General Physics II Lab (PHYS-2021)
Experiment ELEC-6:
Capacitance

Objective:

The purpose of this experiment is to investigate how the capacitance of a parallel-plate capacitor varies when the plate separation is changed and to qualitatively see the effect of introducing a dielectric material between the plates. A computer model of the system will be developed and the student will observe some of the power of computer modeling.

Theory:

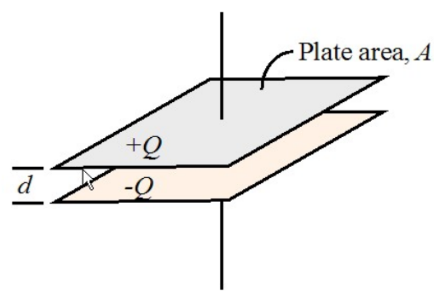
A capacitor is used to store charge. A capacitor can be made with any two conductors kept insulated from each other. If the conductors are connected to a potential difference, V, as in for example the opposite terminals of a battery, then the two conductors are charged with equal but opposite amount of charge Q, which is then referred to as the "charge in the capacitor."

$$C = \frac{Q}{V}$$

Rearranging gives:

$$V = \frac{Q}{C} \tag{1}$$

The simplest form of a capacitor consists of two parallel conducting plates, each with area A, separated by a distance d. The charge is uniformly distributed on the surface of the plates. The capacitance of the parallel-plate capacitor is given by:



$$C = \kappa\epsilon_0 \mathrm{A}/\mathrm{d}$$

Where κ is the dielectric constant of the insulating material between the plates ($\kappa = 1$ for a vacuum; other values are measured experimentally and can be found in tables), and ϵ_0 is the permittivity constant, of universal value $\epsilon_0 = 8.85 \text{ x } 10^{-12}$ F/m. The SI unit of capacitance is the Farad (F).

The system we use is more complex. In addition to the two moveable parallel plates, the connecting wires and the electrometer also have some capacitance. This capacitance is roughly equal to the capacitance of the moveable plates when the plates are 1 cm apart and cannot be ignored. Including this gives:

$$C = \kappa\epsilon_0 \mathrm{A}/\mathrm{d} + C_{sys} \tag{2}$$

where C_{sys} is the capacitance of the rest of the system. Substituting Equation (2) into Equation (1) yields:

$$V = Q/(\kappa\epsilon_0 \mathrm{A}/\mathrm{d} + C_{sys}) \tag{3}$$

Dielectrics Theory:

Any material placed between the plates of a capacitor will increase its capacitance by a factor κ called the dielectric constant where:

$$C = \kappa C_0 \tag{4}$$

with C_0 being the capacitance when there is a vacuum between the plates of the capacitor. Dielectric materials are non-conductive. Any dielectric material can be used to keep the plates in a capacitor insulated from each other (preventing them from touching and discharging). To three significant figures, $\kappa = 1.00$ for air. For all materials, $\kappa > 1$. If the charge on a capacitor is kept constant while a dielectric is inserted between the plates, Equations 1 & 4 yield:

$$Q = CV = C_0V_0 = C/(\kappa\epsilon_0 V_0)$$

so,

$$V = V_0/\kappa$$

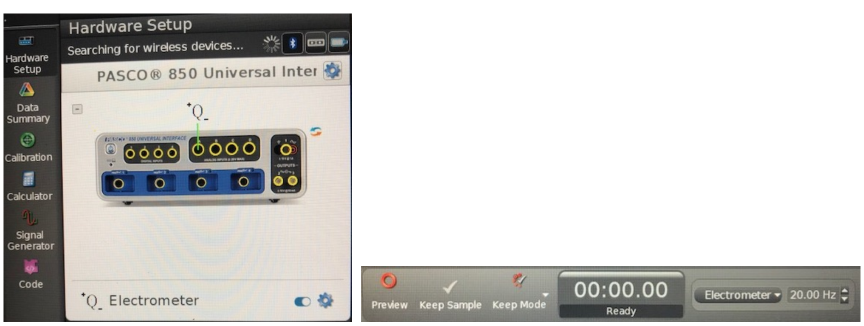
Where V_0 is the voltage before inserting the dielectric and V is the voltage after insertion. Then we now have

$$V = V_0/\kappa \tag{5}$$

since $\kappa > 1$ always.

Procedure A: The Effect of the Plate Separation

1. Verify your *PASCO 850 Universal Interface* is ***ON***.
2. Turn ***ON*** the *Electrometer* and set the range button to the 100 V scale.
3. Turn ***ON*** the *Voltage Source*, located in the back of the device.



(a) Output Voltage Sensor (b) Common Sample Rate

Figure 1: Setup

4. Click the *Hardware Setup* tab on the left side of the screen. Verify that Analog Input A on your PASCO Interface is has the Electrometer selected as shown in Figure 1(a).
5. On the bottom of the screen, set the Mode to *Keep Mode* as shown in Figure 1(b).
6. In PASCO Capstone, create a table and create a user-entered data set called Separation with units of cm. Enter the values shown in Table I. Select the Voltage measurement in the second column.
7. Set the capacitor plates 0.3 cm apart by setting the movable plate so leading edge of its indicator foot is at the 0.3 cm mark.
8. Remove any charge from the capacitor by momentarily touching both plates at the same time with your hand or using the copper pad provided.
9. Zero the electrometer by pressing the 'ZERO' button until the needle goes to zero.
10. Use the red cable connected to the +30V outlet in the voltage source and touch the free end to the back of the movable capacitor plate. This will charge the capacitor.
11. Read the following steps. They need to be performed quickly since the charge will slowly escape from the electrometer, especially if the humidity is high. One person should run the computer while one moves the capacitor plate. Everyone else should stay back. Everyone should try to be in the same position for each reading. Anybody who is close is a significant part of the system and can make the readings change.
12. Slide the movable plate so it is at 8.0 cm (leading edge of the indicator foot). Once the plate is in position, the person moving the plate should move away 50 cm or so and try to be in the same position for each measurement.
13. In Capstone, click the PREVIEW button at the lower left to begin collecting data. Colored numbers will appear in first row of the table. The person doing the computer should click the Keep Sample (red checkmark in the lower left) button. The number in the first row will turn black and the colored number will move to the second row. The person at the computer should read the next separation (7 cm) out loud and wait.
14. Move the plate to 7.0 cm and repeat the process until 0.3 cm.
15. Click the STOP button to end the data collection.
16. Examine the graph. If it looks like a smooth curve, you are done. If not, repeat the process until you get a nice looking run.
17. After you have finished comparing the model to your experimental curve, print your results to the Departmental Printer in Brown Hall 262 to turn in as part of your lab report. Remember, you will have to first log in to the wireless on the laptop. Your instructor will show you how to do that.

Analysis A

Recall from Equation 3 in the Theory section A, it was shown that if $C_{sys} = 0$, then V is directly proportional to d and the Voltage vs. Separation graph on the Data page should be a straight line. This is clearly not the case. To verify Equation 3 for the case where C_{sys} is not zero, we need to know Q and C_{sys}. We determine these by fitting the math model (Equation 3) to the data.

First we note that

$$\kappa\epsilon_o A = (1.00) * (8.85x10^{-12} F/m)(2.46x10^{-2} m^2) = 2.18x10^{-13} Fm = 2.18x10^{-11} Fcm.$$

the parallel plate capacitance when d = 1 cm is $C_{1.0} = 2.18\text{x}10^{-11}$ F. Note that this value is entered in line 2 of the Calculator.

When d is small (0.3 cm) the first term in the denominator dominates and

$$Q \sim V_{0.3}(\kappa\epsilon_o A)/d = (30V) * (2.18x10^{-11} Fcm)/(0.3cm) = 2.2x10^{-9} C.$$

This value is entered as an initial guess for the value of Q in line 1 of the calculator. Q is constant so when d becomes large, C_{sys} dominates in the denominator and we have:

$$C_{sys} \sim Q/V_8 \sim 2.2x10^{-9} C/80V = 2.7x10^{-11} F$$

Where V_8 is the voltage when d = 8 cm. This is taken as the initial guess for C_{sys} ($=C_1$) on line 3 of the calculator.

Note that C_{sys} is about equal to $C_{1.0}$ at 1.0 cm. At 0.3 cm, $C_{0.3} = 7\text{x}10^{-11}$ F so $C_{0.3} \sim 3\ C_{sys}$ and the approximation above is decent but not great. At 8 cm C8 = $2.7\text{x}10^{-12}$ F = C_{sys} /10, so the approximation is good, but not perfect.

1. In the Calculator, create the following calculations:
   `Q = 3.0 * 10`$^{-9}$ `# Units of C`
   $\kappa\ \epsilon_o$ `A = 2.18 * 10`$^{-11}$ `# Units of (F cm)`
   C_1 `= 3.6 * 10`$^{-11}$ `# Units of F`
   `V model = [Q]/([`$\kappa\ \epsilon_o$ `A]/[Separation] + [`C_1`])` `# Units of V`

   NOTE: Figure 2 on page 6 shows where to find Greek Letters in Capstone.

2. Use the Data Display button to overlay the model data over your experimental results.

3. Adjust the values for Q on line 1 of the Calculator and for C_1 on line 2 to make the model match the experimental curve as well as possible.

Procedure B: The Effect of a Dielectric between the Plates

1. In PASCO Capstone, open a new page and create a Digit Display for the Voltage measurement. Enter your results in Table 2.
2. You will use cardboard as the dielectric to be inserted between the plates.
3. Position the movable plate of the capacitor at 8 cm.
4. Turn on the electrometer and set the range button to the 100 V scale.
5. Remove any charge from the capacitor by momentarily touching both plates at the same time with your hand or by using the copper pad.
6. Zero the electrometer by pressing the 'ZERO' button. The needle must be at zero.
7. Use the red cable connected to the +30V outlet in the voltage source and momentarily touch the free end to the back of the movable capacitor plate. This will charge the capacitor.
8. Click on the PREVIEW button.
9. One student holds the cardboard directly above the gap between the capacitor plates so that the long side is vertical. Hold the cardboard with one hand and keep the other hand on the metal connector attached to the signal input of the Electrometer so that there is no static charge on the student holding the paper. Press the Keep Sample button to record the voltage when the paper is not between the plates.
10. Lower the cardboard between the two plates until it touches the base. Do not let the cardboard touch either plate! Keep your hand as far above the plates as possible. Press the Keep Sample button to record the voltage when the cardboard is between the plates.
11. Pull the cardboard back above the plates and repeat steps 8 and 9 several times.
12. Click the STOP button to stop monitoring the data.
13. If the final voltage with the cardboard out is much different from the initial cardboard out value, you probably touched the plates and should repeat the experiment.

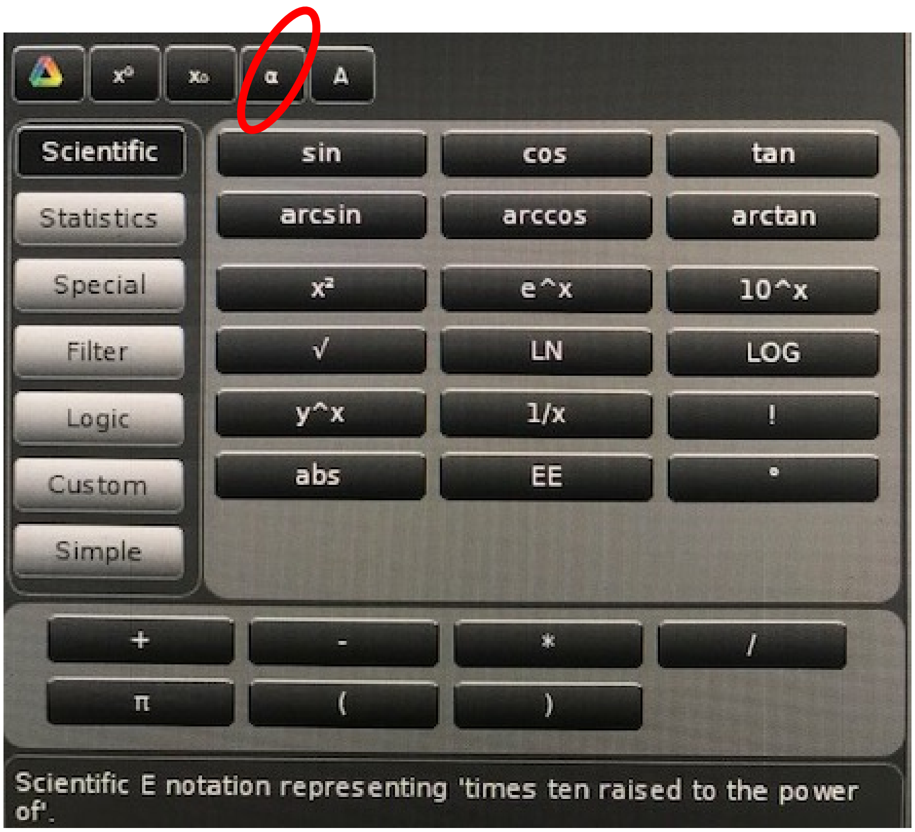


Figure 2: Greek letters in Capstone for calculations.