Lab 4: Capacitance

Introduction

Doing some simple experiments, including making and measuring the capacitance of your own capacitor, will help you better understand the phenomenon of capacitance. In this lab, you will use a commercially available demonstration capacitor to investigate the basic principle of capacitance, expressed in the equation: \( C = \frac{q}{V} \), where \( C \) is the capacitance of some system of conductors and insulators, \( q \) is the charge associated with the system, and \( V \) represents the potential difference between the parts of the system.

Equipment

The electrometer, the high voltage source, the insulated sphere and the proof plane are all equipment that you used in the first lab, Electrostatics. Recall how to read the analog scale on the electrometer properly. Also recall how to properly zero the electrometer.

The demonstration capacitor consists of two conductive discs, approximately 18 cm in diameter, mounted on a base. One disc is fixed to the base, the other disc is attached to a support which can be moved to change the spacing between the discs. Terminals are provided so that electrical connections can be made to the discs.

1. Investigating the capacitance equation

a. Proportionality of potential difference to charge

Introduction

The capacitance equation, \( C = \frac{q}{V} \), applied to a parallel plate geometry, seems to imply that the capacitance of the system depends on the charge on the plates and the potential difference between them. But, in fact, this is not the case. The capacitance of a device depends only on its geometry and the insulating material between the plates. It is independent of the values of \( q \) and \( V \). This must mean the ratio \( \frac{q}{V} \) remains constant even as the charge and potential difference change.

Rearranging the equation it reads \( q = CV \). This says that for a given capacitance the potential difference between the two plates of the capacitor will be directly proportional to the charge on the capacitor. That is, doubling the charge should double the potential difference, tripling the charge should triple the potential difference, and so forth. This is the correct way to interpret the fundamental capacitor equation. Let’s see if the demonstration capacitor obeys this relationship.

Procedure

- Adjust the demonstration capacitor so that the two plates are approximately 2.0 mm apart. This can be most easily done using the scale printed on the base of the capacitor.
- Connect the electrometer to the capacitor by connecting the black wire from the electrometer to the fixed plate of the capacitor and the red wire to the movable plate. Zero the electrometer by shorting the two plates with your hand while
simultaneously depressing the zero button. To start, select the electrometer’s 30 volt range.

- Connect the insulated sphere to the +1000V terminal of the electrostatics voltage source and connect the “com” terminal on the voltage source to the “gnd” terminal on the electrometer as you did in lab 1. Make sure that the insulated sphere is as far away from the electrometer and the capacitor as possible in order to avoid erroneous readings due to the electric field of the sphere. (Keep the sphere well away from the computer monitor also.) Now turn on the voltage source.

- Re-zero the electrometer if necessary, charge the proof plane by touching it to the sphere, and transfer the charge to the movable plate of the capacitor. You only need to touch the proof plane to the edge of the plate, but be careful that you only touch the movable plate. Do not let the proof plane touch the fixed plate at any time. After transferring the charge note the voltage reading on the electrometer and record it in Table 1 below. For the time being we will call the amount of charge transferred from the proof plane 1 ctu, where “ctu” stands for “charge transfer unit”. This is a made up name for this amount of charge that we will use until you can determine how many Coulombs are transferred.

In the same way, transfer a second “ctu” of charge and record the voltage reading. Do this six times. The voltage reading on the electrometer should increase with each transfer. Do not zero the electrometer after each transfer.

[Note: Depending on atmospheric conditions and other factors in the lab it is possible that the capacitor will “leak”. That is, some of the charge will not stay on the capacitor but will be conducted off by moisture in the air or dirt or other contaminants on the supporting structure of the capacitor. If this happens, the potential difference across the plates of the capacitor will immediately begin to decrease after the capacitor has been charged. Should this occur, you will have to transfer the charges rapidly and make quick voltage readings in order to minimize the effects of this leakage on your experiment.]

<table>
<thead>
<tr>
<th>Transfer #</th>
<th>Charge on Capacitor (charge transfer units – ctu)</th>
<th>Electrometer Reading (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1 ctu</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td></td>
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<tr>
<td>3</td>
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<td>6</td>
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<tr>
<td>7</td>
<td>7</td>
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</tbody>
</table>

*Table 1*
• Use Graphical Analysis to make a graph of \( q \) vs. \( V \), plotting \( q \) in ctu’s on the vertical axis and potential difference on the horizontal axis. Attach a copy of the graph to your report.

**Conclusions**

Analyze your data and see if it supports the proportionality between charge and potential difference predicted by the fundamental capacitor equation, \( q = CV \). If the graph is reasonably straight then you can conclude that the prediction of the capacitance equation has been verified. If the graph is not straight think about whether that is due to capacitor leakage, or some other unforeseen factor affecting what is going on.

State your conclusion here, and discuss any unusual aspects of your data.

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**b. Estimating the charge of one “charge transfer unit”**

**Introduction**

If your graph is reasonably straight, its slope should be equal to the capacitance of the capacitor. This provides one method for determining its capacitance. There is also a second method. If the plates are not too far apart, the demonstration capacitor can be correctly modeled as a parallel plate capacitor, which obeys the equation,

\[
C = \frac{\varepsilon_0 A}{d}.
\]

**Procedure**

• Use the equation above to calculate the capacitance of the demonstration capacitor in SI units. Show your work.

• Now, using your calculated value of capacitance, and your graph of \( q \) vs. \( V \), calculate the charge, in Coulombs, of one “charge transfer unit” of charge. In other words, calculate the actual amount of charge that the proof plane is picking up from the insulated sphere and passing on to the capacitor each time you carry out a transfer. Show your work.
Finally, calculate how many fundamental units of charge are being transferred each time you touch the proof plane to the capacitor. Show your work. Does this number represent the number of electrons being transferred to the capacitor or removed from the capacitor?

b. Testing the inverse proportionality between \( V \) and \( C \)

**Introduction**

The capacitance equation can be rearranged to give, \( V = q/C \). This says, for a fixed value of charge, increasing the capacitance of the capacitor should decrease the potential difference across the plates, and vice-versa. Here you will investigate this prediction. You should prepare to take the measurements quickly to avoid problems with capacitor leakage. Read the entire procedure and then conduct the experiment.

**Procedure**

- With the capacitor plates initially about 2mm apart, transfer two ctu’s of charge to the capacitor, and record the resulting potential difference in Table 2.
- Increase the plate separation 2mm at a time and record the new potential difference each time. Record the potential with as much care and precision as possible.

<table>
<thead>
<tr>
<th>Electrometer Range:________</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \text{Separation (mm)} )</td>
</tr>
<tr>
<td>---------------------------</td>
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*Table 2*
• Combine the equation for the capacitance of infinite parallel plates with the capacitor equation, \( V = \frac{q}{C} \), to obtain an expression for the plates’ potential difference as a function of the separation for a fixed charge on the plates. Show your work.

• If this expression was used to plot potential difference vs. plate separation what would the graph look like? Be specific. (Make a sketch of your expectation.)

• Use Graphical Analysis and plot your data, potential difference vs. separation. Print your graph and attach it to the lab.

  Mark on your graph the range of separations for which the data matches the expectation for parallel plates. What criterion did you use to answer this question?

  Mark the range of separations which exhibit significant deviations from the expected relationship. Discuss why this might be occurring.
2. Making a capacitor and measuring its capacitance

**Introduction**

In this section you will construct a parallel plate capacitor. Then you will use a basic property of capacitor networks to measure its capacitance.

**Procedure**

- Cut from a roll of aluminum foil a piece that is about 15cm long.
- Cut this piece into two equal parts as shown in *Figure 1* below. Discard the shaded pieces. The goal is to make two approximately square pieces with tabs on them which look like *Figure 2*. These pieces will be the capacitor plates.

![Figure 1](image1)

![Figure 2](image2)

- Inspect the two pieces for any rough or sharp edges. Smooth any rough edges with your finger.
- Place a large sheet of mylar plastic on the worktable. Wipe the plastic with a damp (not wet!) paper towel to rid it of any dirt or stray charge which might affect the results of your experiment. Make sure there is no stray moisture left on the plastic.
- Place one of your foil pieces in the center of this sheet of plastic.
- Take a small sheet of mylar, clean it on both sides with a damp paper towel, and place it on top of the foil piece. Make sure the mylar completely covers the foil piece except for about two or three centimeters of the tab.
- Place the other foil piece on top of the mylar, with the tab on the opposite side from the first tab.
- Clean a third sheet of mylar and place it on top of the second piece of foil, making sure that only the two tabs protrude from under this sheet. When finished the stack should look like *Figure 3* below.

![Figure 3](image3)

- Place a heavy book on top of the stack, leaving the tabs exposed so you can make connections to them. (Do not allow the tabs to touch the book. The book’s surface can be somewhat conductive providing a path for charge leakage.)
- Connect the electrometer to your capacitor. Be careful not to tear the tabs.
• Connect two wire leads to a 6 Volt battery and charge your capacitor by briefly touching the leads from the battery to the tabs of the capacitor. Watch the electrometer to see whether the capacitor “leaks”. If there is little or no voltage drop after about 30 seconds or so, then the capacitor is holding charge satisfactorily. Consult your instructor if this is not the case.

• If your capacitor passes this test, discharge the capacitor by simultaneously touching both tabs with your fingers. You are now ready to measure the capacitance of your capacitor.

• At your lab station, find the small 2nF capacitor. Connect one terminal of this capacitor to the negative tab of your capacitor. Connect another wire to the other terminal of the 2 nF capacitor, but do not yet connect it to your capacitor. We’ll call this the “test wire”. At this point, the circuit should look like the Figure 4 below.

![Figure 4: Capacitor test circuit](image)

• Discharge both capacitors by briefly touching their terminals with your fingers.

• Charge your capacitor by briefly touching its terminals with the leads from the 6 Volt battery. The polarity is important. Make sure you touch the negative battery lead to the negative tab of your capacitor. Note and record the electrometer reading in Table 3 below. We’ll call this reading $V_{before}$.

• Now briefly touch the test wire to the positive tab of your capacitor. The electrometer reading should drop to a new, lower value. Note and record this reading for the first trial in Table 3. We’ll call it $V_{after}$.

• Discharge the capacitors by briefly touching the terminals with your fingers. Repeat the procedure twice more, each time recording your results in Table 3.

<table>
<thead>
<tr>
<th>Electrometer Range:</th>
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<tbody>
<tr>
<td>Trial</td>
<td>$V_{before}$</td>
</tr>
<tr>
<td>1</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Average</td>
<td></td>
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</tbody>
</table>

*Table 3*
The data you have just collected can be used to determine the capacitance of your capacitor by the method of shared charge. In a sense you are testing your capacitor against a known capacitance, which will reveal the unknown capacitance. Here we will outline the theory behind this method.

When two capacitors are connected in parallel, as shown in Figure 5 below, they act as a single capacitor, which has a capacitance equal to the sum of the individual capacitances.

\[ C_{\text{total}} = C_1 + C_2 \]

![Capacitors in parallel](image)

*Figure 5: Capacitors in parallel*

If a charged capacitor, \( C_1 \), having an unknown value, is connected in parallel with an uncharged capacitor, \( C_2 \), whose value is known, some of the charge from \( C_1 \) is transferred to \( C_2 \). As this transfer occurs, the potential difference across \( C_1 \) decreases and the potential difference across \( C_2 \) increases until they arrive at a common final value, which we can call \( V_{\text{after}} \). This process takes place almost instantly. The total charge of the system remains the same, it has just been redistributed. In equation form we would write:

\[
(1) \quad V_{\text{before}} = \frac{Q}{C_1}
\]

\[
(2) \quad V_{\text{after}} = \frac{Q}{C_1 + C_2}
\]

Note that both \( Q \) and \( C_1 \) are unknown quantities in this system of equations. However, if we divide equation 1 by equation 2 we can eliminate \( Q \) between them and arrive at a single equation involving only one unknown, \( C_1 \). This equation can then be solved for \( C_1 \) in terms of the known quantities \( C_2, V_{\text{before}} \) and \( V_{\text{after}} \).

**Procedure cont.**

- Derive an expression for the capacitance of your capacitor, \( C_1 \), in terms of the known quantities \( C_2, V_{\text{before}} \) and \( V_{\text{after}} \). Show your work.
Calculate the capacitance on your capacitor in nano-Farads. Show your work.

Questions

- Take a look at the commercially available capacitor on the instructor’s desk. It has a value of 0.47 μF. This capacitor is also made of plastic and foil, in much the same way as you made yours. Assuming that the plastic in this capacitor is the same thickness as the plastic you used to make yours (it’s not, but assume that), what would the plate area of this capacitor have to be in order for it to have the capacitance it has? If these plates were square, what would be the length of one side? Show your work.

- In view of your answers to this last question, how do you think the manufacturers managed to make their capacitor as small as they did?