PHYS 40C: Lab 4
Capacitors
(Includes Pre-Lab Assignment)

Objectives

In this lab, you will first explore the relationship between capacitance and the plate separation of a single parallel-plate capacitor. You will then place another capacitor in series and measure the effects of plate separation on the capacitance as a system. Finally, you will introduce a dielectric between the capacitor plates and calculate the dielectric constant of that material.

Introduction

A capacitor is an electrical device that stores electric potential energy. There are different configurations and geometries, but the most basic capacitor consists of two parallel metal plates. One of the plates can be charged positively and the other can be charged negatively by connecting to the appropriate terminals of a voltage source such as a battery. In both plates, the charges are squeezed together against the repulsive forces between the neighboring charges. This means that something did work to counteract the Coulombic repulsive force and bring the charges together. This work is stored as electric potential energy in the capacitor. It can be recovered as kinetic energy via moving charges (current) when the capacitor is discharged.

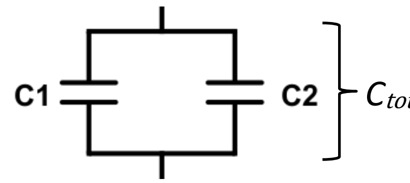
The standard picture of a capacitor is two parallel plate electrodes on which the charge is stored. Such a capacitor has a capacitance with units of Farads (F).

$$C = \frac{\kappa \varepsilon_0 A}{d} \quad \text{(Eq. 1)}$$

where *A* is the plate area, *d* the plate separation, κ is the *dielectric constant* of the material between the plates, and ε_0 = 8.85 pF/m is the permittivity of free space.

Measuring Capacitors in Parallel

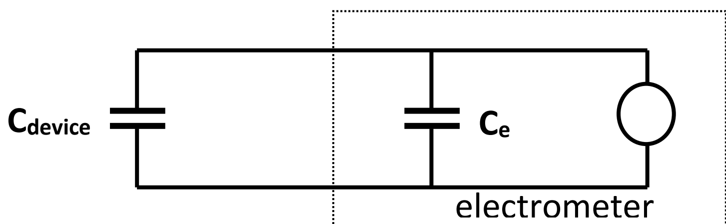
As a general rule, when two capacitors are in *parallel* configuration in an electric circuit (see right), the combined capacitance is determined by a linear sum:



$$C_{tot} = C_1 + C_2$$

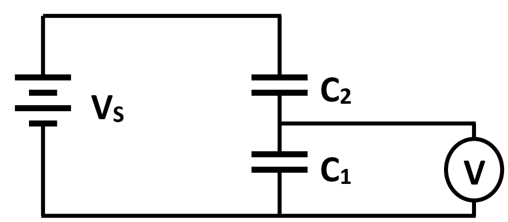
You will use an electrometer (a special kind of voltmeter) to measure the potential difference across an external capacitor. By connecting the electrometer, an additional capacitance is introduced in *parallel* with the device under study as shown in the figure below. This electrometer capacitance, C_e, results from the internal capacitance of the electrometer and the capacitance of the cable used to measure the voltage. Every time you use the electrometer to measure the voltage across a capacitor, you are measuring:

$$C_{tot} = C_e + C_{device} \quad \text{(Eq. 2)}$$



For the electrometers and cables you will use in this lab, C_e = 84 pF. Whenever a capacitance is probed with the electrometer, this value of parallel input capacitance of the electrometer and cable *must* be included.

Measuring Capacitors in Series

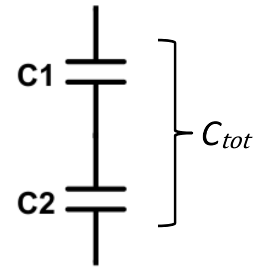


In Part 2, you will use a circuit like the one shown at right to measure the relative size of two capacitors. If C_2 is known, applying a source voltage V_s across the capacitors induces a charge Q on each. If the voltage across C_1 is V, then the voltage across C_2 is V_s-V, so, since we know $Q = CV$:

$$Q = C_1 V = C_2(V_S - V) \text{ or } C_1 = C_2 \frac{(V_S - V)}{V} \qquad \text{(Eq. 3)}$$

Remember that for your experiments, $C_1 = C_e + C_{device}$!

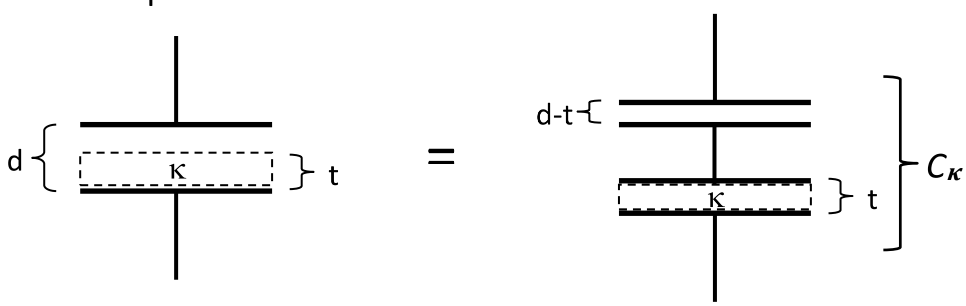
Measurement of the Dielectric Constant



As a general rule, when two capacitors are in *series* configuration in an electric circuit (see right), the combined capacitance can be determined by an inverse sum:

$$\frac{1}{C_{tot}} = \frac{1}{C_1} + \frac{1}{C_2}$$

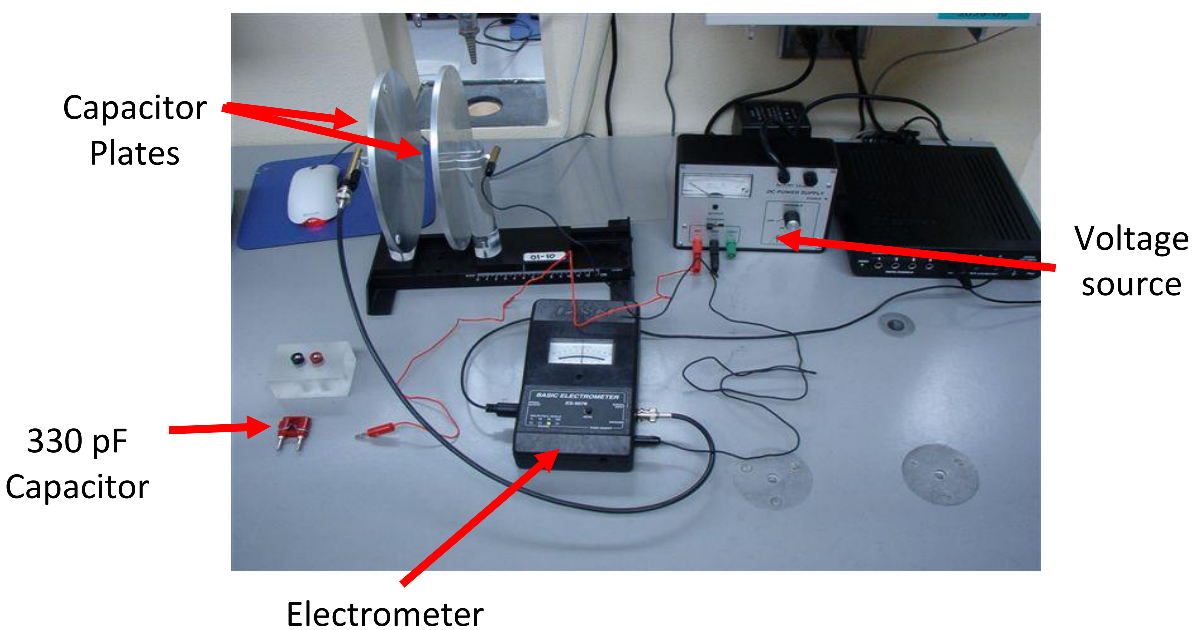
As discussed above, for a capacitor *without* any material present between two parallel plates, the capacitance is given by Eq. 1 with κ = 1. When the capacitor gap is partially filled with a dielectric with constant κ as shown below, the material, with thickness *t*, and the remaining gap, with thickness *d-t*, can be regarded as two capacitors connected in series.



The equivalent capacitance across both elements, which we will call C_κ, is:

$$\frac{1}{C_\kappa} = \frac{1}{\frac{\kappa\varepsilon_0 A}{t}} + \frac{1}{\frac{\kappa\varepsilon_0 A}{d-t}} \quad \text{(Eq. 4)}$$

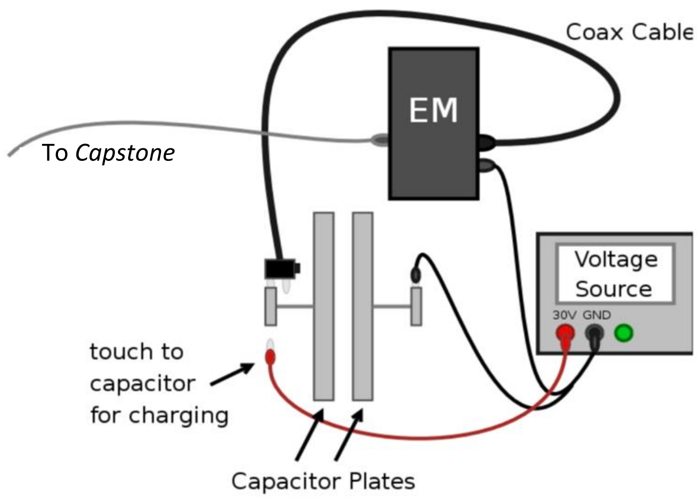
Experimental Apparatus:



1. Single Capacitor

In this section, you will measure the voltage across the capacitor apparatus at a series of different separation distances to develop an understanding for how the amount of charge stored in a capacitor varies according to Eq. 1.

1.1: Turn on the 850 Universal Interface and ensure the electrometer is plugged into "Analog Input Pin 1". Open the *Capstone* template corresponding to this week's lab. With the voltage source and the electrometer turned off, assemble the circuit shown to the right.



1.2: Once the circuit has been assembled, draw a circuit schematic to represent the apparatus. Treat the electrometer like a capacitor and be sure to indicate across which elements voltage is measured. Check your drawing with your TA before proceeding.

1.3: You are now ready for voltage measurements. Move the capacitor plates to be 5 cm apart and turn on the electrometer.

NOTE: When the capacitor plates are close together, there exists a 1.0 mm gap between the plates which can been measured with a ruler. Remember to account for the offset when setting the distance between the plates.

1.4: Zero the electrometer by hitting the "Zero" button on the electrometer. Hit the "Record" button in *Capstone* and turn on the 30 V-DC voltage source. Touch the voltage lead from the voltage source to the non-grounded plate of the capacitor. Turn off the voltage source.

1.5: Record the voltage at 5 cm in your data table. Then carefully and quickly adjust the spacing between the plates to 4 cm and record the voltage.

NOTE: Be careful to move as little as possible during the measurement. Any static charge can affect the measurement. Also, work quickly to avoid loss of charge.

1.6: After recording the voltage, return the spacing to 5 cm and recharge the capacitor by following step 1.4. Record the voltage for the remaining gap values. Be sure to return the spacing to 5 cm and recharge before continuing to the next gap distance. When you are finished collecting data, hit "Stop" in *Capstone* to end voltage measurements.

1.7: Rearrange the relation below into $y = mx + b$ form with $y = (1/V1)$ and $x = (1/d1)$. This is a statement of "$Q = CV$" with Eq. 1 and Eq. 2 plugged in for C.

$$Q = \left(C_e + \frac{\varepsilon_0 A}{d}\right) V$$

1.8: In the graph display, set the y-axis as "1/V1" and x-axis as "1/d1". Add a linear fit to the graph. Determine charge Q using the intercept from the fit. Take a snapshot of your screen so that you may print it later.

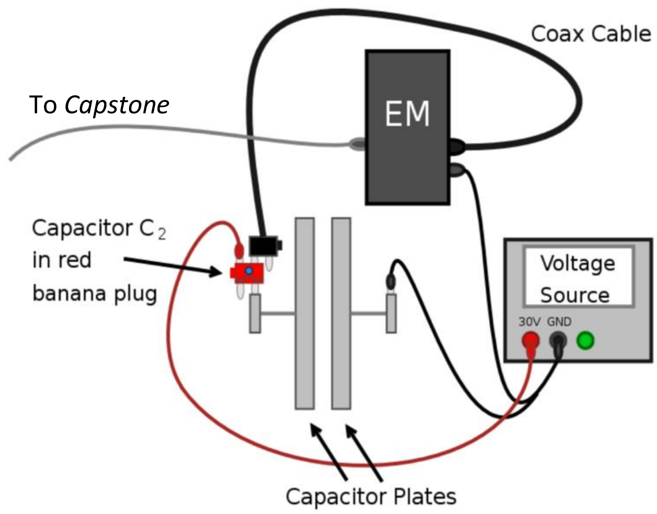
- Looking at your graphed data, can you infer anything about the charge lost from the time you charge the capacitor to the time you record the voltage after adjusting the separation distance? Explain.

Thought Experiment: What would happen if the separation distance was increased or decreased when you charged the capacitor? Do the plates maintain the same amount of charge? Why or why not?

2. Capacitors in Series

In this section, you will measure the capacitance of your capacitor apparatus as a function of distance by taking advantage of the relation between two capacitors in series shown in Eq. 3. You will use a capacitor of known value for C_2.

2.1: With the voltage source and the electrometer turned off, assemble the circuit shown on the following page by connecting the voltage source across the capacitor and adding the 330 pF capacitor in series. Once the circuit has been assembled, turn on the electrometer. In *Capstone*, switch to the "Part 2: Capacitors in Series" page.



2.2: Draw a circuit schematic to represent the apparatus. Treat the electrometer like a capacitor and be sure to indicate across which elements voltage is measured. Check your drawing with your TA before proceeding.

2.3: Remove the voltage lead to the 330 pF capacitor and briefly connect to the voltage source ground to discharge the capacitor.

2.4: Replace the voltage lead to the 330 pF capacitor, and zero the electrometer by hitting the "Zero" button on the electrometer.

2.5: Set the capacitor plates to a gap value of 5 cm. Turn on the voltage source and record the voltage in your data table.

2.6: Repeat steps 2.3 through 2.5 for the remaining gap values. Do not return the spacing to 5 cm to recharge before continuing to the next gap distance.

2.7: In your data table, you have a column labeled "C_{device}". You will have to input the calculation yourself. Open the "Calculator" panel on the left side of the screen and do so now. Note that it should combine Eq. 2 and 3. (Hint: Do your calculations in pF, and don't forget to incorporate the electrometer capacitance!)

2.8: In the graph display, set the y-axis as "C_{device}" and x-axis as "1/d2". Apply a linear fit to your graph and write down the best-fit equation. To what physical values does the slope of the fit refer? Take a snapshot of your screen and then print both of your snapshots (from steps 1.8 and 2.8).

3. Changing the Dielectric

In this section, you will demonstrate the effect of the dielectric medium between the parallel plates on the capacitance value.

3.1: For this final experiment, we will be using the same circuit used in Part 2. In *Capstone*, switch to the "Part 3: Changing the Dielectric" page. We are again ready for voltage measurements.

3.2: Draw another circuit schematic to represent the apparatus. Represent the capacitor apparatus as two capacitors in series as described in the introduction and be sure to indicate across which elements voltage is measured. Check your drawing with your TA before proceeding.

3.3: Remove the voltage lead to the 330 pF capacitor and briefly connect to the voltage source ground to discharge the capacitors.

3.4: Replace the voltage lead to the 330 pF capacitor, and zero the electrometer by hitting the "Zero" button on the electrometer.

3.5: Select a plastic sheet. Using a ruler, record the thickness of the sheet, t, and calculate $d = t+1$ mm. Place the sheet between the two capacitor plates. Make d as small as possible by pressing the plates together. Press just hard enough so the sheet is held in place. If you press the plates too close together, d will change when the sheet is removed.

3.6: Re-zero the electrometer. Turn on the voltage source and record the voltage in your lab notebook. Label this voltage as V_κ. Turn off the source.

3.7: Now you have enough information to be able to calculate the dielectric constant of the plastic sheet material. To do this, you will use the equation you derived in the pre-lab, meaning you need values for A, t, C_κ, and C_0.

3.7.1. First calculate A. Use a ruler to measure the dimension of the circular plates and calculate the surface area in m^2.

3.7.2. Now calculate C_κ using the same method as was used in Part 2. Use C_e = 84 pF, C_2 = 330 pF, V_S = 30 V, and your measured value of V_κ from 3.6.

3.7.3. Now determine a value for C_0. To do this, reference the best-fit linear equation that you found in Step 2.8. Determine C_0 for the separation distance found in 3.5 (which is synonymous with the *y* term in the fit) by plugging in 1/d (which is synonymous with the *x* term in the fit).

3.7.4. You should now have all the information you need to plug values into the equation from your pre-lab assignment, in which you solved for $1/\kappa$. Plug in your values and determine κ.

- *Thought Experiment:* What would happen if you put two different materials in between the parallel plates of your capacitor? With one material, we modeled the system as two capacitors in series. Draw and describe what the model might look/function like with another material (with a different dielectric constant).

Write a brief summary of the experiment you performed today. In your summary, think about the following questions:

- What is capacitance?
- Why are capacitors important devices to allow us to control location and interaction of charges for use in electrical circuits?
- Today we studied parallel plate capacitors, meaning the capacitance was dependent on the distance between the plates and the area of the plates. Think about a different geometrical configuration (maybe think about what geometries you studied in last week's "Equipotential Mapping" lab). What geometric properties will affect the capacitance of this different configuration?
- How significantly would your measurements and calculations have been changed if you did not include the electrometer capacitance (C_e) term? Discuss.

Pre-Lab Assignment (1 point)

1. Suppose a parallel plate capacitor (with capacitance C_0) is fully charged (to a value Q_0) by a battery. The battery (which supplies a potential difference of V_0) stays connected to the capacitor. If the plates of the capacitor are then moved further apart such that the separation distance, d, between the plates is tripled, describe ***quantitatively*** what happens to:
    a. The capacitance of the capacitor
    b. The potential difference between the plates
    c. The energy stored in the capacitor
    d. The stored charge on the plates.

2. A heart dysfunction that can cause death is ventricular fibrillation. This is an uncoordinated quivering of the heart as opposed to regular beating. An electric shock to the chest can cause momentary paralysis of the heart muscle, after which the heart will sometimes start organized beating again. A defibrillator is a device that applies a strong electric shock to the chest over a time of a few milliseconds. The devise contains a capacitor of several microfarads, charged to several thousand volts. Electrodes called paddles, about 8 cm across and coated with conducting paste, are held against the chest on both sides of the heart. Their handles are insulated to prevent injury to the operator, who calls “Clear!” to warn others to stand clear of the patient and then pushes on one paddle to discharge the capacitor through the patient’s chest.

    Assume that the capacitor in the defibrillator is 10.0 μF and is charged to 5,000 V.

    a. How much charge is stored in the capacitor before it is discharged?
    b. How much energy is released when the capacitor is discharged?
    c. If the capacitor completely discharges in 2.5 ms, what is the average current delivered by the defibrillator?