Potential Mapping Lab

Physics 141

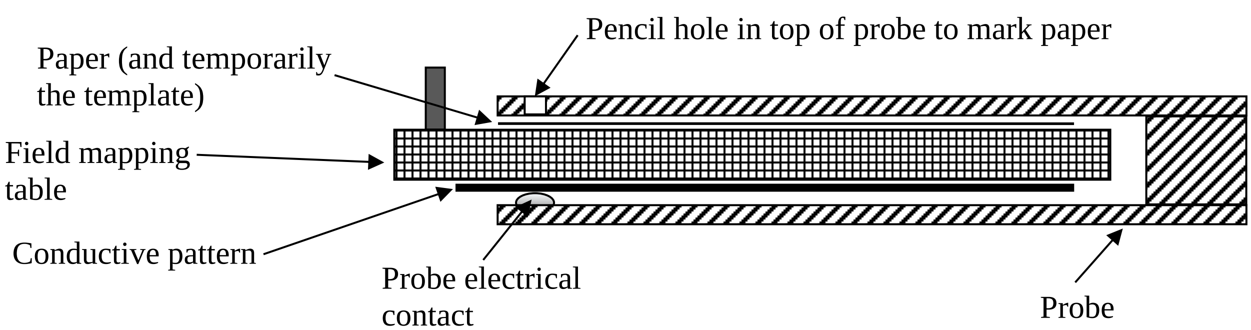
Theory:

- The electric field is the rate of change of the potential, $E = -\frac{dV}{ds}$.
- An equipotential is a line or surface along which the potential is *constant*.
- The electric field crosses an equipotential at a 90° angle. If it didn't there would be a component of the electric field along the equipotential, the potential would be changing, and it would not be an equipotential!
- Two different equipotential lines cannot cross, having two different potentials at the same place. At very small distances two equipotentials will become almost parallel to each other (or else they would very soon cross).

Equipment: Potential mapping apparatus (see drawing below), consisting of:

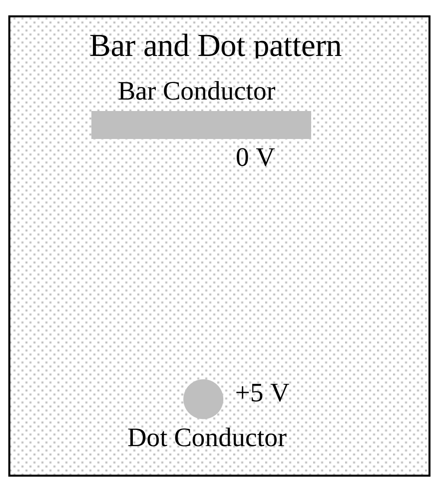
- Field mapping table with screws underneath to attach black conductive plastic field patterns.
- Probe with two long black plastic arms to go above and below the table
- 3 patterns, made of slightly conducting black plastic with different metal **conductor shapes** on their surface: Bar and Dot, Conductor and Insulator, and Faraday Ice Pail
- 2 clear plastic templates
- Power supply, with power cord and pair of red and black wire leads.
- Instek GDM 8341 digital multimeter, with power cord and pair of red and black leads (2 pairs altogether).
- Paper to draw the equipotentials, and tape to hold the paper down.

Edge view of table and probe



Information:

Basic idea: You will mount a plastic pattern, such as the Bar and Dot pattern shown at the right, to the underside of the table. You will connect the metal conductor shapes on the pattern (called electrodes, shown in gray) to a power supply, one at 0 V and the other at 5 V as shown. A very small electrical current will flow through the plastic pattern from the (+) electrode to the (-) one, creating an electrical potential gradient that slowly changes from 5 V at one end to 0 V at the other end. On the top of the table you will tape a piece of paper. Then you will use a voltmeter to find a series of places on the pattern that are all at exactly the same potential (so it is an equipotential), marking each of these places on the paper. You will do this for several fixed voltages between 0 V and 5 V. Later you will draw smooth lines through the points at each potential to show the shape of the equipotential.



Setup

- Be **very careful to touch the patterns only at the edge**. If you touch the surface, oils and acids on your fingertips will mess up the way the current flows and change the shape of the equipotential lines.

Some rules regarding electrical setup and measurement:

Power supply

a) Connect a pair of leads (wires with banana connector at one end and alligator clip at the other end) to the power supply (PS), matching red and black leads to the red and black terminals. Leave the PS turned off.

b) **Never** connect the poles of a power supply directly to each other, creating a short circuit which could damage it, burn out a fuse, cause sparks, or melt wires and spit out red hot melted metal (though our power supplies are supposed to be protected against this)!

Digital multimeter:

c) Connect another black lead to the black terminal of the Instek multimeter, and the red lead to the red terminal marked **V, Ω** (for volts and ohms), ***not*** the one marked 12A (amperes) or white one marked 0.5A.

d) **Important: The default input resistance is 10 MΩ. To get enough accuracy for this lab to work properly the input resistance must be set to 10 GΩ, 1000 times larger. To do that:**

(1) Turn the meter on and set the multimeter function to DC voltage by pushing the DCV button

(2) Press the AUTO key, to fix the voltage range instead of allowing it to autorange.

(3) Press the up or down button to set the range to 5V DC (*10 GΩ is only available on the 5 V and 500 mV ranges*). Unfortunately it does not say what range you are on, but the decimal point on the displayed voltage is your clue. It should show one digit to the left of the decimal point and four digits to the right of it, with units of volts (V), not millivolts (mV).

(4) Press the MENU key

(5) Press the up or down button to put it on Level 1 (on the right of the display), if it isn't already

(6) Press the left or right button to go to MEAS mode (on the main display, on the left side)

(7) Press the up or down button to go to Level 2

(8) Press the left or right button to go to INPUT R mode

(9) Press Enter, then use the up or down button to set the input resistance to 10GΩ, not 10MΩ

(10) Press the Enter key to confirm.

(11) **Press the EXIT key.**

e) Touch the meter red and black leads together, check if it reads 0.0000 V (notice, 4 digits to the right of the decimal)

f) Although we need the high input resistance, the last two decimals are very distracting because they change constantly, extremely rapidly. You can cover them with a piece of masking tape to make your life easier!

Procedure:

- Turn the black field mapping table upside down.

  Fasten a pattern to it with the thumbscrews, with the metal aluminum foil conductors facing up toward you.

  Tighten the thumbscrews snugly on the electrodes but do not overtighten, which can damage them.

  If the plastic pattern is curled so the edges are curled up, tape them down flat with masking tape (not Scotch tape) but only cover a thin strip along the edges so the tape doesn't affect the conduction.

- Turn the table back upright. Attach a sheet of paper to the top surface with masking tape.

- Find the clear plastic template with the pattern you are using (there are two templates, each one has holes for 3 different patterns). Align the holes in the template onto pins on the table in the same orientation as the pattern under the table. Trace the pattern onto the paper so it matches the shape of the electrodes straight below it.

• You will find and mark the potentials (voltages) using a U-shaped probe. Check that all bolts and electrical connections on it are tight. Also check electrical connections on the mapping table. Slide the probe over the table from the <u>smooth</u> edge (see the diagram at the top of page 1). The *hole* at the end of the probe goes on top. The pencil goes through it to mark the paper. The *smooth round metal contact* below the hole goes below to touch the pattern and measure the voltage at that point.

• If a pattern is curled enough that you can't completely tape it flat, squeeze the top and bottom of the <u>probe</u> together with your fingers to get good contact.

• Connect the power supply leads to electrode connectors at the ends of the field mapping table. Red is positive lead and black is the ground (0 V) lead. <u>See instructions below for Bar and Dot, and Faraday's Ice Pail</u>.

• Connect both the meter and power supply <u>black leads together</u> at the <u>same end</u> of the mapping table.

• Turn the power supply on and adjust it to read 5 V or slightly less (its reading is less accurate than the meter, and the exact value does not matter).

<u>If you have *any* question about whether your connections are correct, ask your instructor</u>.

•Temporarily touch the positive (red) meter lead to the positive (red) power supply (PS) lead. Adjust the PS until the <u>voltmeter</u> (not the PS's meter) reads close to 5.00 V or less. Don't spend time getting *exactly* 5 V – what is important is <u>knowing</u> the value. We will call this value V_o. If you turn the voltage too high the meter will display OL (overload), so turn it down. **<u>Write the exact voltage on the paper above the positive electrode</u>**. **<u>Write 0.00 V above the negative electrode</u>** drawn on the paper. **Do this with <u>each new</u> pattern.**

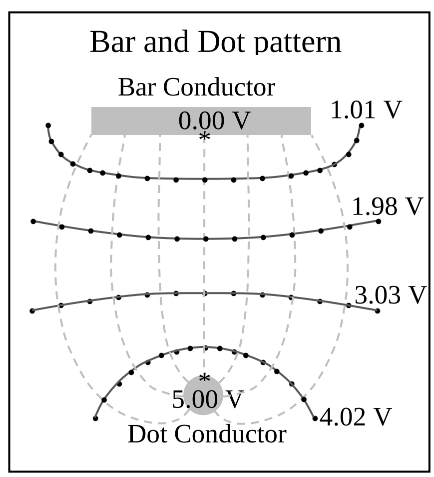
• Check the voltage on each actual electrode on the pattern, as follows:

<u>Temporarily turn the table upside down and touch the red meter lead to the pattern's 5 V electrode to see if it reads exactly the same as V_o.</u> If it doesn't there could be a loose connection.

• Prepare the probe to make measurements:

Clean the tip of the probe with alcohol, before starting each new pattern. You may also need to clean the plastic patterns with alcohol, but be very careful not to catch the paper on the aluminum foil. Attach the positive (red) <u>meter</u> lead to the metal post on the probe. If there is a screw near the tip on the top arm of the probe make sure it does not stick out of the underside of the arm because that will make the probe tippy, so the bottom contact will move back and forth even with the top arm held in one place. Slip the probe over the table. The voltmeter will show the potential wherever the contact (directly below the pencil hole) touches the pattern. You will find <u>equipotentials</u> at four values, approximately 1, 2, and 3 volts, and as close to 4 volts as you can get, for the bar and dot, and additional ones for the other two patterns.

• Measure equipotentials: The drawing shows a rough (but <u>not accurate</u>) idea of what they might look like.



One partner: Hold the probe. For best control get your finger tips as close as possible to the hole on top and contact below. Move the probe until the meter reads about 1 V. A value close to 1.0 volts (such as 0.98 or 1.03 V for example) is fine. Another partner: put a pencil <u>vertically</u> through the hole on top and mark the paper (tipping the pencil will move the mark to one side). Write the <u>exact</u> voltage to <u>*two decimal places*</u> (i.e. the nearest 0.01 V) by that point. Ignore decimal points beyond that (you may want to tape a piece of paper over the digits to the right of that to block out their rapidly changing values). <u>You may not be able to get to 4 V</u> because of the probe hitting the thumbscrew below. In that case find the highest voltage you can follow all around the dot, record the exact voltage, and trace <u>that</u> equipotential.

After marking the first dot move sideways a centimeter or two, and move up or down until you find exactly the same potential (within ±0.02V) and mark the spot. **You only need to write the voltage on the paper at one point** as shown in the drawing – don't label the voltage of every point in the equipotential.

Repeat this until you have marked places along one complete equipotential (see the drawing), finding 12 or more points along the equipotential, across the width of the paper. ***Use closer spacing in curved areas*** so a curve through them can be drawn accurately. Try to get close to each edge of the paper if possible.

If the voltage is changing, not constant: check connections, clean the probe tip and the pattern with alcohol.

Later you will draw very smooth equipotential curves through these points for your lab report (as shown in the drawing). If the curve does *not* look smooth, check the electrical connections and ask for help if necessary and redo your work. Then: do the same for the 2 V, 3 V, and 4 V equipotentials.

Special instructions for specific patterns:

Bar and Dot

• Connect the power supply 0 V to the bar and the 5 V to the dot.

Conductor and Insulator (no drawing shown)

• Mark on your paper which circle is the conductor and which is the insulator (a hole in the plastic!).

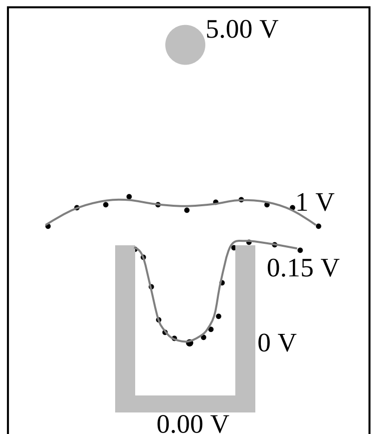
• Use 9 different equipotentials: **1, 1.5, 2, 2.25, 2.5, 2.75, 3, 3.5, and 4V**, to see their behavior in the middle area.

• Find and record the potential *on the conductor* (turn the table upside down and actually touch the Al foil conductor). Check it in several places – is it the same? The electric current and the field have to curve around the *insulator*, so very close to it the *field* will parallel its edge. Then which way will the equipotentials point? Notice that equipotentials and the field have opposite behavior around the *insulator* compared to the *conductor*!

Faraday's ice pail

• Connect **0 V to the U-shaped "ice pail"** and the **5 V to the dot** (see drawing), not the other way around.

• Map 7 different equipotentials to investigate the field inside the pail. Altogether try to map equipotentials at **0.050 (50 mV), 0.150 (150 mV), 0.5, 1, 2, 3, and 4 V (but 4 V may not be possible. 0.050 may also not be possible. Find a voltage that works and use that**). Note: For the 0.050 V and 0.15 V equipotentials change the multimeter range to 500 mV (push the Auto button then the down arrow to the 500 mV range), and only use the first two digits. Inside the ice pail you will not be able to follow the potential quite to the ice pail – it will suddenly go to zero when the probe touches the ice pail. When that happens you are finished with that end of the equipotential.



Faraday's Ice Pail

Lab Report:

Note: You don't need to do a formal lab report with objectives, procedures, etc. I think that is a waste of time. You can organize the report however you want, but try to do it in a logical order.

Analysis and Questions (can be done later, you have 1 week to turn it in):

1) Equipotential curves. Use a pencil to lightly draw the **smoothest possible curve** through the dots for each potential, for all 3 patterns. If a line through all the dots is not smooth then smooth the curve by going **near but not through** dots that are out of line, as shown in the Faraday's Ice Pail drawing. Erase and redraw the line until the line is very smooth, not jerky or with sudden bends. You have probably seen a mathematical straight line fit through experimental data, with data points scattered above and below the line. Do a similar thing, but with smooth curves drawn by eye. Jerky or sloppy drawings will hurt your grade.

2) Field lines (do *not* do this before drawing in the equipotential lines!). *After* your equipotential curves are very smooth, lightly sketch electric field lines going all the way from the dot to the other conductor(s). See the gray lines in the bar and dot drawing on p. 3 for a rough illustration. Start out in about 12-15 different directions around the dot electrode. Start each field line going out ***exactly perpendicular*** from the dot. Do not draw the field lines with any preconceived idea about where they should go, just follow wherever the equipotentials tell you to go by making a smooth curve and crossing each one at 90°, drawing very lightly so you can erase and redraw. Curve the field lines so they cross each equipotential at ***exactly*** 90°. Your grade will be hurt if they are not ***exactly*** perpendicular. Use a small square object, or corner torn from a page, to make sure all field lines cross equipotentials and conductor edges at ***exactly 90°***! Remember that conductors (the electrodes at each end, and the conductor in the Conductor and Insulator pattern) are also equipotentials so lines must go into them at exactly 90°. Not doing this right is by far the most common reason that lab grades get marked down.

Make the field lines curve ***very smoothly*** across equipotentials and between them. Not making the curves smooth will also hurt your grade. Ignore the original equipotential dots as you draw field lines (don't try to go through the dots, their location doesn't mean anything). Take time, erasing and correcting, to get the field lines right. You will almost certainly need to draw and erase many times, maybe 6 or 8 times, to get the field lines both smooth and perpendicular to the equipotentials. It is trickier than it looks.

After the field lines are perfect you can go over them in another color if you wish. Put arrows on these field lines to show the direction of the electric field. Include these drawings in your report, of course.

3) Conductor and Insulator pattern: We would expect an equipotential near a conductor to become more parallel to it as it gets closer to the conductor, but does it really? Discuss how your equipotentials compare to this. Conversely, the electric field near an insulator should become more parallel to it as they get closer to it (so the equipotentials should come in perpendicular to it, like field lines into a conductor). Discuss how your electric field lines compare to this.

4) Bar and Dot pattern: draw a straight vertical line down the center of the page from the center of the bar at the top to the center of the dot (see the line marked by asterisks at each end in the drawing on p. 3).

a) Along this line use the table below to calculate the average electric field between each set of equipotential lines. Use $\bar{E}_y = \frac{-\Delta V}{\Delta y}$, where Δy is the distance between a pair of equipotentials, and the bar over E means it is an average value. For example in the bar and dot example drawing on p. 3 the second potential difference is $\Delta V_2 = 1.98 - 1.01 = 0.97$ V. Measure the distances as accurately as possible with a ruler (accurate to 0.5 mm or better) and express them in meters. For conductors measure to the nearest edge of the conductor.

b) Use the field closest to the bar and use the relationship $\eta = \varepsilon_o E$ near a conductor to determine the surface charge density η_{bar} the bar would have at its center *if it were a 3-dimensional plate perpendicular to the paper*. Also find η_{dot} next to the dot, and write these values in the table.

c) Calculate the ratio η_{dot}/η_{bar} of these charge densities, and explain the result. (Hint: how should the total charge on the conductors compare with each other? They are acting as a capacitor)

Approximate voltage intervals (i) →	(*1*) 0 V to 1 V	(*2*) 1 to 2	(*3*) 2 to 3	(*4*) 3 to 4	(*5*) 4 to 5
Exact potential difference ΔV_i					
Spacing Δy_i, m					
Electric field magnitude $\bar{E}_{yi}$, V/m					
"Surface" charge density η near bar, dot					

d) If you could measure *local* electric field values very close to the conductors instead of average ones do you think E_{dot} would be about the same or different? How about E_{bar}? How about E_{dot}/E_{bar}? Explain.

5) Faraday's ice pail: Examine the shape of the field around and inside the "Faraday ice pail": Draw a vertical line from the center of the pail to the center of the dot.

a) Calculate the average electric field between each set of equipotentials as above, including *inside* the ice pail. Compare the electric field values inside the "ice pail" to the other values along the centerline. Discuss what you find and why you think it is that way (Hint: is it acting like a partial Faraday cage?). For the distance to the bottom of the pail *measure to the **nearest edge** of the conductor, not to the center of the dot*. Note: If you needed to use different voltages, or you used more than 7 different ones, then feel free to cross out and change the approximate intervals and put in correct ones, or redo the table.

Approximate voltage intervals (i) →	(*1*) 0 to .05	(2) .05 to .15	(3) 0.15 to 0.5	(4) 0.5 to 1	(*4*) 1 to 2	(*5*) 2 to 3	(*6*) 3 to 4	(*7*) 4 to 5
Exact potential difference ΔV_i								
Spacing Δy_i, m								
Electric field magnitude $\bar{E}_{yi}$, V/m								
"Surface" charge density η near bar, pail								

b) Find the "surface" charge densities of each conductor and the ratio η_{dot}/η_{pail}. Is this ratio significantly different from the Bar and Dot ratio? If so discuss the reasons why this is so.

c) Using what you know about electric field lines judge the strength of the electric field at different places around the Ice Pail surface, such as corners, flat edges, inside, outside, etc. Also discuss the distribution of charge density along these surfaces – is it uniform or not, and if not where is the charge density the greatest? Is it where you would expect it to be the greatest?