Demonstration 1: Faraday Ice Pail and Charge Production

Equipment Required:	
Electrometer (ES-9078)	Faraday Ice Pail (ES-9042A)
Charge Producers (ES-9057B)	Test Leads
Earth ground connection	Proof plane (optional)

Suggestions for Introducing the Experiment

Start by showing that the electrometer is directly measuring potential difference by connecting a battery to it and measuring its voltage. You can explain that when using the ice pail, you will be only indirectly measuring charge, knowing that the amount of charge is proportional to the voltage. The readings will be in volts, not in coulombs. Change the polarity of the leads to show how the meter needle deflects in the opposite direction. Explain how this can tell us the type of charge in the ice pail.

Equipment Setup

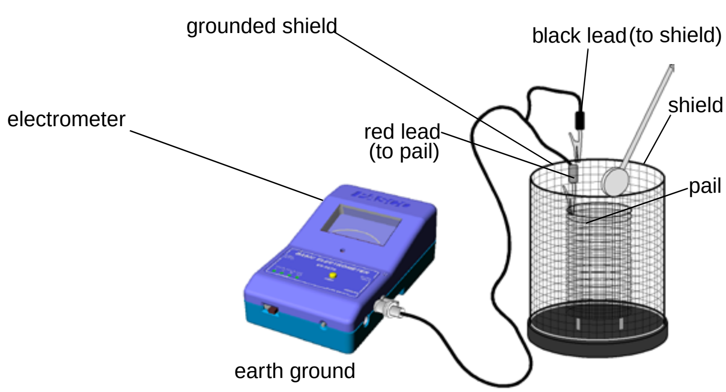

Figure 1.1: Demonstration Setup

Introduction

The purpose of this demonstration is to investigate the relation between the charge induced on the ice pail by a charged object placed in the pail, and the charge of the object. This demonstration is also useful for investigating the nature of charging an object by contact as compared to charging it by induction, and to demonstrate the conservation of charge.

Before beginning any experiment using the ice pail, the pail must be momentarily grounded. When the ice pail is connected to the electrometer, and the electrometer is connected to an earth-ground, simply press the ZERO button whenever you need to discharge both the pail and the electrometer. While conducting an experiment, it is convenient to keep yourself grounded, by continuously resting one hand on the upper edge of the shield, or by direct contact with the earth-ground connector.

WARNING: Make sure the electrometer is connected to an earth ground, or the pail will not be properly grounded. Performing tests or experiments with an ungrounded pail could cause possible electrical shock or injury.

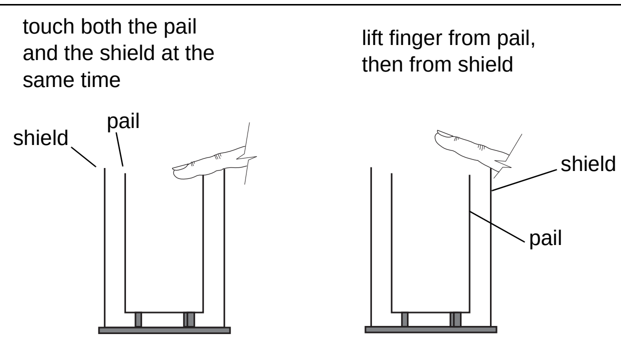

Figure 1.2: Grounding the ice pail

Procedure 1A: Charging by Induction vs. Charging by Contact

1. Connect the electrometer to the Faraday Ice Pail as shown in Figure 1.1. Make sure to ground the electrometer and the ice pail. The electrometer should read zero when grounded, indicating there is no charge in the ice pail. Press the **Zero** button to completely remove all charge from the electrometer and the ice pail.
2. Always start with the voltage range in the higher setting (100 V) and adjust down if needed. Analog meters are typically most accurate in the range of 1/3 to 2/3 of full scale.
3. The charge producers will be used as charged objects. Here is a general procedure to follow when charging the producers:

- Always remove any stray charge on the necks and handles of the charge producers by touching the necks and handles to the grounded shield. You must also be grounded while doing this. It also helps if you breathe on the neck of the charge producer, so that the moisture in your breath removes any residual charge on the neck.
- Rub the white and blue surfaces together to separate charges.
- Keep in your hand only the producer you are going to use. Put the other charge producer away, far from contact with any of the ice pail surfaces.
- Before inserting the charged disk in the ice pail, make sure you're touching the grounded shield.

4. Carefully insert the charged object into the ice pail, all the way to the lower half of the pail, but without letting it touch the pail. Note the electrometer reading.

5. Remove the object and again note the electrometer reading. If the handle never touched the pail, the reading must be zero.

Question: Why was there a potential difference between the pail and the shield only while the charged object was inside?

6. Push the **Zero** button to remove any residual charge. Now insert the object again, but let it touch the ice pail. Make sure your students know and see that you are touching the ice pail with the charged disk this time.

7. Remove the object and note the electrometer reading.

Questions: Why is there now a permanent potential difference between the ice pail and the shield? Where did the charge on the ice pail come from?

8. To show that the charge gained by the ice pail was lost by the disk, ground the ice pail to remove all charge. Press the ZERO button to remove residual charges from the electrometer. Insert the wand again into the ice pail. Does any charge remain on it?

Procedure 1B: Conservation of Charge

1. Starting with initially uncharged charge producers, rub the blue and white materials together. Follow the general procedure for charging listed in part 1A, except that in this case you must keep both producers from touching anything else after charging. (Keep them in your hands, without letting them touch each other or the ice pail.)

2. Use the Faraday Ice Pail to measure the magnitude and polarity of each of the charged wands by inserting them one at a time into the ice pail and noting the reading on the electrometer.

Questions: What is the relation between the magnitude of the charges? What is the relation between the polarity of the charges? Was charge conserved in the demonstration?

3. Completely remove all charge from the charge producers by grounding them. Do not forget to also remove any stray charge from the necks and handles.

4. Insert both charge producers into the ice pail and rub them together inside the pail. Note the electrometer reading. Do not let the charge producers touch the pail.

5. Remove one charge producer and note the electrometer reading. Replace the charge producer and remove the other. Note the electrometer readings. Using the magnitude and polarity of the measurements, comment on conservation of charge.

Extra Things to Try

1. Try repeating Procedure 1A with the opposite charged wand.

2. Try rubbing the white charge producer with a proof plane, then measure the magnitude and polarity of the charges produced.

3. Try rubbing the blue material with a proof plane. Measure the magnitude and polarity of the charges produced.

4. Construct a list of materials such that if a material lower in the list is rubbed with a material higher in the list, the higher material is always positive.

Demonstration 2: Charge Distribution

Equipment Required:	
Electrometer (ES-9078)	Faraday Ice Pail (ES-9042A)
Electrostatic Voltage Source (ES-9077)	Proof Planes
Conductive Spheres, 13 cm (ES-9059B) (2)	Test leads
Earth ground connection (patch cord)	

Equipment Setup

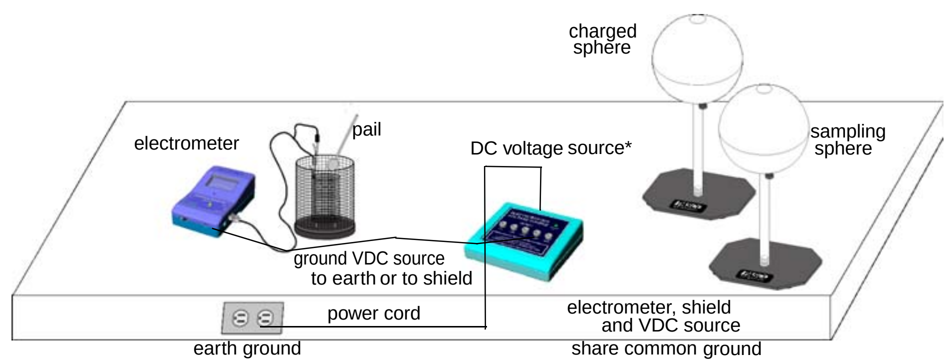

Figure 2.1 Demonstration Setup

*An earth ground for the system is obtained through the DC voltage source wall-mount power.

Introduction

The purpose of this demonstration is to investigate the way charge is distributed over a surface by measuring variations of charge density. A charged surface will be sampled with a proof plane. The proof plane will then be inserted in the Faraday Ice Pail to measure the charge. By sampling different sections of the surface, the relative charge density can be observed. For example, you may find that the amount of charge on two equal sized regions on the surface of a conductor may differ in magnitude or even in sign. This occurs for non-uniform charge distribution. Alternately, you may observe that everywhere on the surface the charge has the same magnitude and sign. This occurs for uniform charge distribution.

An important aspect of measuring charge distributions is charge conservation. The proof plane removes some charge from the surface it samples. If the proof plane is grounded after each measurement, the surface will be depleted of charge with consecutive measurements. However, by not grounding the proof plane (and by not letting it touch the ice pail), the charge on the surface is not depleted. That charge which the proof plane removed for one measurement is always returned to the surface when the next sampling is made.

NOTE: When the disk of the proof plane touches the surface being sampled, it essentially becomes part of the surface. To minimize distortion of the surface shape when sampling, hold the proof plane flat against the surface, as indicated in the accessory instructions. Please refer to the accessory instructions for details on how to use the proof planes.

Procedure:

1. Before starting, make sure the Faraday Ice Pail is properly grounded, with the shield connected to earth ground. The electrometer, connected to the pail, must also be grounded. Follow the setup in Figure 2.1, with the black lead connected over the edge of the shield and the red lead connected over the edge of the ice pail.

2. Place the two aluminum spheres at least 50 cm apart. Connect one of the spheres to the Electrostatic Voltage Source (ES-9077), providing 2000 VDC. The voltage source is to be grounded to the same earth ground as the shield and the electrometer. The connected sphere will be used as a charging body.

3. Momentarily ground the other sphere to remove any residual charge from it.

4. Start the demonstration by sampling and recording the charge at several different points on the sampling sphere. (The sphere that was grounded in step 2.) Choose points on all sides to represent an overall sample of the surface.

5. Now bring the 2000 VDC sphere close to the grounded sphere, until their surfaces are about 1 cm apart. Turn the voltage source ON, then sample and record the charge at the same points sampled before.

6. Momentarily ground the sampling sphere again, by touching one hand to the grounded ice pail shield and the other hand to the sphere. (Make sure the ice pail is grounded before doing this.) Again, sample and record the charge at the same points sampled before.

7. Remove the 2000 VDC sphere until it is at least 50 cm away from the sampling sphere. Again, sample and record the charge at the same points sampled before.

Analysis

1. What produced the charge distributions at each step of the experiment?
2. Why did any charge remain on the second sphere even after it was grounded?

Extra Things to Try

1. To show that the charge on a conductor always resides on the outside surface, bend a flexible sheet of metal into a cylinder. Charge the cylinder and measure the charge density in the inner and outer surfaces. Notice that charge is always on the outside.
2. To show how the surface shape affects charge density, try touching two charged proof planes together so that they are symmetrical around their point of contact. Measure the charge on each. Next touch them in an asymmetrical manner and measure the charge in each. Does one have more charge than the other? Which one? (Be sure to eliminate stray charges from necks and handles, to prevent erroneous readings.)

Figure 2.2: Test of Different Sampling Configurations

Demonstration 3: Capacitance and Dielectrics

Equipment Required:	
Electrometer (ES-9078)	Faraday Ice Pail (ES-9042A)l
Charge Producers (ES-9057B)	Proof Planes (ES-9057B)
Electrostatic Voltage Source (ES-9077)	Test leads
13 cm Conductive Spheres (2) (ES-9059B)	Variable Capacitor (Parallel Plates) (ES-9079)
Capacitor (about 30 pF) (ES-9043)	Sheet of dielectric material (See Table 3.1 for options)

Introduction

The purpose of this series of demonstrations is to investigate the relationship between charge, voltage and capacitance for a parallel plate capacitor. Each one of the variables will be held constant in turn, varying one of the others while measuring the third. The capacitance of a parallel plate capacitor is given by $C = \frac{\varepsilon A}{d}$, where ε is the dielectric coefficient, A is the plate area, and d is the plate separation. Various materials can be inserted between the plates to measure the dielectric coefficient of the materials.

NOTE: *At this point, the students should understand the theory of capacitors connected in parallel. If not, go to Procedure D of this demonstration.*

For all experiments, the electrometer can be thought of as an infinite impedance voltmeter in parallel with a capacitor, as shown in Figure 3.1. The capacitor C_E represents the internal capacitance of the electrometer, plus the capacitance of the leads.

Whenever you want quantitative measurements of charge, voltage or capacitance, you need to consider the effect of the internal capacitance of the electrometer, unless you are certain that the capacitor you are using has a high enough capacitance to disregard C_E. The capacitors in the PASCO RC Network (ES-9053), for example, are high enough that

C_E need not be considered. This is not true, however, when using the Basic Variable Capacitor (ES-9079).

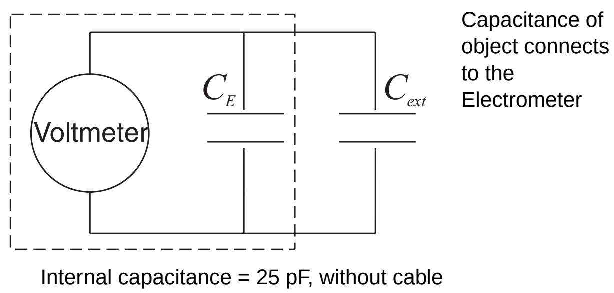

Figure 3.1: Ideal Schematic of the Electrometer

Procedure 3A: Measuring the Electrometer's Capacitance

Use this procedure to measure a precise value of the capacitance provided by the electrometer and all cables connected to it. If you are interested in qualitative, rather than quantitative experiments, this procedure is not necessary.

When a capacitor of known capacitance C is charged by a known voltage V, the charge in it is given by $Q=CV$.

If the known charged capacitor is connected across the leads of the electrometer, it is connected in parallel with the internal capacitance of the electrometer, C_E. The total capacitance becomes $C + C_E$.

The known capacitor will discharge across the electrometer and a voltage, V_E, will be read. Since the total charge in the system is still just the charge of the known capacitor, we know that $CV=(C + C_E)V_E$.

1. Obtain a low leakage (polypropylene, or air dielectric) capacitor of known value, C, around 30 pF.
2. Charge the capacitor with a known voltage V, not higher than 100 V (the limit of the electrometer).
3. Remove the charged capacitor from the power supply used to charge it, being careful not to ground it in any way, to avoid removing the charge.
4. Connect the charged capacitor across the electrometer input leads. Note the voltage V_E indicated by the electrometer.
5. Calculate the internal capacitance of the electrometer.

$$CE = \frac{(V - V_E)}{V} \cdot C$$

Procedure 3B: Measuring C, V and Q for a Parallel Plate Capacitor

The purpose of the experiments listed in this part is to qualitatively study the relationship between C, V, and Q for the parallel plate capacitor. Values read by the electrometer are to be used as relative, comparative measurements. The electrometer can be connected to a computer and used with a *ScienceWorkshop®* interface to obtain a graphical display of information.

3B.1: V Measured, Q Variable, C Constant

1. Figure 3.2 below shows the equipment set up. The Parallel Plate capacitor is connected to the electrometer. The electrometer is grounded to earth. One of the spheres is connected to the voltage source, set at 2000 VDC. Take care to place the capacitor sufficiently far away from the sphere and the voltage source, to prevent it from being charged by induction.

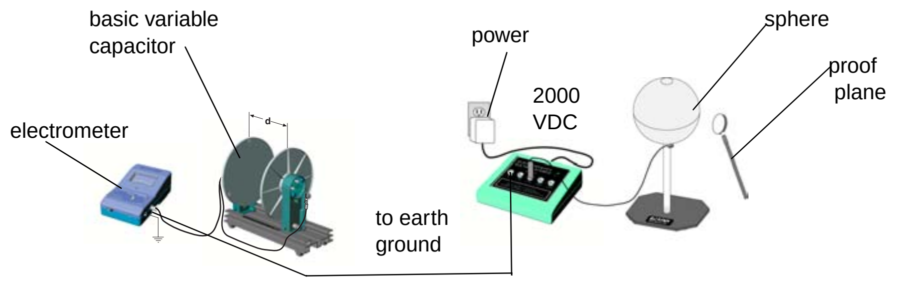

Figure 3.2: Demonstration Setup

2. Press the **ZERO** button to remove any residual charge from the electrometer and the plates of the capacitor.

3. Set the plate separation to about 2 mm. Use a proof plane to transfer charge from the charged sphere to the capacitor plates. The charge is transferred merely by touching the proof plane to the sphere and then to one capacitor plate. If you always touch the sphere and the capacitor plate at the same place, equal amounts of charge will be transferred each time.

   Question: Why is it sufficient to touch only one plate of the capacitor?

4. Observe how the potential difference reading from the electrometer varies as more charge is put in the capacitor.

5. Double the plate separation and repeat the experience. What happens to the potential now? Compare the values to the previous case.

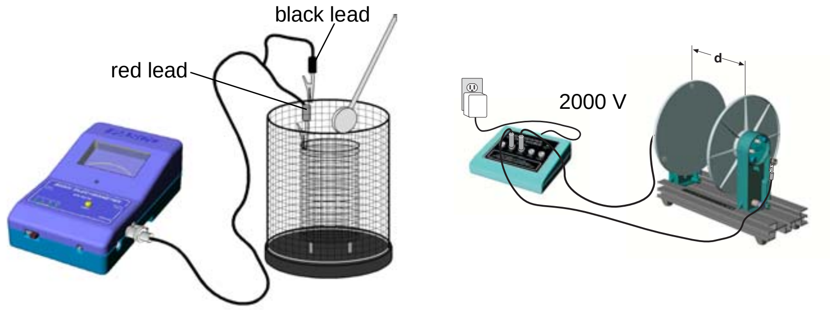

Figure 3.3: Demonstration Setup

3B.2: Q Measured, C Variable, V Constant

1. Figure 3.3 above shows the equipment set up. The Parallel Plate capacitor has an initial plate separation of 6 cm and is connected to the voltage source, set at 2000 VDC. The Faraday Ice Pail is connected to the electrometer, and the electrometer is grounded to earth.
2. Momentarily ground a proof plane and then use it to examine the charge density of the capacitor, using the ice pail to measure the charge. Investigate the charge density at various points on the plates — both on the inner and the outer surfaces. How does the charge density vary over the plate?

3. Choose a point near the center of one capacitor plate and measure charge density in this area at different plate separations. (Keep in mind whether you are increasing or decreasing the capacitance by moving the plates.) How does the charge vary with capacitance?

3B.3 Q Measured, V Variable, C Constant

1. Figure 3.3 shows the equipment set up, which is identical to the setup for B2. The Parallel Plate capacitor has an initial plate separation of 6 cm and is connected to the voltage source, set initially at 3000 VDC. The Faraday Ice Pail is connected to the electrometer and the electrometer is grounded to earth.
2. Keep the plate separation constant and change the potential across the plates by changing the setting of the voltage source. You have

to move the connecting cable from the 3000 V to the 2000 V slot. Examine the charge density near the center of one capacitor plate. How does the charge vary with the voltage? Repeat with 1000 VDC.

3B.4: V Measured, C Variable, Q Constant

1. Figure 3.4 shows the equipment set up. The Parallel Plate capacitor is connected to the electrometer and the electrometer is grounded to earth. The voltage source will be used to only momentarily charge the capacitor.

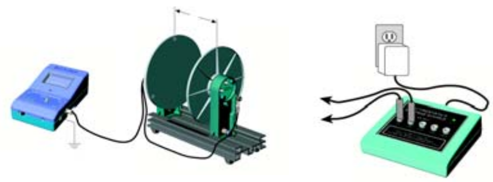

Figure 3.4: Demonstration Setup

2. With the plate separation at 2 mm, charge the plates by momentarily connecting them across the voltage source, set at 30 V. Adjust the scale sensitivity of the electrometer so that the initially charged plates represent a meter reading of about 1/5 scale.

3. Increase the plate separation and note the electrometer's readings at various separations. How does the potential vary with capacitance?

NOTE: An alternative method is to charge one of the spheres and then transfer some charge to the capacitor. The charge, however, will not be as high.

Procedure 3C: Dielectric Coefficients

The dielectric coefficient κ is the dimensionless factor by which the capacitance increases (relative to the value of capacitance before the dielectric) when a dielectric is inserted between the plates. It is a fundamental property of the dielectric material and is independent of the size or shape of the capacitor. Table 3.1 on page 28 lists the dielectric coefficients of some common materials.

The ideal procedure to measure κ would be to simply slip a piece of dielectric material between a set of charged capacitor plates and then note the changes in potential. However, sliding a dielectric between the plates of the capacitor when they are too close together can generate a significant static charge that will alter the measurements. Hence, it is best to proceed as follows:

NOTE: Depending on the model of parallel plate capacitor you have, there may be only one plate that is movable. If your model allows both plates to be moved, choose one to keep fixed and the other to be the movable one.

1. Connect the electrometer across the plates of the capacitor and set the separation between the plates to about 3 mm.
2. Raise the side of the set up nearest the movable plate by setting a block about 3 cm high below it, as shown in Figure 3.5.
3. Use the voltage source to momentarily touch the plates and charge them to about 4/5 full scale. Record the voltage reading of the electrometer, V_i.

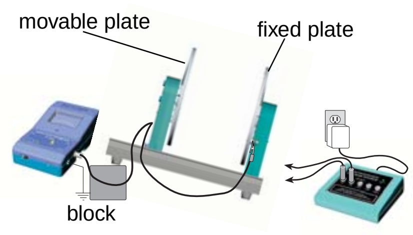

Figure 3.5: Experimental Setup

4. Carefully increase the separation of the plates until it is enough to insert the dielectric without forcing it. It should be enough so that you can simply lean the dielectric sheet against the stationary plate. Make sure the dielectric you are using is free of residual charge before inserting it.
5. After inserting the dielectric, return the plates to the original 3 mm separation and record the new electrometer reading, V_f.
6. Pull the plates apart again, and lift and carefully remove the dielectric sheet.
7. Return the plates to the original 3 mm separation and check that the electrometer reading agrees with the original V_i reading.

Analysis:

The calculations needed to determine the dielectric constant are long, but straight forward:

Figure 3.6: Circuit diagrams with and without the dielectric

Before inserting the dielectric...

Let q_p be the charge on the capacitor plates, and C_p be the capacitance of the plates, without the dielectric.

Let q_E be the charge on C_E, the internal capacitance of the electrometer.

Let V_i be the initial reading of the electrometer.

The total charge in this initial system is given by

$q_P + q_E = (C_P + C_E)V_i$

After inserting the dielectric…

Let q'_p be the new charge on the capacitor plates; the capacitance is now C'_p.

Let q'_E be the new charge on C_E, the internal capacitance of the electrometer. Since there is no dielectric in C_E, its value is still the same.

Let V_i be the new reading of the electrometer.

The total charge in the system after inserting the dielectric is given by

$$q'_p + q'_E = (C'_p + C_E)V_f$$

Now, the total amount of charge in the system was never changed, so

$$q_p + q_E = q'_p + q'_E$$

and $(C_p + C_E)V_i = (C'_p + C'_E)V_f$

After some algebra and rearranging, you find that

$$\frac{C'_p}{C_p} = \frac{C_E(V_i - V_f) + C_p V_i}{C_p V_f}$$

where the ratio (C'_p / C_p) is the dielectric coefficient κ :

$$\kappa = \frac{\varepsilon A_d}{\varepsilon_O A_d} = \frac{C'_p}{C_p}$$

Table 3.1: Some Dielectric Coefficients

Material	κ
Vacuum	1
Air	1.00059
Polystyrene	2.6
Paper	3.7
Pyrex	4.7
Mica	5.4
Porcelain	6.5

Procedure 3D: Capacitors in Series and in Parallel

The purpose of this demonstration is to examine the effect of placing capacitors in series and in parallel. You will need two capacitors of known value (between 200 - 400 µF, to ignore the internal capacitance of the electrometer), a DC voltage source, the electrometer, some cables, and a double throw switch.

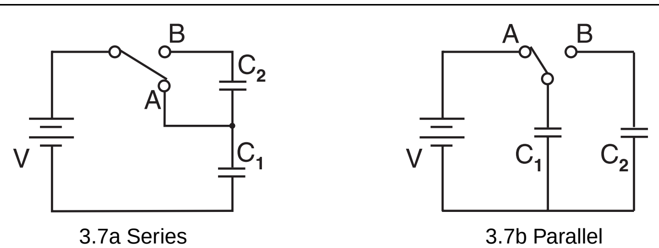

Figure 3.7: Circuit Diagrams

3D.1: Capacitors in Series

Make sure all capacitors are uncharged before connecting them. (Use a short wire to momentarily short each one.)

1. Set up the series circuit, as shown in Figure 3.7a.

2. Plug in to the 30 VDC output on the Voltage Source. Close switch A to charge capacitor C1.

3. Using the known value of C_1, calculate the initial amount of charge on C_1. Let's call it Q_o. (Remember Q=CV.)

4. Throw the switch to position B. C_1 and C_2 are now in series.

5. Use the electrometer to measure the voltage drop across each of the capacitors (V_1 and V_2).

6. Using the known values of capacitance, determine the amount of charge in each of them. (Q_1 and Q_2).

7. Questions: Can you find a relation between V_1, V_2 and the voltage of the source? How does Q_1 and Q_2 relate to the original charge on C_1?

3D.2: Capacitors in Parallel

1. Make sure all capacitors are uncharged before connecting them to the circuit.

2. Set up the parallel circuit, as shown in Figure 3.7b.

3. Set the voltage source to 30 VDC. Close the switch to charge the capacitors.

4. Use the electrometer to measure the potential difference across each of the capacitors. How does it compare to the voltage of the source?

5. Use the known value of the capacitances to determine the charge in each capacitor. How are the charges related?

Analysis:

1. Compare series and parallel capacitors in terms of charges, voltages and capacitance.