E&M Lab 4: Conductors and Capacitors

Experiment Overview

In this lab, you'll investigate the electric potential near charged conducting objects, and experimentally confirm that a parallel-plate capacitor behaves as theoretically predicted. The theory says that for any capacitor,

$$Q = C\,V \qquad (1)$$

where Q is the charge on the capacitor, C is its capacitance in farads, and V is the voltage across it.

Our biggest challenge with this lab is that charge Q is not easy to measure. We will make use of a reference capacitor, whose stored charge is known, and make indirect comparisons with other objects.

In class, I showed that the capacitance of a parallel-plate capacitor was:

$$C = \frac{\varepsilon_0 A}{d} \qquad (2)$$

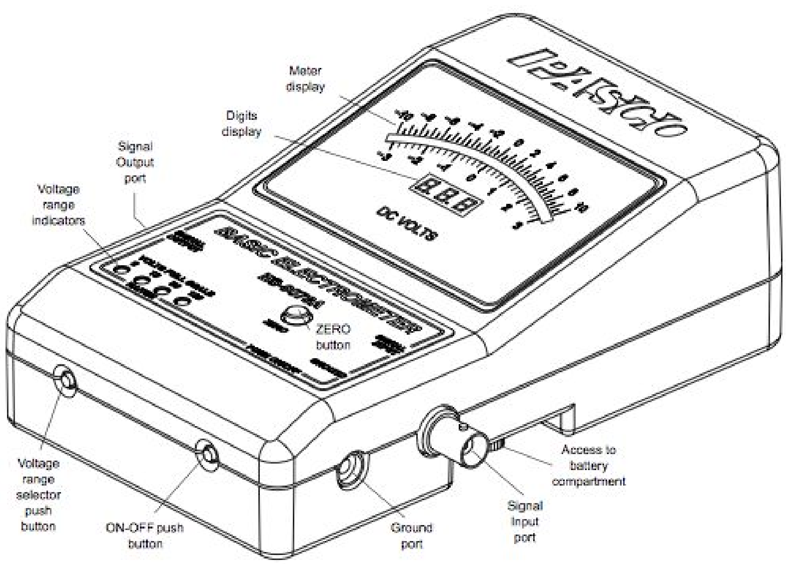
where *A* is the area of the plates, *d* is their separation, and $\varepsilon_0 = 8.85 \times 10^{-12}$ in SI units.

You'll test equations (1) and (2) with two mini-experiments.

As a third mini-experiment, we will revisit the charged balls from the Coulomb's Law experiment. In that experiment, we assumed that the charge on the ball was related to its voltage according to the relationship $q = C\,V$, where *C* = 2.11e-12 coulombs/volt, or Farads. However, the voltage reading on the power supply we used isn't particularly accurate. So in the third mini-experiment, we will measure the charge on the ball directly.

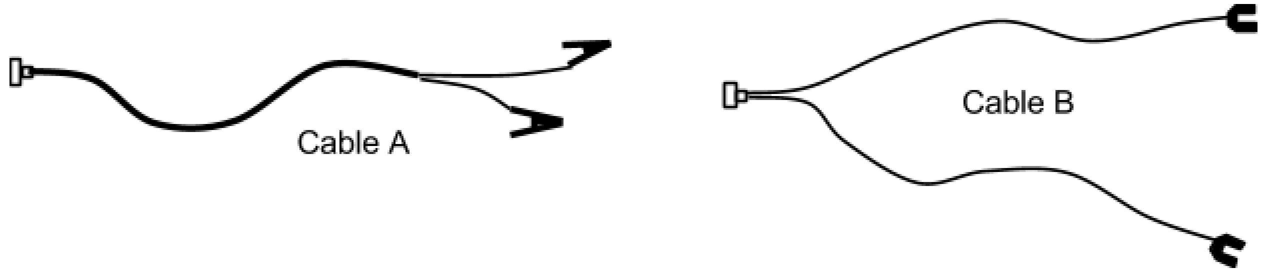
Equipment

Electrometer: This is similar to the voltmeters you've used in Intro Physics: it measures the difference in electric potential between two objects. However, this one is specially designed to allow zero current to flow through it, so it can measure voltage without allowing the charges that create that voltage to move.



Signal Input Cables: The

electrometer comes with two signal input cables: one has alligator clips on the end (Cable A), the other has spade terminals (Cable B).



Variable Parallel Plate Capacitor: Two circular parallel metal plates 9 cm in radius, whose separation can be adjusted. At their closest, they are 1 mm apart; in general, the separation distance can be read off the scale on the base.

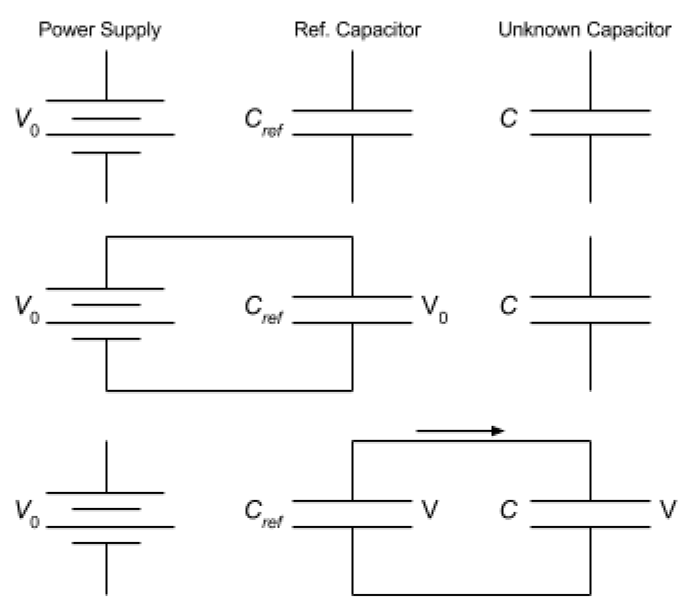
Reference Capacitor: This capacitor has a known capacitance of 33 picofarad (pico = 10^{-12}): other capacitors will be compared to it.

Low-voltage Power Supply: Just two 9-volt batteries connected in series. You should measure the voltage: it won't be exactly 18 volts.

Background: Measuring an Unknown Capacitance

Here's how to use a reference capacitor to measure an unknown capacitor. Suppose the reference capacitor is C_{ref}, the unknown capacitor is C.

1) Measure the voltage created by your low-voltage power supply (batteries). It might not be exactly 18 volts! Call this V_0.
2) Remove all charge from your unknown capacitor. You can do this by touching the two sides of the capacitor together, or just by bridging the two sides with your finger (your finger is a decent conductor.)
3) Touch the two leads of your capacitor to the low-voltage power supply, charging it up to V_0. It is now storing a charge $Q = C_{ref} V_0$.
4) Remove the power supply and touch the two leads of your capacitor to the two sides of the unknown capacitor. Some of the charge will flow onto the unknown capacitor, until both have the same (smaller) voltage V. Since no charge was lost, the total charge on the two capacitors will add up to Q.
5) Because the total charge before and after is the same, you can (and will) show that



$$C = C_{ref} \frac{V_0 - V}{V} \qquad (3)$$

Experiment 4.1: Measuring Capacitance of a Parallel Plate Capacitor

Please read Appendix A, Tips for Accurate Results before beginning!

We will verify equation (2) by measuring the capacitance of a parallel plate capacitor for a variety of plate separations *d*. We will use the "reference capacitor" technique described above.

1) Connect signal cable B to the electrometer, and connect the "ground port" of the electrometer to a true electrical ground (the yellow-and-green port on the back of the high-voltage supply will work.) Turn the electrometer on, and set the voltage range to 10 V.
2) Connect the ends of signal cable B to the two plates of the variable parallel plate capacitor.
3) Connect the "black wire" side of the variable capacitor to ground. Try not to move any cables from this point onward.
4) Remove all charge from the variable capacitor by touching both sides with your finger. Simultaneously, press the "zero" button on the electrometer.
5) Set the spacing of the variable capacitor's plates to 1 mm (as narrow as it will go).
6) Follow the procedure in the Background section to measure the capacitance of the variable capacitor.
7) Remove all charge from the variable capacitor by touching both sides with your finger. Simultaneously, press the "zero" button on the electrometer.
8) Repeat this procedure 4 times to get an average.
9) Repeat steps 8-7 with a plate spacing of 2, 3, 5, 10, and 30 mm. (For the larger separations, you may have to change the range of the voltmeter.)

You should notice that as the separation *d* increases, the capacitance decreases, in accordance with Equation (2). Equation (2) further predicts that as *d* gets very large, *C* should go to zero. Does it? Make a quick graph of your capacitance data to check.

In reality, we're measuring *two* capacitors connected in parallel: the parallel plates are one (C_{plates}) and the wires and electronics that make up the electrometer are another (C_{meter})! The capacitance we measure is

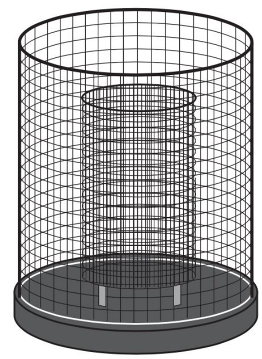
$$C = C_{plates} + C_{meter}$$

As the separation of the plates increases, C_{plates} –> 0, but C_{meter} remains constant. In your analysis, you'll find a value for C_{meter} and compare C_{plates} to the theoretical value.

Experiment 4.2: Relationship between C and V when Q is constant

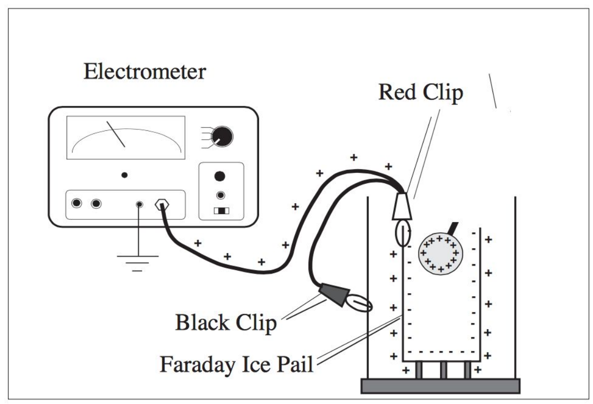
1) Return the plates to 1 mm separation.
2) Briefly touch the terminals of the low-voltage power supply (batteries) to the plates to charge them up to about 18 volts. Measure this voltage with the electrometer.
3) <u>MAKE A PREDICTION</u>: If you pull the two plates apart to increase their separation, what will happen to the voltage on the plates? Will it stay the same, increase, or decrease? Discuss your prediction with your partner and write it down before you continue.
4) Pull the plates apart gradually and watch what happens to the voltage.
5) Return the plates to 1 mm separation, and re-charge the plates using the batteries.
6) Pull the plates apart to 2 mm separation, and record the voltage.
7) Repeat steps 5 and 6 four times to compute an average. Don't forget to repeat step 5 each time!
8) Repeat steps 5-7 for final separations of 3, 5, 10, and 30 mm.

Experiment 4.3: Measuring charge for the Coulomb Experiment



In the Coulomb's Law experiment, we assumed that the charge on each sphere was related to its voltage according to the relationship $q = C_{ball} V$, where C_{ball} = 2.11e-12 coulombs/volt, or Farads. However, the voltage reading on the power supply we used isn't particularly accurate. So let's measure the charge on the ball directly.

To do this, you will use the "Faraday Ice Pail". This is composed of two metal cylinders made of wire mesh, one inside the other. Thus, they form a capacitor. If you touch a charged object to the *inside surface* of the inner cylinder, all the charge will flow to the outside of the inner cylinder. Then, by measuring the voltage across the pail, you can measure the unknown charge.



1) Use Cable A to connect the Faraday Ice Pail to the electrometer. Make sure the black wire (ground) ties to the outer cylinder, the red wire to the inner cylinder.
2) To start, we must measure the capacitance of the pail and electrometer. Use the reference capacitor technique of Experiment 4.1 to find it. (You're on your own here!)
3) Next, turn on the high-voltage power supply you used in the Coulomb's Law experiment, set it to 4000 V, and touch it to the conductive ball to charge it. Don't touch the ball with your hands, or the charge will leak off!
4) Use the string to touch the ball to the inner surface of the inner cylinder of the Faraday pail, then remove it. Measure the pail's voltage on the electrometer.
5) Repeat this process a few times.

Analysis:

Background

Derive Equation (3). Remember that the total charge before and after we connect the capacitors together is the same.

Experiment 4.1

As discussed in the experimental procedure, we are measuring the sum of two capacitances: the capacitance of the parallel plates, plus the capacitance of the wires and electronics in the electrometer:

$$C = C_{plates} + C_{meter}$$

The capacitance of the parallel plates should be given by equation (2):

$$C = \varepsilon_0 A\,(1/d) + C_{meter}$$

Thus, a plot of the measured C vs 1/d should give a straight line, with a slope equal to $\varepsilon_0 A$ and a y-intercept equal to C_{meter}. Create this plot, and measure its slope and intercept. What is the capacitance of your electrometer? Does the measured slope equal $\varepsilon_0 A$?

Note that this gives you a way to calculate the Coulomb constant ε_0 (or k), using an experiment that's much simpler than the one we used for Lab 3. If you assume equation (2) is true and use your measured slope to estimate ε_0, how close to the accepted value do you get?

Experiment 4.2

In this experiment, the charge on the capacitor should remain constant, because no charge can enter or leave the plates:

$$Q = C\,V$$

as C decreases, V must increase and vice versa. Use the capacitances measured in Experiment 4.1 to calculate the charge on the capacitor for each experiment. Is it indeed more or less constant? (Find the mean charge, standard deviation, and compare them.)

Experiment 4.3

In your analysis, you should answer the question: **does the charge on the ball measured using the Faraday ice pail technique agree with the charge calculated using the C_{ball} equation above? If not, could this explain any discrepancies in the results of your Coulomb's Law lab?** (Note that one possible source of error is that the power supplies might not put out their listed voltage, and you might not be using the same one this week. It can help to compare data with the other lab group.)

Appendix A, Tips for Accurate Results

As you move around, your hair and clothes rub against your skin, and your shoes rub against the floor, creating static electricity. Just running your hand through your hair can create a potential of thousands of volts, which is enough to swamp the small voltages you're trying to measure.

For best results, you should ground your body as often as possible by touching one of the black ground wires. If possible, touch a ground wire while performing all important measurements. Try to stay as still as possible while performing the experiments.