pith balls will then repel one another according to the Law of Repulsion mentioned above.
Try rubbing a glass rod with a piece of silk, and place the rod in the rotating stand. Now charge the perspex rod using the cat’s fur. When you bring the perspex rod near the glass rod, you should observe that the rods attract one another. The perspex rod is negatively charged, and the glass rod is positive.
Many experiments have shown that there are two and only two types of electrical charge, positive and negative, and that the total amount of electrical charge is conserved.

Insulators and conductors

Materials in which charges can move about freely are called “conductors”, while materials which do not have this property are called “insulators”. (“Semiconductors” such as silicon and germanium are a special case.)

Most metals (particularly copper, silver and gold) are good conductors of electricity, while most non-metals (rubber, glass, plastic) are not. The negative charges which move about in a conductor are electrons. The atoms remaining in place have a net positive charge when electrons are missing.

Induced charges

Insert a rod (an insulator) with a metal ball (a conductor) at one end, so that the rod is supported vertically as shown in Figure 3.

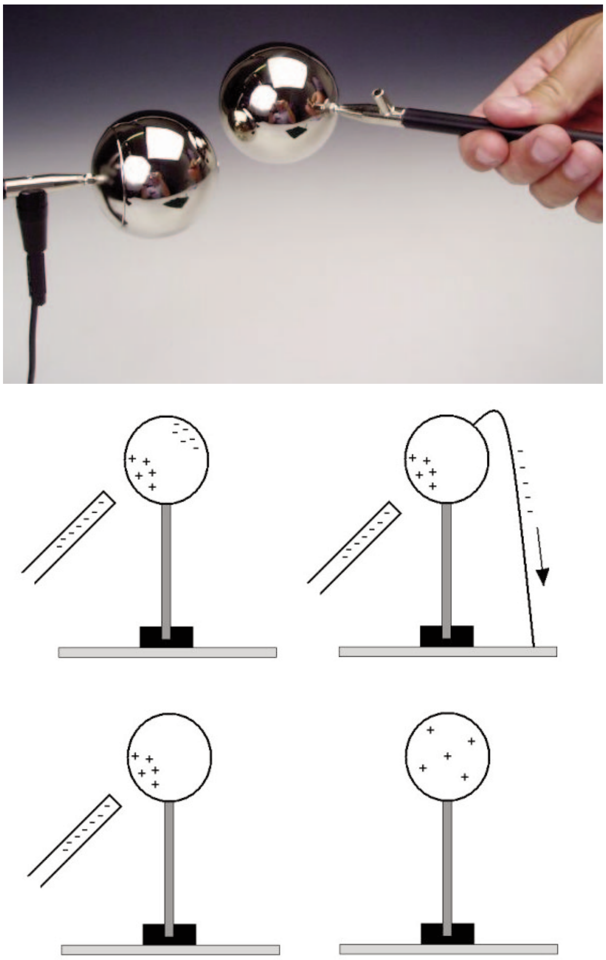

Figure 3: A negatively charged rod (4380.00) is moved towards a conducting sphere supported by an insulated rod (4415.00). Charge moves on the surface of the sphere, as the negatively charged free electrons in the metal are repelled by the negatively charged rod. If the opposite side of the metal sphere is grounded before the charged rod is removed, then the sphere will acquire a net positive charge. This charge is called an “induced charge”.

A negatively charged rod (such as a perspex rod which has been rubbed with cat fur) is placed near the conducting ball as shown, then negative charges (free electrons) in the ball will be repelled to the far side, while the side nearest the rod will be positive. If the far side of the ball is touched with a wire connected to ground, excess electrons will leave the ball through the wire to ground leaving the ball positively charged. Charge induction in this manner makes it possible to charge a body with a charge opposite the charge of the rod used to induce it.

Place an uncharged metal rod in the support stand. Charge the perspex rod with the cat’s fur. When you bring the perspex rod near the metal rod, you will observe attraction. Explain why. What would you expect to happen if you repeated this experiment with the glass rod charged with a piece of silk?

Polarization of charge

If a comb is pulled through dry hair in a low-humidity environment, the comb will become negatively charged. If the comb is moved near e.g. small scraps of paper, the paper will be attracted to the comb. Why does this happen, if the scraps of paper are neutrally charged?

This is caused by “polarization” of the paper scraps. Even though charge cannot move freely in the paper (an insulator) it can shift slightly, thus becoming more positive on one side and more negative on the other. Thus the paper scraps will be attracted to the comb.

The phenomenon of polarization is important in a wide variety of technological applications:

- electrostatic dust precipitators used to remove hazardous particles from the air or from smoke
- attracting drops of paint to an object in a painting chamber to reduce waste and enhance safety
- attracting toner to charged regions of the imaging drum in a copying machine (xerography)

2 Coulombs Law Background

In the experiment Electric Charge we learned that like charges repel one another, and opposite charges attract. Here we will study this phenomenon more closely. Two small charged particles (point charges) having magnitudes Q_1 and Q_2 and separated by a distance R exert forces of attraction or repulsion along the line joining the two charges. The physical law describing the magnitude and direction of these forces is Coulomb’s Law.

Coulomb’s Law

The electrostatic force F between Q_1 and Q_2 separated by a distance R has been found in careful experiments to be given by:

$$F = k \cdot Q_1 \cdot Q_2 / R^2$$

Equation 1: Coulomb’s Law

If the charges Q_1 and Q_2 have the same sign, then the expression will be positive indicating a repulsive force. If the charges are of the opposite sign, then the expression will be negative, indicating attraction. The electric charge is measured in the unit “coulomb”. Forces are directed along the line joining the two charges.

One coulomb/second passes through a wire when the current is one ampere. Thus the definition of the coulomb (C) is based on the SI (Système Internationale) definitions of the second and the ampere. Note that the equation for Coulomb’s Law is analogous to Newton’s Law of gravitational attraction, where the product of two masses appears in the numerator instead of the product of two charges. A different constant also applies.
The constant k for Coulomb’s Law has been found to be $k = 8.99 \cdot 10^9\ N \cdot m^2/C^2$.

Example 1
Two positive charges each 1 mC are 1 meter apart. What electrostatic force acts between them? Inserting the values for Q_1, Q_2 and the distance R = 1 meter, we find:

$F = 8.99 \cdot 10^9\ N \cdot m^2/C^2 \cdot (1 \cdot 10^{-3} C \cdot 1 \cdot 10^{-3} C)/\ (1m)^2$
$= 8990\ N$

The two millicoulomb charges one meter apart are attracted to one another by a force of nearly 9000 newtons!

Superposition of forces
If more than one charge is present, then each of these charges acts upon a given charge as described by Coulomb’s Law. The total force can be computed by vector addition of each of the forces, as is the case with gravitational forces:

$$\boldsymbol{F_{TOT} = F_1 + F_2 + F_3 + \ldots + F_N}$$

Spherical Conductors
Consider the spherical conductor shown in Figure 4. Charge the sphere e.g. by rubbing a perspex rod on a piece of cat’s fur. Touch the charged perspex to the sphere. The sphere may also be charged using a Van de Graaff generator or a high voltage supply. Place the rod and the cat’s fur aside. Now take a pith ball on a string and investigate the charge on the sphere. Before touching the sphere, the uncharged pith ball will be attracted to it due to polarization of the charges in the pith ball. Once the pith ball touches the sphere, it will acquire the same charge and be repelled. By moving the pith ball around, above and below the sphere, you can determine that charge is distributed all around the surface.

The First Shell Theorem
If the force on the pith ball is observed some distance (several diameters) away from the charged sphere, you will note that the force will be the same as if all charge on the sphere were concentrated at the center.

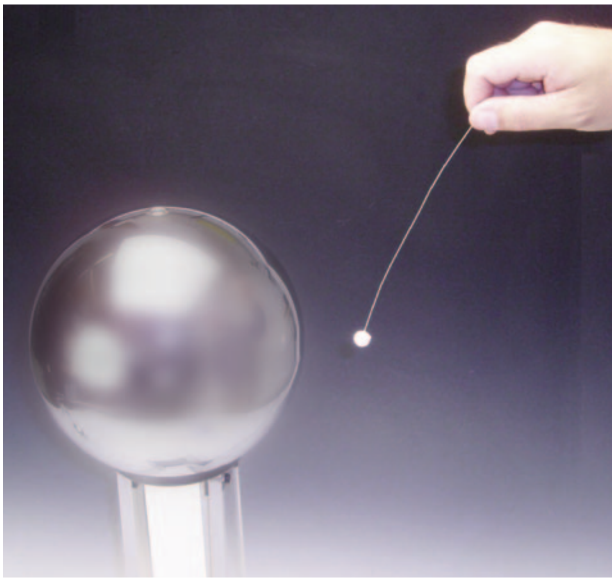

Figure 4: A conducting sphere (4428.00) is mounted on an insultated rod (4410.02) and placed in a stand. When the sphere is charged, the charges will repel one another and move on the outer surface of the sphere to distribute themselves evenly on the surface. Pith balls (4400.00) can be used to investigate the charge distribution.

3 Electric Fields Background
In Experiment-2, Coulomb’s Law, we learned that like charges repel one another, and opposite charges attract. Furthermore, the force acting between such charges Q_1 and Q_2 separated by a distance R is given by Coulomb’s law for electric charge:

$$F = k \cdot Q_1 \cdot Q_2/R^2$$

If the charges are measured in coulombs, and the distance is measured in meters, then the constant $k = 8.99 \cdot 10^9\ N \cdot m^2/C^2$. In this experiment we will explore the concept of the electric field. Electric field lines can provide an excellent overview of the forces acting upon charges in a given region of space.

The Electric Field
Imagine a small test charge with positive charge q which can be freely moved about in space. The charge is so small that it will not affect other charges in the region. Suppose further that you can measure the force F acting on this small test charge. Force is measured in newtons, and it is proportional to the magnitude of the test charge. If the test charge is moved about near a positive charge Q, the forces on it will appear as in Figure 5.

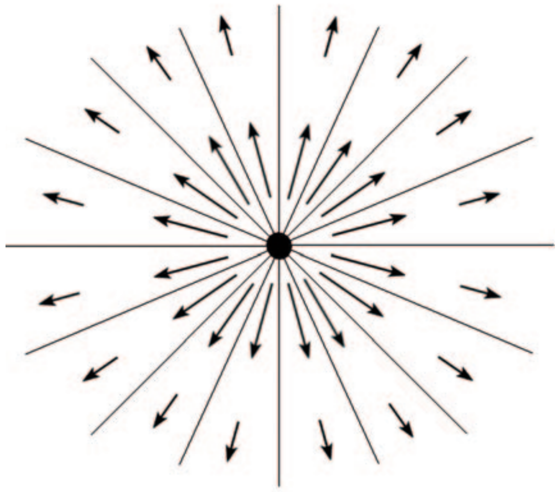

Figure 5: The electric field around an electric charge Q causes forces to act upon a small test charge which is moved about near the charge.

The forces in Figure 5 are vectors with magnitude and direction. If a given force F is divided by magnitude of the test charge q in Coulombs, the resulting vector E has the physical unit newton/coulomb. This is the unit of the electric field.

Example 2

Consider a point charge $Q = 10\ \mu C$. What is the strength and direction of the electric field at a distance $R = 1{,}0$ meter away?

The direction of the field vector is directly away from the center of the charge. The magnitude is:

$$E = F/q = (k \cdot Q \cdot q)/(R^2 \cdot q) = k \cdot Q/R^2$$

Inserting the numerical values: $E = 8.99 \cdot 10^3$ N/C is the strength of the electric field.

Electric field lines give a good impression of the size and direction of the force per unit charge acting in a region near electric charges. An electric field line is drawn so that at every point it is tangent to the direction of the electric field vector at that point. Figure 5 shows electric field lines around a positive charge Q. The concept was introduced in England by Michael Faraday (1791-1867). Note that the field lines themselves indicate the direction of the field. The density of the lines indicates the field strength. When the lines are very close together, the field strength is high.

Experiment 1 -
Field around a spherical charge

Mount a conductor sphere on a rod. Charge the sphere using a Van de Graaff Generator or other source of electric charge. Use a pith ball on a string. Allow the pith ball to briefly touch the sphere, so that it obtains the same charge as the sphere. Move the pith ball around the sphere, and observe the direction of the force.

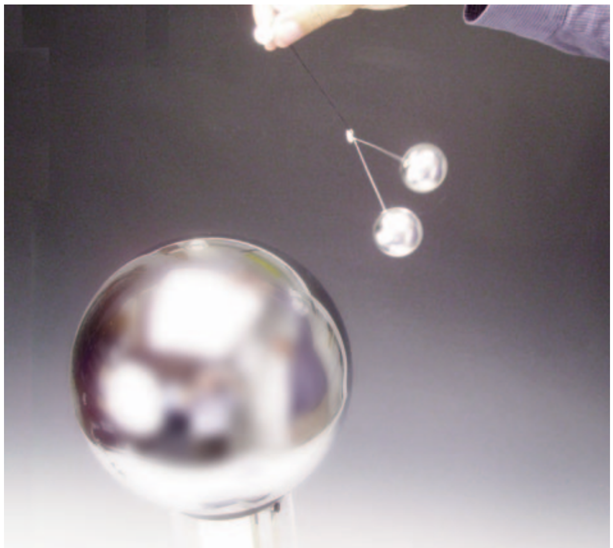

Figure 6: Either a metal sphere (3705.00) mounted on an insulating rod (or the sphere of a Van de Graaff as shown here) is charged. Forces acting on pith balls or metalized balls placed near the sphere indicate the presence of an electric field.

Experiment 2 - The capacitor

Consider a parallel plate capacitor as shown in Figure 7. Imagine that one plate is positively charged, and the that the other is negatively charged. A positive test charge q anywhere between the two plates will be acted upon by a force perpendicular to the plates of the capacitor and pointing from the positive plate towards the negative plate.

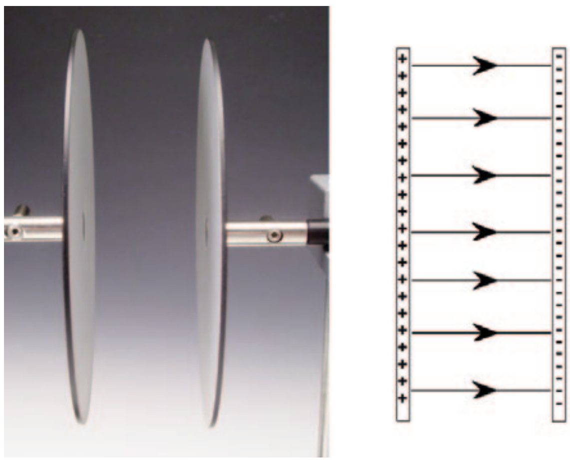

Figure 7: A parallel plate capacitor is shown. At the left the charged plates and the electric field between them is illustrated. Note that the field lines go from the positive to the negative plate of the capacitor.

You can check this by using a pith ball suspended by an insulating thread. Suspend the pith ball between the charged capacitor plates, and observe the force on the pith ball.

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Experiment 3 - The musical capacitor

Suspend a metal ball from a laboratory stand by means of an insulated thread as shown in Figure 8. The ball should just fit between the plates of the flat plate capacitor with some room to spare. Charge the plates of the capacitor with a high voltage power supply (3660.50) or using a Van de Graaff generator (3700.50).

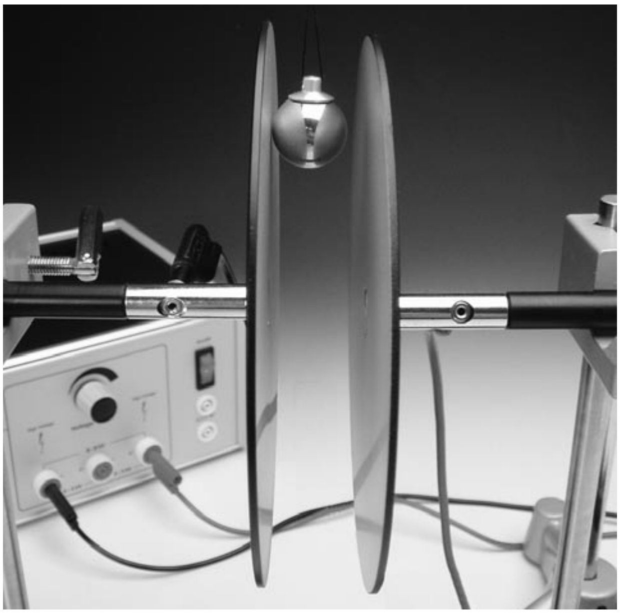

Figure 8: A parallel plate capacitor is constructed by mounting two plates on lab supports as shown. A metal ball is suspended from above so that it is located in the upper third of the inter-plate region and centered between the two plates. The distance between the plates should be about twice the diameter of the metal ball. The capacitor can be charged using a Van de Graaff generator (3700.50) or a high voltage power supply (3660.50).

If the ball touches one of the plates, it will acquire the same charge as the plate due to the flow of charge between the plate and the ball. The ball will then be repelled from that plate and attracted to the opposite plate. The ball will swing towards and then touch the other plate. Here the ball will exchange charge with the second plate and acquire the same charge. The ball will be repelled and swing over to the first plate again. In this way a small pendulum is created which will swing back and forth between the plates, making a ringing noise as it does so.
The transfer of charge in this manner (a number of coulombs per second) corresponds to a flow of current. If the power supply remains connected to the capacitor, the pendulum will continue to swing indefinitely. If no new charge is supplied the charge transfer due to the motion of the ball will discharge the capacitor.

Experiment 4 - The electroscope

An electroscope (4410.00) can be used to demonstrate the presence of an electric field. Mount a charging ball on top of the device. Use a metal ball on an insulated rod (4415.00) to transfer charge to the electroscope charging ball. Note how the electroscope arm swings outwards and remains in position. This occurs because the charge distributed from the charging ball to the parts of the electroscope causes them to acquire the same charge. The swing arm will then rotate due to repulsion between the charge in the moving arm and the charge in the static part of the apparatus.

Figure 9: An electroscope (4410.00) is shown. It is acted upon by a charged metal ball on an insulating rod (4415.00).

Experiment 5 - Electric Whirl

Figure 10: The "electric whirl" apparatus (4430.00) is shown mounted on a Van de Graaff generator (3700.50). When the sphere is charged, the little mill will rotate.

Mount the electric whirl apparatus (4430.00) on top of the sphere of the Van de Graaff generator (3700.50). When the Van de Graaff sphere is charged

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during operation, the electric field near the points at the ends of the arms of the electric whirl apparatus will be very high. Electrical discharge will occur from these points of high field strength. When the electrical charges move quickly away from the points, they will cause an equal and opposite reaction force on the arms of the apparatus (by conservation of momentum). These forces from all four arms will cause the apparatus to rotate.

Experiment 6 - Insulated stool

A dramatic example illustrating the presence of an electric field can be performed using an insulated stool (4435.00) and a student with long, dry hair. The experiment works best - as indeed do all experiments in electrostatics - on a day with low relative humidity (below 40%). The student should stand on the insultated stool and hold a lead which is connected to the sphere of a discharged Van de Graaff generator. If possible one can place one's hand directly on the sphere. The student should not release the wire or remove the hand from the sphere during the experiment. Wait until the Van de Graaff sphere has been discharged again. The subject should not wear glasses during the experiment, and all sharp, metallic objects, mobile phones, etc. should be removed. When the Van de Graaff begins charging the sphere, the charge is distributed to the surface of the student's body and hair. Charges in the hair cause repulsion which can create a dramatic effect with nearly all the hair on the student's head standing on end.

To avoid a shock, stop the Van de Graaff generator and discharge the charging sphere by connecting it with a wire to ground. The student can then release the connection to the Van de Graaff without getting a shock.

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