Lab 1: Background and Useful Information

Objective

As a result of performing this lab, you will be able to:

1. measure an unknown capacitance by connecting it in parallel to a known capacitance and a voltage sensor;
2. explain why the human body can act as a capacitor;
3. measure equipotential contour lines and make predictions about equipotential contour lines given the shape of the electrodes

Background

Electric potential

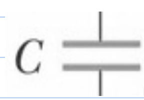
- Any arrangement of static charges produces an electric potential in its vicinity. In lecture you have learned bout Coulomb's Law and the principle of superposition, which make it possible to (theoretically) calculate the field produced by a set of charges. In this lab, you will determine the electric potential produced by a set of electrodes held at fixed voltages. The working surface of the experiment will be a two-dimensional sheet of paper. Rather than measure the potential at every single point, you will use equipotential contour lines to visualize the potential.

Equipotential contours:

- 1. Always form closed loops (except at the boundary of the paper)
- 2. Never cross other equipotential contours
- 3. Never pass through electrodes
- 4. Are closer together in areas where the gradient is higher
- 5. Any good conductor is its own equipotential.

Capacitors

- Capacitors are circuit elements that store charge, consisting of two separated conductors (usually taken to be adjacent parallel plates). They are represented by the following symbol:



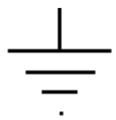
- The voltage across a capacitor is equal to the charge stored on it divided by its capacitance, $\Delta V = Q/C$. Capacitance is measured in farads (F); 1 farad = 1 coulomb per volt. For a parallel-plate capacitor (the most common kind), the capacitance is given by $C = \kappa\varepsilon_0 A/d$, where κ is the dielectric constant, ε_0 is the permittivity of vacuum, A is the area of each plate, and d is the separation distance.
- To speak of the current "through" a capacitor is technically incorrect, as a capacitor consists of two non-touching conducting plates, and charge cannot flow from one to the other across the gap. However, everybody uses that phrase. What actually happens is that current deposits charge on one plate of the capacitor and an equal current removes charge from the other plate at the same rate, so that the two plates always have equal and opposite charges; it is actually quite convenient to think of it as being a single continuous current. Note that the current through a capacitor is the *rate of change* of the charge on the capacitor: $I = dQ/dt$. (There may be a minus sign, depending on whether the current is depositing charge on the + plate or the - plate.)
- Capacitors in parallel add: $C_{eq} = C_1 + C_2 + \ldots$
- Capacitors in series add inversely: $1/C_{eq} = 1/C_1 + 1/C_2 + \ldots$
- Capacitors store energy, which means it takes energy to charge a capacitor. However, unlike resistors, you can get the energy back and use it to do useful work (like melting a piano wire into a zillion glowing pieces, for instance). The energy stored in a capacitor is given by $U = ½\, C\Delta V^2 = ½\, Q^2/C = ½\, Q\Delta V$. When a capacitor is charging, energy is being put into it; when discharging, energy is being taken out of it and can be used elsewhere. Thus, the electrical power consumed by a

capacitor can be positive or negative.

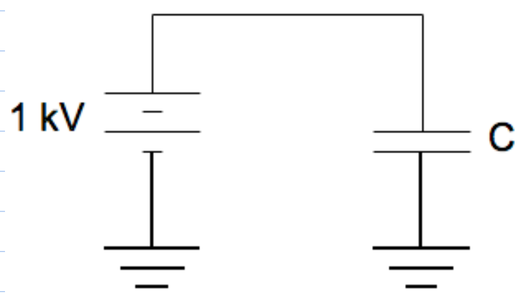
- Most capacitors are filled with a dielectric material, which increases its capacitance by reducing the electric field between the capacitor's plates. However, every dielectric material has a limit, called the *dielectric strength*--the maximum potential gradient that it can support before it breaks down. If the dielectric strength is exceeded, the dielectric will temporarily become conducting. If this happens, typically a spark jumps across the dielectric and reduces the potential difference across the capacitor's plates to nearly zero. This is the physical basis behind the phenomenon of static electric shocks and, on a more impressive scale, lightning—the dielectric breakdown of air.

Ground

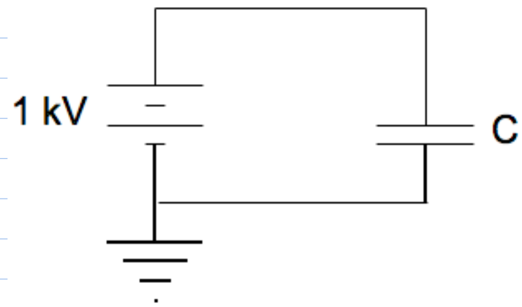
- As you already know, the potential can be arbitrarily defined to be equal to zero at any one place. In an electrical circuit, the place where V is defined to be zero is called *ground* and is represented in a circuit diagram by this symbol:



- The term "ground" comes about from that fact that this location in the circuits of many electric devices is actually electrically connected to the Earth. The Earth is a fairly good conductor and a huge reservoir of charge, so you can flow a lot of current into or out of it without significantly affecting its potential; this makes the Earth an ideal ground. Just about every building with an electrical system has a set of wires that are connected to the Earth (*e.g.*, a metal rod stuck into the Earth) to be used as circuit ground for anything plugged into that building.
- In a circuit containing an explicit ground, we can talk about the "voltage" of a single point (remember, the word "voltage" refers to a potential difference between two points), meaning the voltage of that point relative to ground. In this usage, "voltage" is interchangeable with "potential" since ground is defined to have a potential of zero.
- With a ground, you can have a circuit which doesn't even appear to be a complete circuit because anything connected to ground is at the same potential and thus might as well be connected by a wire. For example, suppose you have a capacitor C. You ground both plates so that there is no voltage across C (and hence no charge). Then you touch one end of the capacitor to a high-voltage power supply at V = +1 kV. Even though you don't appear to have made a complete circuit, you actually have made the following circuit:



One end of the capacitor is still grounded because it was grounded before and it's been kept electrically isolated since then. The other end is now at +1000 V (relative to ground). In the circuit diagram the two places labeled with the ground symbol are at the same potential, so this in turn is actually equivalent to:



In other words, you have charged up your capacitor to a voltage of 1 kV across its plates.

- The existence of a huge conducting ground also means that we can define the concept of capacitance for a single isolated conductor. It is simply equal to the capacitance of the system consisting of the conductor plus the Earth (which is far away and at V=0).
  - For example, consider a metal sphere of radius R. You can take a charge Q out of the Earth (ostensibly leaving the Earth with -Q, but that doesn't affect the potential of the Earth because it is so vast) and put it on the sphere to give it charge +Q.
  - The charge will distribute itself evenly over the sphere's surface.
  - The potential of the sphere relative to V=0 at infinity can be found by integration to be $Q/(4\pi\varepsilon_0 R)$ (just like the potential a distance R from a point charge Q).
  - If the sphere is "isolated" (far away) from the Earth, you now have a capacitor with "plates" of +Q and -Q charge and a potential difference $\Delta V = kQ/R$. Using the definition of capacitance, $C = Q/\Delta V = R/k = 4\pi\varepsilon_0 R$. That's what "the capacitance of a sphere" means; it's the capacitance relative to ground (the Earth).
  - Your own body is a reasonably good conductor. What do you think the capacitance of your body is? We'll answer that in this lab!

Materials

Potential plotting board

- 1. This is just a board with two rows of screw holes which are electrically connected to the terminals at the edge of the board.
- 2. Screwing an electrode tightly into one of the holes will create an electrical contact that will maintain the electrode at the terminal voltage.
- 3. Another way of attaching an electrode is by placing a piece of conducting tape on the sheet and connecting it to an external power supply using alligator clip leads.

Conductive paper

- 1. This is a sheet of carbon paper which is slightly conducting. Unlike metal, the sheet itself is not a good conductor that is at the same voltage everywhere. Rather, the presence of electrodes held at fixed potentials not he sheet will cause a distribution of voltages and fields all over the sheet, which can then be probed using a digital voltmeter.
- 2. The two sides of the sheet are not identical. To make sure you are working on the correct side, place the sheet on the equipotential board so that the edges of the paper curl upwards. The side you sill be working on is the less glossy, more matte black side.
- 3. Try to handle the sheet as little as possible, and only around the edges. While you are making a voltage measurement, you can touch the paper lightly but do not rest your weight on it, as that could distort the electric potential on the paper.

Digital Multimeter

- 1. The multimeter is the tool you will be using to measure voltages. There are several settings on the dial; the one you will be using is the setting that says V with a pair of straight lines (not V with a wavy line, which is used to measure oscillating voltages).
- 2. Depending on the model for multimeter, you may also have to set the range of the instrument. For the purposes of this

lab, you should use the 20-volt setting.

- 3. The multimeter probes must both be in contact with something in order to get a reading. The digital readout will indicate the voltage of the red probe minus the voltage of the black probe.
- 4. This is a general convention for electric components: red terminals and leads are considered "positive" and black ones "negative". For a meter, nothing bat will happen if you reverse the two -- you will just get a negative reading if you put the red probe at a lower voltage than the black probe.
- 5. If your probes are disconnected or you are switching probes, make sure to plug the red probe into the jack labeled "VΩ" and the black probe into the jack labeled "COM".

DC power supply

- 1. This supply will maintain a constant voltage between terminals The red terminal is held at a higher voltage than the black terminal, in accordance with the usual color convention.
- 2. you can adjust the voltage of the power supply using the knob. The puss-button switch toggles between the 0 and 12 volt and the 12 and 24 volt settings.

Electrodes (either two rectangles or two circles)

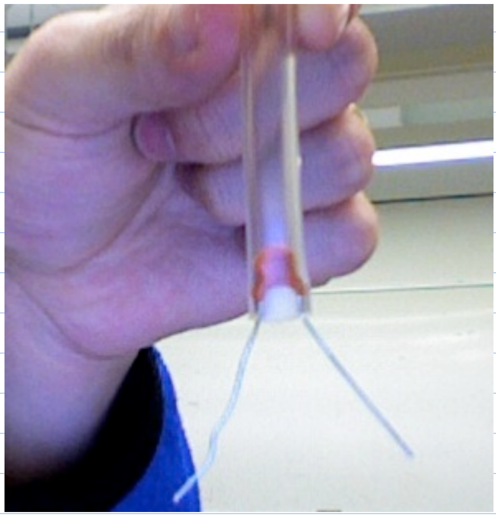
- 1. These are metal conducting blocks with screw holes.
- 2. To achieve the best electrical contact with the paper, place the side with raised edges facing down. Also, you may want to rub that side down with steel wool to make sure it is clean.

White and red pencils and crayons

- 1. These pencils will make non-conductive marks on the paper, unlike a regular lead pencil. Use them to draw equipotential contours.

Capacitor C_1 = 100 pF

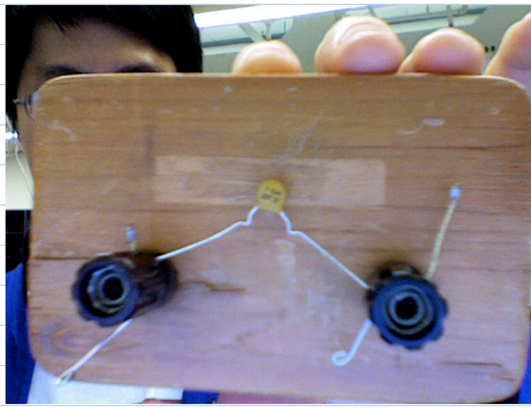
This capacitor is the one which is stuck in a little plastic sheath:



This is so that you can handle it without accidentally discharging it through your fingers.

Capacitor C_2 = 0.11 μF

This is a relatively large capacitor connected across a pair of banana plug sockets on a wooden board:



You will use this capacitor in conjunction with the charge sensor (see below). **Do not connect this capacitor directly across the high-voltage power supply!** It was not designed to handle high voltages.

High-voltage power supply (HVPS)

- This is a DC power supply. It maintains a very large voltage across its terminals; however, the current that it can supply is limited to under 10 μA (for safety reasons).
- The black cable plugged into the "COM" terminal of the HVPS is connected to the building ground (and thence to the actual Earth itself). The red cable can be plugged into any of the three terminals marked 1000 V, 2000 V, or 3000 V (or also to the +30 V, but that would be boring—kilovolts are *so* much more interesting) depending on which voltage you need.
- If you plug the red banana cable into the 3000 V terminal, anything you bring into electrical contact with the red plug will be brought to 3 kV above ground. Likewise, to ground something (bring its potential down to zero), just touch it to the black plug in the COM terminal.

Charge sensor

- This is another probe that connects to the LabPro interface and can be used to input data into Logger Pro.

  It acts almost exactly like the differential voltage probe, except that its "internal resistance" is much higher, so that it won't discharge a capacitor while you are trying to measure its voltage. The downside is that the charge sensor has an internal time constant of 0.1 s, so you can't use it to measure anything that changes more rapidly than that.
- Zeroing the charge sensor is slightly different from zeroing the differential voltage probe. First, touch the leads of the charge sensor together. Then, while they are connected, press the button located on the charge sensor itself (not a software button in Logger Pro) and hold for about a second to zero. Now you can disconnect the leads and measure something.
- The charge sensor has three settings, controlled by a switch on the box. You should use the setting marked ±10 V. Even on this setting the sensor is limited to about ±9 V. If you attempt to put more than 9 V across it, it will saturate. If this happens, be sure to zero the charge sensor before attempting to make another measurement.
- The reason that this object is called a "charge sensor" rather than just a voltmeter is that it is intended to be connected across a large capacitor of known capacitance (in this case, C_2 = 0.11 μF). By measuring the voltage across the capacitor, you can calculate how much charge is on it.
- The charge sensor should always be used in conjunction with C_2 (and vice versa). Just as C_2 is not intended to support high voltages, neither is the charge sensor. Try not to put more than 10 volts across it.

Procedures

Drawing equipotential contours

- 1. Set up your potential plotting board and carbon conductive paper as described in the Materials section. Remember to place the correct side of the sheet facing up.
- 2. Place two electrodes on your paper and bolt them into the board tightly. Use eight two small circles or two long bars, so that you get one of the configurations you made predictions for in the warm up exercise. If you are using the long bars, each bar should be attached with two bolts, one at either end of the bar.
- 3. Connect the red and black terminals of the board to the DC power supply. Turn on the power supply and use the know to adjust the output to about 20 volts.
- 4. Using an alligator clip lead, connect the black terminal of the multimeter to the edge of the conducting paper, halfway between the terminals of the board, as in the picture below:
- 5. Using the red probe of the multimeter, measure the voltage of the positive and negative terminals of the board relative to the point halfway in between them where you clipped the alligator lead. Adjust the position of the alligator clip until you get approximately equal magnitude with opposite sign values for the voltage on the terminals.
- 6. Move the red probe around the sheet of paper to explore the electric potential on the sheet. Make sure the probe is in contact with the sheet, but you do not need to press it very hard (the weight of the probe itself is usually sufficient), and be sure not to drag the probe across the surface. Above all, do not poke a hole through the paper or tear it. Be especially careful around the places in the board where there is a screw hole beneath the paper surface. By exploring the sheet with the multimeter probe, you can "map out" the potential in the two-dimensional space you are working in.
- 7. Move the red probe around the sheet until you find a point which gives you a reading of a voltage your team agreed on. Mark that point with the pencil. Move the probe a short distance away from this point until you find another point with the same voltage. Mark this point with the pencil. Continue in this fashion until your contour either closes in on itself or reaches the edge of the paper. At places where the contour is highly curved, it will be necessary to take more measurements closer together than in the areas where the contour is fairly straight. The idea is to get enough points that you can be fairly sure of the shape of the equipotential contour.
- 8. Map several equipotential contour lines around your electrodes. Make sure you switch tasks among the members of your team so everyone gets a chance to use the equipment.

Using the charge sensor with the LoggerPro file "Lab1.cmbl"

- 1. Open the "Lab1.cmbl" LoggerPro file. Click on the {insert image of data collection button} button and set the collection length to 60 seconds, then click OK.
- 2. The charge sensor's leads should be connected across capacitor C2. Connect the black terminal of C2 to the HVPS ground. Using a banana plug touch the terminals of C2 together and then press the button on the charge sensor to zero the reading. You should see a reading of close to 0 volts in the lower right of the LoggerPro window. Unplug the banana cable so that C2 is no longer shorted out (but leave its black terminal grounded).
- 3. Start collecting data in LoggerPro. The file displays the voltage across C2 as a function of time.

Lab 1: Report

Warm-up (20-30 minutes)

- Do the warm-up!

Who are you? (Picture and names, please)

- A:

Equipotential contours (1 hour)

- In this part of the lab, you will use a multimeter probe to map out equipotential contours around a pair of electrodes on a sheet of conducting paper. Follow the instructions for doing this in the Background writeup for this lab, under the subheading "Procedures". When you are done, find another group that has a different set of electrodes and share your results with them. Take a picture of both equipotential contour maps and include them below.

- Equipotential lines for two circles:

- Equipotential lines for two rectangles:

- **How do the papers look compared to your predictions made during the warm-up exercise?**
  - A:
- **BONUS** Free-form: decide on a simple figure to use as one of the electrodes, along with either a circle or a rectangle (explain your reasoning behind choosing such figure). Include a picture of a drawing of the electrodes and your prediction for the equipotential contours. Ask your TF to help you set up the experiment and find and draw the equipotential contours for this setup of electrodes. How does your prediction compare to the contours you found?
  - A:

Are you a capacitor? (20-30 minutes)

- In this part of the lab your will charge and discharge a capacitor and then repeat the procedure with yourself in order to determine if you are a capacitor.

  Warning: If you have a pacemaker or other implanted electronic medical device, do not do any of these parts on yourself. Let your lab partners do all the shocking work (pun intended). It should not cause any damage, but there is no reason to take unnecessary risks.

- Start by plugging the red plug of the HVPS into the +3000 V jack.

- One thing we know about capacitors is that we can put a voltage across one and it will stay there until we discharge it. To demonstrate this, take capacitor C1 (the one in the plastic tube - **not** the one attached to the wooden posts), and clip one end of it to ground using an alligator lead. Taking care to only hold it using the plastic tube, touch the free end of the capacitor to +3 kV for a moment. Now bring the free end (which is now at +3 kV) near a grounded wire and touch it to ground. **What happens?**
  - A:
- Just as you charged and discharged C1, you can do the same with your own body! First, ground yourself by touching the ground terminal of the HVPS. Then touch the +3 kV end and hold it for a second. **This will not hurt.** Now go back and touch the ground again.

  - **(1) What happens?**
    - A:

(2) Are you a capacitor? If so, where's the other terminal?

A:

What is your capacitance? (1 hour)

In this part of the lab you will learn how to measure the capacitance of a charged capacitor by connecting it in parallel with another capacitor of known capacitance and measuring the voltage across. You will then use the same procedure to measure your own capacitance.

Switch the positive terminal of the HVPS to the +1000 V jack.

Start collecting data in LoggerPro using the file "Lab1.cmbl"; you can find instructions on how to use this file in the Background writeup for this lab under the subheading "Procedures". Charge C1 to high voltage by attaching one end to ground and touching the other to the +1 kV lead. This time, instead of discharging it to ground, discharge to the red terminal of C2. Observe what happens to the voltage reading of the charge sensor.

(1) **How much did it change from its previous (near-zero) value when you touched the two capacitors together?**

A:

(2) **How much charge did you put on C2?**

A:

(3) C1 is much smaller than C2. **Using what you derived in the pre-lab / warm-up, how much charge was on C1 before you touched the two capacitors?** (Hint: as long as C1 << C2, you don't need to know the actual value of C1.)

A:

(4) **Calculate the observed value of C1** based on this charge and the fact that it took 1 kV of voltage to put this much charge on C1. **Does your calculation agree with the stated value of C1? Explain.**

A:

Now repeat the measurement except with your own capacitance in place of C1. **Remember to zero the charge sensor before you start taking data.** (At only 1 kV you will not feel a shock.) Only one member of your lab group needs to do this part, although (**BONUS**) if you have time and are interested in your own capacitance, feel free to try it on all three of you. **Warning: if you have a pacemaker or other implanted electronic device, do not do this part.**

(1) **What is the final voltage on C2?**

A:

(2) **What is the capacitance of your body?** (Include a snapshot of your work)

A:

Now you know your capacitance. How much capacitance is that, anyway?

(1) Imagine a solid conducting sphere with the same capacitance (relative to a faraway ground) as your body. **What would its radius be? How does this compare with your own length scale?**

A:

(2) Consider a parallel plate capacitor whose plates each have an area of about 1 cm2. When the plates are separated by 1mm, the capacitance is about 1pF. **At this separation, roughly how big would the plates have to be for this capacitor to have a capacitance comparable to your own?**

A:

Conclusion

What is the most important thing you learned in lab today?

A:

Don't forget to save your file as a pdf and upload it to the isites dropbox!

When printing this file, make sure you only print **page 4**!