Electrostatics with Computer-Interfaced Charge Sensors

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Computer interfaced electrostatic charge sensors[1,2] allow both qualitative and quantitative measurements of electrostatic charge but are quite sensitive to charges accumulating on modern synthetic materials. They need to be used with care so that students can correctly interpret their measurements. This paper describes the operation of the sensors, precautions for using them, and suggestions for experiments with sample readings.[3]

Charge Sensor Operation

A sensor circuit consists of a very high-impedance voltmeter measuring voltage across an internal 10-nanofarad capacitor[1,2] with external leads connected to the capacitor plates. Objects connected to the leads form an external capacitor in parallel with the internal capacitor. With external capacitance, small compared to internal capacitance, the charge can be calculated using $Q = C\Delta V$. For example, the range -0.5 C to +0.5 V on the Vernier charge sensor corresponds to a range in charge of -5 nC to +5 nC. Two metal plates 50 cm on a side placed 5 cm apart in air have a capacitance of about 44 pF, giving only a 0.4% change in the total capacitance and a corresponding small error in determining the charge. The same size plates separated by a 0.5-mm plastic sheet with a dielectric constant of 5 have about 22-nF capacitance, roughly twice the internal capacitance, meaning that the sensor could not be used to measure charge with that arrangement, at least not without reinterpreting the charge scale.

A small Leyden jar made from a plastic film can[4] may be treated as a flat plate capacitor with an area about 4 cm x 9 cm, a separation of 1 mm, and a dielectric constant of 2.25,[5] giving a capacitance of about 0.07 nF or 0.7% of the internal capacitance, a negligible error. However, the voltage limit for the sensor would be only 10 V, much smaller than the voltages at which a film-can Leyden jar would normally be used. The maximum voltage rating of the sensors is about 150 V, so care should be taken in using the sensors with external capacitors capable of high voltage.

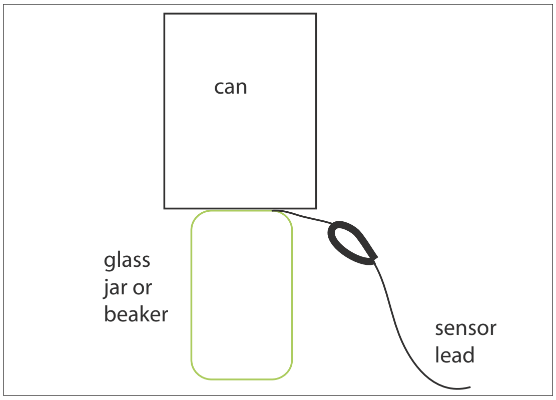

Fig. 1. Tin can on beaker.

Precautions in Using the Charge Sensor

Modern synthetic shoes, fabrics, and plastic insulators readily accumulate stray static charges under moderately dry conditions, so we must take care that the charges measured are those in the experiment, not those on the experimenter. Three simple precautions help.

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- First, most experiments should be done with a ground plane on the laboratory table. A square of wide heavy-duty aluminum foil connected to the grounding lead of the sensor works well. Folding the edges under 1 cm keeps the clip from tearing the foil.
- Second, a conducting sensor body insulated from the ground plane and connected to the ungrounded lead facilitates many experiments. A small tin can, such as a soup can or coffee can, set on top of an inverted glass jar or beaker is convenient (Fig. 1). A glass jar is the preferred insulator, as every plastic cup or jar I tried picked up enough stray charge in handling to affect the charge readings. The tin can may be used to detect charge by induction, by contact, or by using it as a Faraday pail. Unpainted cans work best. Using cans of different sizes, from small to large, allows for a variety of experiments.
- Third, the experimenter should be connected by a grounding lead to the foil ground plane. A commercial grounding bracelet may be used, or you can fold a strip of heavy-duty foil about four times, wrap it around one wrist, and connect it to the ground plane with a long clip lead. It is very easy for the charge on the experimenter to be significant compared to the charges being measured. As an example, while ungrounded I held my fist near the soup can detector described above while scuffing my synthetic-soled shoe on an epoxy-coated floor. At 25% relative humidity, the sensor indicated a charge of 2 nC. Grounding myself with a wrist strap reduced the maximum charge detected to 0.1 nC. (This can be a good initial experiment for students.)

General Procedures for Using a Charge Sensor

Begin measurements by grounding the sensor and discharging the internal capacitor with the zero button. Depending on the experiment, you may need to change the sensor scale and begin an experiment again with a new range. For qualitative measurements you may wish to set up a long recording interval for a graph and include both analog and digital meters in your display.

Detect charge by induction. Bring a negatively charged object near a can connected to the sensor and it will drive electrons in the can onto the plate of the internal capacitor, causing a negative voltage or charge reading. A positively charged object near the can will register a positive charge. Lower a small charged object into the can, without touching the walls of the can, and the same process will occur. Transfer charge to the sensor by contact, touching a charged object to the outside of the can. A charged conductor will share its charge with the can; a charged insulator may transfer some charge on simple contact and more when it is drawn along the can's surface.

Measure charge by dropping a charged object into the can. A conductor will transfer its charge to the can where it will move to the outside of the can. A charged insulator dropped in the can will induce a charge on the outside of the can equal to the charge on the insulator.

Alternative Detector Arrangements

Make a probe with a coin clipped to the sensor lead and fastened with masking tape to a plastic straw or glass rod. A spherical metal drawer knob on an insulating rod can be connected to the sensor lead. Instead of a detector can, connect the clip lead to the metal screw cap of a glass jar and set the jar on the ground plane.

A Set of Possible Experiments Using the Charge Sensor:

1. Detecting positive and negative charge. Rub a plastic straw with a small square of paper towel, craft fur, rabbit fur, or wool. Bring the straw near the can and observe the reading. Observe the charge reading as you slowly lower the charged end of the straw into the can. Rub the straw lightly between your fingers to neutralize its charge and bring it near the can to check. Rub it with the fur and drop the fur immediately into the can, then lower the straw into the can and observe the effect. (Fur and straw will show opposite but unequal charges as the fur loses some of its charge to the hand. At 25% relative humidity, a charged plastic straw had a charge of about -20 nC.)

2. Experiments with charged tape. Charge two short pieces of Scotch Magic™ tape oppositely by

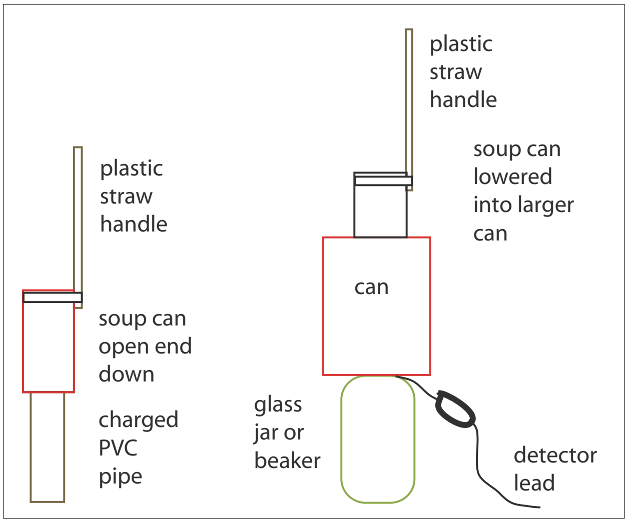

Fig. 2. Charging a can and measuring the charge.

sticking the sticky side of one to the slick side of the other. Draw them lightly between your fingers to neutralize stray charge. Then bring them near the can to check for neutrality. Separate the pieces of tape and observe what happens when you bring them near each other. Then observe the charge reading as you bring each one near the can. Note the effect of distance as you move a piece of tape closer to the can and the competing effect of the two pieces of tape as you move them closer to and farther from the can. (At 25% relative humidity, two 4-cm pieces of tape received opposite charges of about 8 nC). Drop a piece of charged tape into the can without touching the can yourself. Compare the reading with the charged tape inside the can with the maximum reading as you brought it closer to see how putting the charged tape in the can gives a more accurate reading of the charge on the tape. Drop the oppositely charged tape in the can. If you have handled them carefully, the charges should nearly cancel. Charge different lengths of tape and determine the charge per unit length. (I obtained charge values of about 3.0 +/-0.5 nC per cm at 25% relative humidity.) Charge a piece of tape, lower it into the can using a paper strip handle, determine its charge, and remove it from the can. Repeat at 5-min intervals. (At 25% relative humidity, a charged 3-cm piece of tape decayed from 5.6 nC to 5.5 nC in five minutes.)

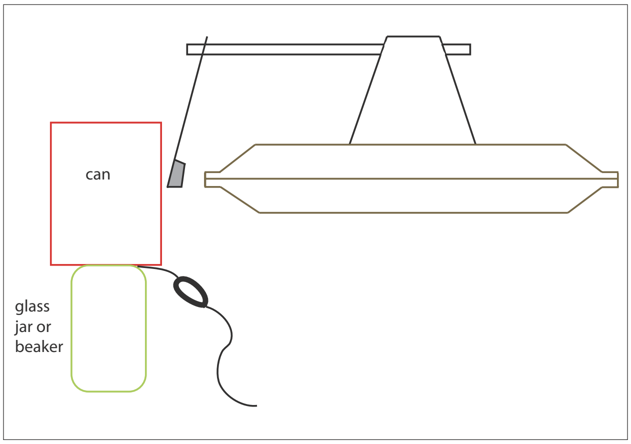

Fig. 3. Pie tin electrophorus transferring charge to detector can. Hanging foil bit on plastic straw poked through foam cup handle on conducting base made of two disposable aluminum pie tins.

3. Detecting charge on plastics. A simple triboelectric series is illustrated by finding the sign of the charges on a foam plastic picnic plate rubbed on a sheet of acrylic plastic window glazing, a foam plastic plate rubbed on a non-foam plastic picnic plate, and the acrylic plastic rubbed on the non-foam plate. Cut a foam picnic plate into 3-cm squares, rub on hair or wool, and drop them into the can to find the surface charge density. (At 25% relative humidity, I got about 1.5 nC/cm^2 by charging up to nine squares of foam. Rubbing lightly, compared to rubbing hard, gave values ranging from 3 to 16 nC of charge on a 27-cm^2 piece of foam rubbed on one side.)

4. Measuring charge on a mini-electrophorus. Volta's electrophorus consists of an insulating base charged by rubbing and a conducting plate with an insulating handle. The metal plate is set on the base, grounded by touching it with a finger, and removed from the base with the handle; a classic example of charging by induction. Make a mini-electrophorus from a 3-cm plastic square cut from a foam picnic plate. Attach a paper strip to it with masking tape, charge it by rubbing, and lower it into the sensor can to establish its charge. Remove it from the can and holding it by its edges, drop a penny on the foam. Ground the penny by touching it with your finger, then let it slide off the foam into the can to measure

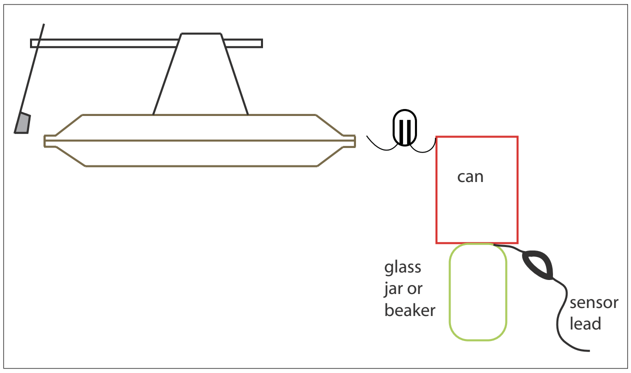

Fig. 4. Neon bulb lighting from charged electrophorus.

the charge on the penny. Repeat the process with additional pennies until you come close to the limit of the sensor setting. Lower the foam into the can and measure the charge on the foam again. Note that charging the pennies had almost no effect on the charge on the foam. (At 25% relative humidity, I obtained about 1 nC per penny, decreasing somewhat as the number of pennies increased. Quarters got a larger charge, roughly proportional to the increased area.) Students who can clearly explain the process of charging by induction using an atomic model have a good understanding of the differences between conductors and insulators and the distant effects of charged objects on each other.

5. Charging a can by induction. A hollow metal can may be charged by treating it as a cylindrical electrophorus. Tape a straw to an empty soup can to form an insulating handle that sticks up when the opening of the can is down (Fig. 2). Cut about a 20-cm length of 2-in-diameter PVC pipe, charge it by rubbing, and set it on end. Lower the open end of the soup can over the charged PVC and touch the outside of the soup can to charge it by induction. Test for charge by bringing the PVC and the can near the sensor. A coin on an insulating handle may be used to transfer charge a little at a time from the electrophorus can to the sensor can to measure both the charging and discharging. Use a larger empty can for the detector and lower the charged can inside the detector to measure the total charge on the soup can. Compare the effect of lowering the soup can only part way over the charged PVC. (At about 30% relative humidity, I obtained charges ranging from 45 nC to 75 nC on a soup can.)

6. Charge transfer. Charge a pie tin electrophorus equipped with a hanging foil bit[6] (Fig. 3) or a can on an insulating base to repeatedly transfer charge to the sensor can as the foil bit bounces back and forth between the charged conductor and the sensor can. [Make a foil bit by wrapping a strip of tape (sticky side out) around a pencil; stick the end of a piece of thread to the tape, wrap a strip of aluminum foil around the tape, and slide it off the pencil.]

7. Neon bulb calibration. Although the charge sensors are fairly robust, they should not be used with high-voltage electrostatic generators. A neon bulb will flash when electrostatic charges are transferred through it and can indicate the polarity of the charge transfer[7] by noting which electrode flashes. The flash polarity can be determined by using the charge sensor before the neon bulb is used with high-voltage generators. Tape one lead of an NE-2 neon bulb to the sensor can with the other lead bent into a curve. Using the highest scale, bring a charged electrophorus plate near the bent electrode (Fig. 4). Note which electrode flashes when the spark jumps and the sign of the charge transferred. (The more negative electrode will flash, i.e., if electrons leave the detector can, the flash will be on the electrode connected to the can. As a result of electrons leaving the can, the sensor shows a positive charge after the flash.)

8. Sharing charge between conductors. Use a coffee can for the detector. Prepare two smaller soup cans and one much larger can with insulating handles by taping a plastic straw to each can with masking tape. With the sensor running on the 100 nC scale, charge a soup can with an electrophorus or by induction from a charged PVC pipe as above. Holding the can by the handle, lower it into the sensor can without touching the sensor can and note the charge. Remove it, pick up the second can by its handle, and touch the two cans together. Keeping them away from each other, lower each in turn into the sensor and note the charge. Now ground the second can and again touch it to the first can, noting the charges on the cans. (At 30% relative humidity, the first can had 75 nC. After sharing charge once it had 33 nC, and after sharing the second time, 14 nC.) Repeat the experiment using a much larger can for the second can and note that the charges are not equally shared. (A 6-cm soup can starting with 61 nC retained only 13 nC when touched by a 15-cm-diameter can.)

9. Quick determination of order of magnitude of Coulomb's constant. Charge two small foam plastic cups hung from 1-m long threads. With the sensor running on the 100-nC scale, lower each cup in turn by its thread into a large detector can to determine the charge on each cup. Hang the cups from a common support and measure the separation between their centers as they repel each other (Fig. 5). With tension, gravitational, and electrical forces in balance, the ratio of electrical force to gravitational force equals the tangent of the angle from the vertical. Using the small angle approximation, this equals the ratio of half the separation distance to the length of the suspension. From the mass of the cup, the local gravitational field strength, and the measured charges, the value of Coulomb's force constant can be approximately calculated. At 30% relative humidity, a 1-m suspension, a 1.8-g cup, 20-cm separation, and charges of 60 nC and 90 nC on the cups gave 13×10^9 Nm^2/C^2, about a 45% overestimate but clearly the proper magnitude. Repeating the experiment in three different classes gave an average value near $10 \pm 4 \times 10^9$ Nm^2/C^2. The experiment may be tried with other light objects such as empty soda cans or charged Ping-Pong balls, or on a smaller scale with charged foil bits. The point is not to make a highly accurate determination of the Coulomb constant but to get the right order of magnitude.

Acknowledgments

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