Lab 1: Electric Potential and Electric Field

I. Before you come to lab...

A. Read the following chapters from the text (Giancoli):

- **1.** Chapter 21, sections 3, 6, 8, 9
- **2.** Chapter 23, sections 1, 2, 5, 7

B. Read through this entire lab handout.

C. Check out the following online applet:

http://www.falstad.com/emstatic/

Play around with the various different configurations and see how the field lines and contour lines are produced by different distributions of charges. (I find the setting "Show E lines" to be the most useful display setting. The arrows give the direction of the field, and the color of the arrows indicates the field strength, with brighter = stronger.) If you're curious, j stands for the electric current (in configurations where there is charge flowing), and rho is the charge density within a conductor. All of the configurations up until you get to the ones involving dielectrics are interesting to look at, but perhaps the most useful are the "Dipole charge" and "Conducting planes."

D. Complete the pre-lab assignment at the end of the handout and bring it with you when you come to lab.

II. Background

A. Electric potential and electric field

1. Any arrangement of static charges produces an electric field in its vicinity. In lecture you have learned about Coulomb's Law and the principle of superposition, which make it possible to (theoretically) calculate the field produced by a set of charges. But in practice it is mathematically very difficult to do so for all but the simplest charge configurations. And even in the simple configurations, the task is difficult because of the vector nature of the electric field.

2. Electric potential, on the other hand, is a scalar, which makes it much easier to work with. And the best part is, the electric potential contains all the same information as the electric field—if you know the potential, you can calculate the field, and vice versa.

- **a.** If you know V(x, y, z), then the electric field is the vector whose components are (-dV/dx, -dV/dy, -dV/dz).
- **b.** If you know the electric field, then you can calculate V anywhere by taking a line integral of the E field. More precisely, you can say that for any two points A and B,

$$V(B) - V(A) = -\int_A^B \vec{E} \cdot d\vec{s}$$

You can still arbitrarily choose any one point to set V=0, but then the line integral above determines V everywhere else:

$$V(\text{any point } P) = -\int_{\text{the place where } V=0}^{P} \vec{E} \cdot d\vec{s}$$

The term *voltage* is often used as a synonym for "potential difference."

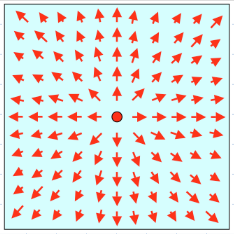
3. What if you know generally how the potential depends on location in space, but not necessarily the functional form of V(x, y, z)? Then the electric field is the vector which:

- **a.** *points in the direction in which V is decreasing most rapidly*; and
- **b.** has a magnitude equal to the *rate of change of V with respect to position along that direction*.

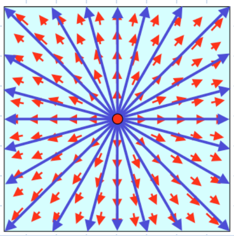
B. Visualizing the electric field and electric potential

1. It can be difficult to develop a useful intuitive understanding of the electric field, which is a vector quantity that is a function of position, i.e. it can be different at every point in space. Even the potential, which is a scalar (a single number) function of position, is not as simple a quantity as a charge or mass (which has only one value, and does not depend on position).

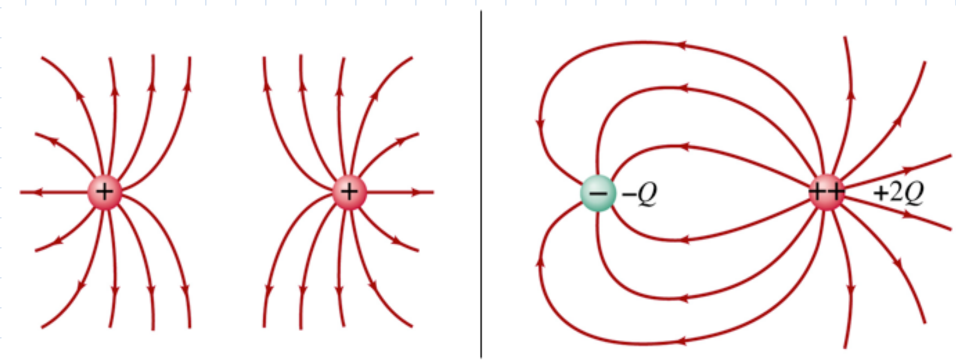
2. One way to visualize the electric field near an arrangement of charges is to draw zillions of tiny arrows, filling the page, each of which points in the direction of the electric field in its vicinity. For instance, the E field surrounding a positive point charge might be represented like this:



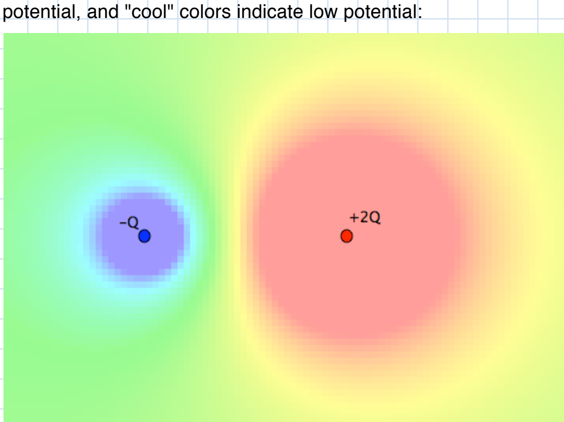
3. Constructing a diagram like the above is kind of a pain. In addition, you have the further pain that it's hard to indicate the magnitude of the electric field in such a representation: if you want to use long arrows for places where the E field is strong, you will find yourself encroaching upon neighboring points. Michael Faraday, in the 19th century, came up with a better plan: draw long, continuous arrows, which point along the direction of the E field (curving, if necessary, as the E field changes direction). Using this technique, we can make a simpler representation of the E field around a positive point charge:



The situation gets more complex, of course, if there are multiple charges. Below, you can see examples of the field lines around more complicated charge distributions (figures taken from Giancoli):

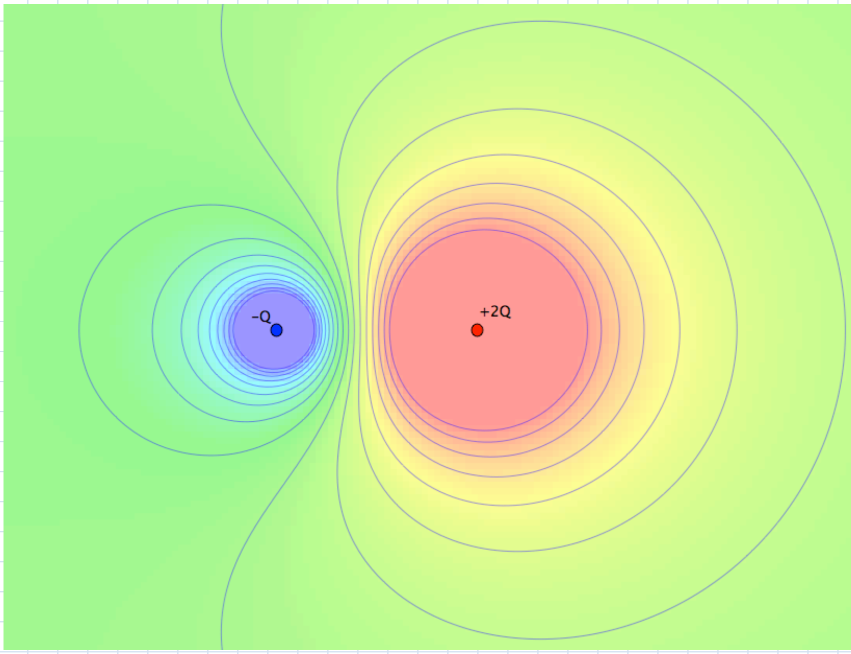


4. Visualizing the electric potential is a little bit easier, since we only need to think about one number at every point instead of a whole vector. For example, here is the same charge distribution as in the previous example (-Q and +2Q charges: you might also recognize this from last week's section problems), with the potential indicated by color: "warm" colors indicate high potential, and "cool" colors indicate low potential:



5. The above image won't look very good if you print it out in black and white. Also, it's very difficult to make such an image

without a computer. In fact, there is an easier way to represent the potential: by drawing **equipotential surfaces** (in 3 dimensions) or **equipotential lines** (in 2 dimensions). Equipotential lines, or contour lines, are lines of constant electric potential. So for instance, you might have one equipotential which includes all locations where V = 0, and another that includes all places where V = +1 volt. The above image could be rendered with equipotential contours drawn in like this:

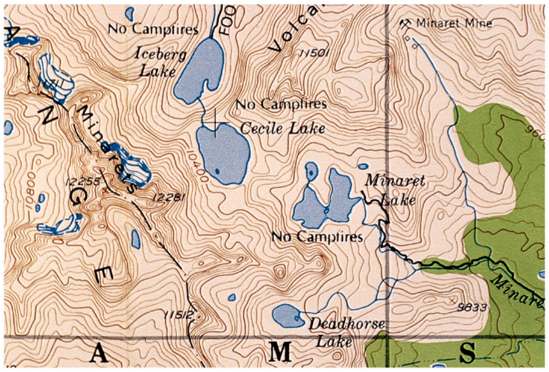


(Note: the contour lines very close to the point charges themselves have been suppressed. Otherwise there would be infinitely many of them in the small region around each charge. Likewise, all of the places that are at higher V than red are just shown as red; and all of the places that are at lower V than purple are just purple.)

6. Contour lines are *equally spaced in terms of potential difference*, but that is definitely not the same thing as saying that they are equally spaced on the page. In particular, regions where the contour lines are very close together (look at the region directly between the two charges in the above diagram are regions where the potential is changing rapidly with position. But mathematically, saying that the potential is changing rapidly with position is equivalent to simply saying that the *magnitude of the electric field is large*. Indeed, the E field between two opposite charges is strongest directly between them, and weaker further away or off-axis—and in the picture above, the contour lines are closely bunched between the charges, and spread further out off-axis, far away, or "behind" one charge or the other.

7. Another important rule about contour lines and electric field is that *field lines always meet contour lines at right angles*. That is because the E field always points in the direction where V is changing most quickly. It makes sense, then, that the direction perpendicular to the E field is the direction where V is not changing at all—in other words, the direction of the equipotential contour line.

8. If you've ever used a trail map while hiking, you've seen contour lines before. In topographical maps, instead of representing places of equal electric potential, contour lines represent places of equal elevation. (You could also think about these as lines of equal "gravitational potential.") If you walk along a contour line, you stay at constant elevation. If you walk perpendicular to a contour line, you are going either straight uphill, or straight downhill.



Similarly, if you "walk" along an equipotential contour line, the potential does not go up or down. If you walk perpendicular, you are going either in the direction towards higher V, or the direction towards lower V. The electric field points in the "downhill" direction, i.e. towards lower potential.

- **C.** Conductors
  - **1.** A *conductor* is a material with the property that the charge in it is free to move around. A material which does not have this property (i.e. one in which the charges are stationary) is called an *insulator*. In practice, almost all metals are good conductors and most other substances are insulators.
  - **2.** A good conductor in static equilibrium has the property that the electric field is zero everywhere inside. The reason is simple: if it weren't zero somewhere, the charge there would move in the direction of the field, so it wouldn't be in static equilibrium.
  - **3.** As a consequence of this fact, there can be no potential difference between any two points on a conductor in static equilibrium, because you could make a path between them which goes only through the inside of the conductor. The line integral of the E field along that path would have to be zero, because E would be zero everywhere along the path. So *in static equilibrium, all points in a conductor are at the same potential*.
  - **4.** Be careful about applying these facts too generally, because it's very easy to have a conductor which is *not* in static equilibrium. Indeed, this is why conductors are most often used: they can maintain a steady flow of charge, which we call current. We'll learn (much) more about current when we cover circuits. A conductor which is carrying a current is not an equipotential; instead, the current flows from high to low potential inside the conductor.
- **D.** Summary of rules for drawing field lines and contour lines
  - **1.** The relationships between field lines and contour lines are outlined below. You don't need to know any calculus to use these rules, but they are all derived from the mathematical relationship between the electric field and V.
  - **2.** Electric field lines...
    - **a.** Begin on + and end on - charges
    - **b.** Do not begin and end except on charges (or at infinity)
    - **c.** Always point from high potential to low potential
    - **d.** Always point in the direction the potential is decreasing most rapidly ("downhill")
    - **e.** Never form closed loops
    - **f.** Never cross other field lines
    - **g.** Always cross equipotential contours at right angles
    - **h.** Are closer together in areas where the field is stronger
  - **3.** Equipotential contours...
    - **a.** Always form closed loops (except at the boundary of the paper)
    - **b.** Always cross field lines at right angles
    - **c.** Never cross other equipotential contours
    - **d.** Are closer together in areas where the field is stronger
    - **e.** Never pass through conductors; any good conductor is an equipotential unto itself

III. Introduction

- **A.** In this lab, you will determine the electric potential produced by a set of electrodes held at a fixed voltage. 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. You can also use these lines to draw the corresponding electric field lines.

B. Objectives for the lab:

- **1.** Learn how to visualize electric fields and potentials using contour lines and field lines
- **2.** Plot contour lines using a digital voltmeter and a sheet of conductive plotting paper
- **3.** Understand the mathematical relationship between the electric field and the electric potential
- **4.** Learn how to "measure" the electric field using only voltage measurements

IV. Materials

A. Potential plotting board

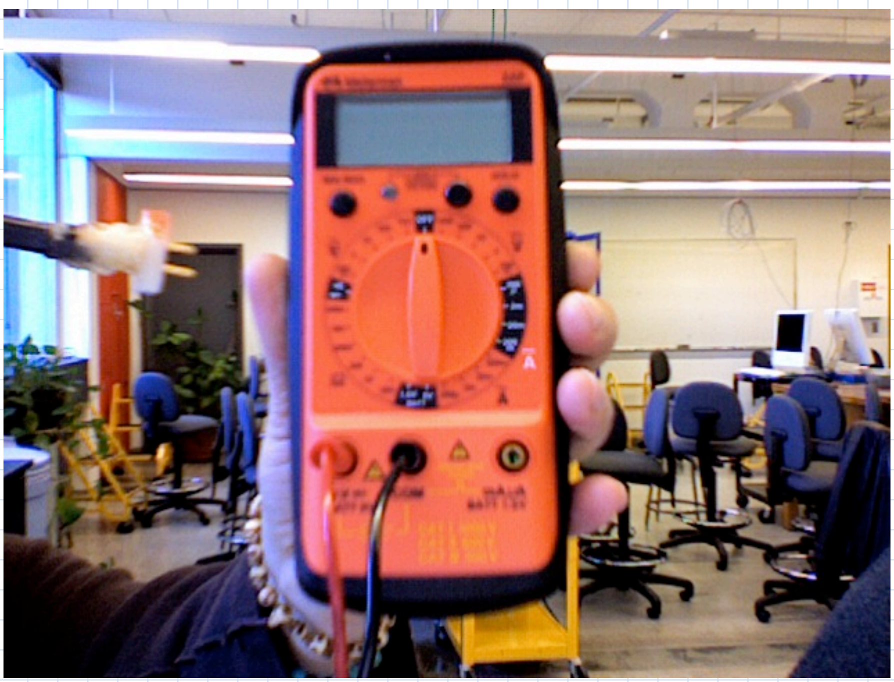
- **1.** This is just a board with two rows of screw holes which are electrically connected to the terminals at the edge of the board.
- **2.** Screwing an electrode tightly into one of the holes will create an electrical contact that will maintain the electrode at the same potential as the connected terminal.
- **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.

B. Conductive paper

- **1.** This is a sheet of carbon paper which is slightly conducting. Unlike a metal, the sheet itself is not such a good conductor that it is at the same potential everywhere. Rather, the presence of electrodes held at fixed potentials on the sheet will cause a distribution of potentials 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 will 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 fields in the paper.

C. 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 of 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 potential of the red probe minus the potential 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 bad will happen if you reverse the two—you will just get a negative reading if you put the red probe at a lower potential 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."

D. Electric field probe

- **1.** This two-pronged probe connects to your digital multimeter in place of the red and black single-pronged probes. It consists of two prongs 0.5 cm apart.
- **2.** This simple device converts your digital multimeter into an electric field meter. Simply press it down onto the conducting sheet (making sure both prongs are in contact with the paper), and read off the voltage from the multimeter. Double that number and you have the electric field strength at that location (or at least, in that vicinity), in units of volts per cm.
- **3.** Note the polarity of the device. The red (positive) probe of the multimeter is connected to the probe at the head of the arrow, and the black probe is at the tail of the arrow. So the probe will give a positive reading when the arrow points in the direction of increasing potential. Which direction does the electric field point?
- **4.** Recall that electric field is a *vector*; the probe only measures the projection of the field in the direction of the probe's orientation. If you orient the probe perpendicular to the actual direction of the field, you will get a reading of zero. If you orient it parallel to the field, you will get (plus or minus) the magnitude of the field. If you don't know the direction of the field, you can use the probe to determine its components (E_x, E_y) by measuring the field strength in the horizontal and vertical directions. Then you can use your knowledge of vectors to determine the magnitude and direction of the vector **E**.

E. DC power supply

- **1.** This supply will maintain a constant voltage between its terminals. The red terminal is held at a higher potential 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 push-button switch toggles between the 0 to 12 volt and 12 to 24 volt settings.

F. Selection of electrodes

- **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.

G. One white pencil and one red pencil

- **1.** These pencils will make non-conductive marks on the paper, unlike a regular lead pencil.

H. Conductive tape

- **1.** This is specialized adhesive tape which is conducting on both sides.
- **2.** This will be used in place of electrodes for the last part of the lab.

V. Procedure

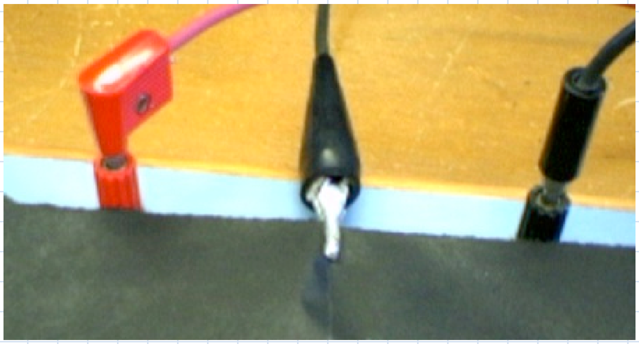
A. Before you begin...

- **1.** Take a picture of your lab group using Photo Booth and drag it into the space below:
- **2.** Tell us your names:
- **3.** Make sure you go over the descriptions of the materials you will be using, so that you will know how to use everything properly.

B. Drawing equipotential contours

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.

- **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 either two small circles, or two long bars, so that you get one of the configurations you made predictions for in the pre-lab exercise. (Your TFs should tell you which configuration to use.) 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 knob 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:



You will measure all voltages relative to this location.

- **5.** Using the red probe of the multimeter, measure the potential of the positive and negative terminals of the board relative to the point halfway in between them where you clipped the alligator lead in the previous part. You should get approximately equal and opposite numbers. If you don't, adjust the position of the alligator clip a little bit to one side or the other to balance them. When you are satisfied with your results, record the voltages here:
  Voltage of + terminal:
  Voltage of - terminal:
- **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 a reading of half of the voltage of the positive supply. When you find such a point, mark it with the white pencil.
- **8.** Move the probe several centimeters away from your previous point and try to find another point at the same potential. Mark it with the pencil. These two points are the beginning of your plot of an equipotential contour at this potential.
- **9.** Continue in this fashion until your contour either closes in on itself or reaches the edge of the paper. At the 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. Far from the electrodes, you probably only need a point every few inches. The idea is to plot just enough points that you can be fairly sure of the shape of the equipotential contour. If you reach the edge of the sheet before the contour closes in on itself, go back to your original starting point and trace the contour in the opposite direction.
- **10.** Using the white pencil, connect the points you have plotted with a smooth curve, and then label the curve with its potential.
- **11.** Repeat steps 7-9 for contours at 0 volts and half of the negative supply. You should switch tasks among the members of your lab group for the different curves.

C. Exploring the electric field

- **1.** Using the red pencil, draw in the electric field lines. Be sure to indicate the direction of the field. Refer to the rules for field and contour lines in the introduction if you do not know how to do this. If you don't have enough contour lines to make an accurate drawing of the field lines, plot some more. A good way to choose which potential to look for is by simply selecting a point about halfway between two existing contours and measuring the voltage there; then plot out the entire contour which passes through that point.
- **2.** How does your paper look compared with the prediction you made in the pre-lab exercise?
- **3.** When you reach this point, talk to your TF. Your TF will indicate four points on your sheet where you are to measure the electric field, using the electric field probe.
- **4.** Remember, the electric field probe only measures one component of the field. To determine the direction, you can either measure the x- and y-components and then use the equations for vector components, or you can just turn the probe until you get a reading of zero, which occurs when the probe is perpendicular to the field.
- **5.** Does your sketch of field and contour lines correctly indicate the direction of the electric field at the four points?
- **6.** Does your sketch correctly indicate the relative electric field strength at the different points?
- **7.** Unscrew your electrodes and remove the sheet of conducting paper. Write your names and your lab section time on it, and turn it in to your TF.

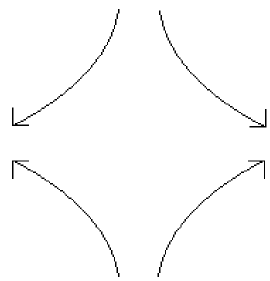
D. Using a fresh sheet of plotting paper, go back and repeat the exercise for the other arrangement of electrodes (i.e. if you started with circular electrodes, do the bars; if you started with bars, do the circles). You don't need to do as many points or as many contour lines the second time; just enough to get an idea of where the contour lines are and which way the field lines go.

After you draw in a few contour lines and a few field lines, you can move on to the next part; you don't need to determine the E field at any particular locations.

E. Challenge puzzles

In this part of the lab, you will be given a diagram of an electric field and asked to determine a configuration of conductors that will produce such a field.

- **1.** Get a fresh sheet of conducting paper and place it on your board. Again make sure that the edges curl upwards.
- **2.** Using Scotch tape, tape the corners of the sheet down to the board.
- **3.** Your goal is to produce the electric field shown below:
  - **a.**



- **4.** Instead of using electrodes bolted into the board, this time you will use pieces of conductive tape. This gives you more flexibility, as you are not limited by the locations of the screw holes in the board.
- **5.** You can use as many or as few pieces of tape as you like (although you must have at least two). For each piece of tape, leave the edge of it curled up instead of stuck to the paper. Attach an alligator clip lead to the edge of the tape to provide an electrical connection to the power supply.
- **6.** Before you start slapping tape down all over the place, consult with your lab partners and try to draw the arrangement you think will produce the desired field. Once you all agree, then put it into practice.
- **7.** When you have arranged your conducting tape in the desired configuration, attach the power supply. Using the electric field probe, determine the electric field direction in key places to see if your configuration actually produces the electric field in the diagram. If not, think about why it didn't work and try again. Talk to a TF if you get stuck.
- **8.** If you successfully finish, get another sheet and try to produce the following configuration:
  - **a.**

  - **b.** You only need to have the field at those two locations point in the indicated directions; anywhere else, it can look however you want. Be warned, though, that this is not as easy as it might sound.

VI. Conclusion

- **A.** Follow the instructions on the laminated sheet at your computer in order to submit the lab report electronically. Remember, you must submit once for each member of your lab group, so that everybody will have their own copy of the report.
- **B.** Congratulations--that's it for this first lab!