LABORATORY IV:
ELECTRIC FIELD AND POTENTIAL

Many forces in nature cannot be modeled as contact forces, such as those you have used to describe collisions or friction interactions. Forces sometimes characterized as “action-at-a-distance” involve an objects exerting forces on each other although not in physical contact. The gravitational force, in fact, fits this characterization. You are just now learning about another action-at-a-distance force: the electric force. Action-at-a-distance can be difficult to fit into our physics framework for two reasons. First, it is hard to conceive of objects interacting when they are not touching. Second, objects that interact by these action-at-a-distance forces form systems that can have potential energy. The concept of action-at-a-distance does not satisfactorily describe where this potential energy resides.

The notion of a "field" solves these problems. In a field theory, an object affects the space around it, creating a field. Another object entering this space is affected by that field and experiences a force. In this picture the two objects do not directly interact with each other; one object creates a field and the other object interacts directly with that field. The magnitude of the force on an object is the magnitude of the field at the space the object occupies (caused by other objects) multiplied by the property of that object that causes it to interact with that field. In the case of the gravitational force, that property is the mass of the object. In the case of the electrical force, it is the electric charge. The direction of the electrical or gravitational force on an object is along the direction of the field (at the object's position). The potential energy of the system can be envisioned as residing in the field.

Thinking of interactions in terms of fields solves the intellectual problem of action-at-a-distance. It is, however, a very abstract way of thinking about the world. We use it only because it leads us to a deeper understanding of natural phenomena and inspires the invention of new devices. The problems in this laboratory are primarily designed to give you practice visualizing fields and their associated potentials, and in using the field concept to solve problems.

In this laboratory, you will first explore electric fields by building different configurations of charged objects (physically and with a computer simulation) and mapping their electric fields and potentials. In the last two problems of this lab, you will measure the behavior of electrons moving through an electric field and compare this behavior to your calculations.

As you progress through the problems in this laboratory, pay particular attention to learning about relationships among (and differences between) the oft-confused concepts of *field*, *force*, *potential*, and *potential energy*.

OBJECTIVES:

After successfully completing this laboratory, you should be able to:

- Qualitatively determine the electric field at a point in space caused by a configuration of charged objects based on the geometry of those objects.
- Calculate the electric field at a point in space caused by a configuration of charged objects based on the geometry of those objects.
- Qualitatively determine the electric potential at a point in space caused by a configuration of charged objects based on the geometry of those objects.
- Calculate the electric potential at a point in space caused by a configuration of charged objects based on the geometry of those objects.
- Relate the electric field caused by charged objects to the electric potential caused by charged objects.

PREPARATION:

Read sections 19.1-19.7 and 20.1-20.4 in Serway & Jewett.

You may find the supplementary text, "There Are No Electrons" by K. Amdahl, (ISBN 096 278 1592), a useful resource for conceptual understanding of electricity.

Before coming to lab you should be able to:

- Apply the concepts of force and energy to solve problems.
- Calculate the motion of a particle with a constant acceleration.
- Write down Coulomb's law and understand the meaning of all quantities involved.
- Add vectors in two dimensions.
- Calculate the electric field due to a point charge.
- Calculate the electric potential due to a point charge.

PROBLEM #1:
ELECTRIC FIELD VECTORS

As part of your internship with a local power company, you have been assigned to a team reviewing published research about the effects of electric fields on human health. To evaluate the merits of apparently conflicting research, you need a computer program to simulate the electric field due to complicated charge configurations. Your team leader has assigned you the task of evaluating such a program. To test the program, you will compare its predictions to your own understanding of the electric field created by a few simple charge configurations. You start with the very simple configuration of a single positive charge. You then try a single negative charge. Finally, you consider a positive charge near a negative charge of equal magnitude (a dipole configuration.) Qualitatively, determine the electric field distributions of a single positive charge, a single negative charge and a dipole.

EQUIPMENT

You will use the computer application EM Field. This program will draw the electric field vector at any point near any given charge distribution. Instructions for use of the program are in the program.

PREDICTION

Using your knowledge of the forces exerted by charged objects, draw vectors representing the electric field around the following charge distributions: (i) A positively charged point object; (ii) A negatively charged point object; (iii) A dipole (two equal but oppositely charged point objects separated by a small distance). As usual, the length of the vector should represent the magnitude of the field. In each case, draw enough vectors to give a qualitative idea of the behavior of the field. Where do you think the electric field will be the strongest? The weakest?

WARM-UP

Read Serway & Jewett: sections 19.2, 19.5, 19.6.

To solve this problem it is useful to have an organized problem-solving procedure such as the one outlined in the following questions.

1. Draw a positively charged point object. What does the electric field look like surrounding a positive charge? How is this different from the field surrounding a negative charge?

2. At a point in space some distance from the positively charged point object, imagine you have another positively charged point object. The force on such a "test charge" (1 Coulomb) is the electric field at that point due to the charge configuration. Draw a vector representing the magnitude and direction of the force on the test charge due to the other charge.

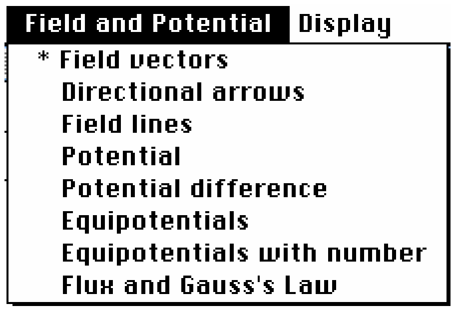
3. Now move your test charge to another point and draw the vector representing the force on it. (How does the magnitude of the force on the test charge depend on its distance from the positively charged point object? Make sure the length of your vector represents this dependence.) Continue this process until you have a satisfactory map of the electric field in the space surrounding the positively charged point object.

4. Repeat the above steps for a negatively charged point object and a dipole. (Should your test charge have a positive or negative charge in these cases?) For the dipole, remember that if two objects exert a force on a third object, the force on that third object is the **vector sum** of the forces exerted by each of the other objects.

EXPLORATION

Before beginning to use the computer simulation, do a quick check to see if the program works the way you think it should.

Open EM Field and click anywhere in the window for the instructions. From the *Sources* pull-down menu, select *3D point charges*. Drag any positively charged point object to the center of the window of EM Field. Select *Field vectors* from the *Field and Potential* pull-down menu (as shown)



Move the cursor to where you would like to place a field vector and click the mouse button. An electric field vector should appear. Repeat this procedure until you have created a reasonable map of the electric field. To clear the EM Field window, select *Clean up screen* from the *Display* pull-down menu.

You can get a second visual representation of the electric field by selecting *Directional arrows* from the *Field and Potential* menu. In this representation all arrows are the same length and the magnitude of the field is given by its color. Try this out for a single positively charged point object. If you switch to *Field vectors* without clearing the screen, you can see how the representations correspond to each other. Unfortunately, the *Directional arrows* representation is poor for printing on black and white printers.

Repeat your favorite electric field representation for a single negatively charged point object. How does the direction and magnitude of the electric field compare to that for the positively charged point object? Try clearing the screen and selecting a larger charge. What happens to the electric field?

Clear the screen and create a dipole by dragging two equal, but oppositely charged point objects onto the window of EM Field. You may want to use the *Show grid* and *Constrain to grid* features in the *Display* pull-down menu to position your dipole. Using your favorite electric field representation, make a map of the electric field caused by a dipole. Make sure that you carefully map the electric field at points along all axes-of-symmetry of the dipole.

Try a different spacing between the two charged objects in the dipole to see how that changes the electric field map. Try larger charges.

If you are very far away from the dipole, how does the field compare to that due to a single charged point object? How about when you are *very* close to one of the charged objects in the dipole?

MEASUREMENT

Use EM Field to get the electrical field distributions of a positive charge, a negative charge and a dipole. Print out the result of vector representation (select *Print Screen* from the *File* pull-down menu).

You should experiment with and print out other electric field representations. Specifically, try to understand what role symmetry plays in the creation of electric fields.

ANALYSIS

Look at the electric field graphs of the single positive charge and the single negative charge. What is the same about the two graphs, and what is different?

Qualitatively, can you re-create the electric field vector due to the dipole at any point by *adding* the electric field vectors due to the positive charge and the negative charge? Select several points and try. Explain why this technique does or does not work.

Looking at the electric field map of your dipole, imagine a positively charged point object at the tail position of each vector. Where is the force on the "imaginary" object the greatest? The least? How would the force change if the "imaginary" object were negatively charged?

CONCLUSION

How does each of the printed field maps compare with your prediction? Investigate both direction and magnitude of the electric field vectors on these printouts. How does the magnitude of the electric field change with position in each case? Where is the field strongest in each case? How is this shown in your map? Where is the field weakest in each case?

For the dipole, how does the magnitude of the electric field change with the position change along (a) the line passing through both charged objects of the dipole, and (b) the line passing through the dipole's center and perpendicular to the first line. Can you generalize this observation?

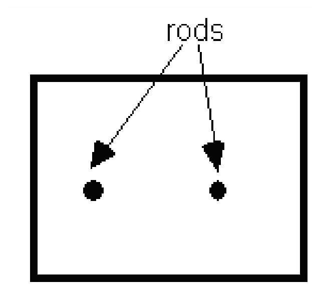
Suppose the objects making up your dipole were fixed in space, and that you placed a positively charged mobile object nearby. If the mobile object started at rest, how would it move? (Be careful not to confuse the object's acceleration with its velocity!) Does the way the mobile object moves depend on where you start it?

PROBLEM #2:
ELECTRIC FIELD OF A DIPOLE

In your summer job with a bioengineering company you have been studying the electric fields generated by Amazonian Electric Eels. Your specific assignment is to test a portable instrument designed to measure electric fields underwater. To find out if it works correctly, you decide to use it to determine the electric field created by a simple pattern of charged objects. You create a two-dimensional dipole field by giving two parallel metal rods opposite charges with a battery while their tips are touching conductive paper (meant to simulate a thin layer of water).. You then measure the electric field on the paper. Determine what electric field pattern is created by the tips of two metal rods with opposite charge.

EQUIPMENT

You will be using the conductive paper setup described in Appendix D. There is a coordinate grid drawn on the conductive paper. Two brass rods (electrodes) stand upright with their tips in contact with the conductive paper and connected to opposite terminals of a battery or power supply. The electric field probe (Pin Tip Probe) should be connected to a digital multimeter (DMM) set to read volts. You will also have the EM Field program. A white sheet of paper with a grid similar to the grid on the conducting paper is useful for recording the field (**do not write on the conductive paper**).



Overhead view of conductive paper for this problem.

PREDICTION

Based on your knowledge of the strength and direction of the electric force, sketch a map of the electric field created in a plane perpendicular to two parallel metal rods with opposite charges. Where do you think the electric field will be the strongest? The weakest? Do you anticipate any symmetry in the strength and/or direction of the field vectors?

When you get to lab, check your sketch by making a field map of *2D charged rods* using the EM Field simulation.

WARM-UP

Read Serway & Jewett: sections 19.2, 19.5, 19.6.

1. Draw a picture of the dipole similar to the one shown in the equipment section. Label one of the charged point objects "+" and the other "-".

2. At a point in space some distance from one charged object, imagine you have another positively charged point object. Draw a vector representing the force on that "imaginary" object. How does the magnitude of the force on the "imaginary" object depend on its distance from the positively and negatively charged objects that you drew originally? Make sure the length of your vector represents this dependence. Remember that if two objects exert a force on a third object, the force on that third object is the vector sum of the force exerted by each of the other objects.

3. Now move your "imaginary" object to another point in space and draw the vector representing the force on it. Continue this process until you have a satisfactory map of the electric field in the space surrounding the dipole.

EXPLORATION

You may compare your prediction with a field map of *2D charged rods* produced by the EM Field simulation program, located on the desktop. For instructions on how to use this program see the Exploration section of Problem 1.

Set up the conductive paper as instructed in *Appendix D*. For use of the DMM and power supply, see *Appendix D*.

Once the rods are connected to the battery, set the digital multimeter (DMM) to volts and turn it on. Place the tips of the probe on the conductive paper midway between the tips of the two rods. Does the probe measure the electric field? What does the probe measure? Based on your warm-up questions, what is the direction of the electric field at that position? Rotate the probe so that the center of the probe stays in the same spot. Record the meter readings as you rotate the probe. Do the values change (pay attention to the sign)? Is there a minimum or maximum value? Are there any symmetries in this data? If there are large fluctuations, determine how you will measure consistently. Describe how you will use the probe to determine the field **direction** at other points.

Now place the field probe near, but not touching, one of the rods and rotate the probe as you did before. Record your data. Determine the direction of the electric field. Compare the maximum DMM reading at this point to the one you found at the midway point. Compare your measurements to your prediction; does the value displayed on the DMM become larger or smaller when the electric field becomes stronger? Describe how you will use the probe to determine the electric field **strength** at other points.

Where on the conductive paper is the electric field strongest / weakest? Does this match your prediction?

Complete your measurement plan for mapping the electric field on the conductive paper. How will you record the magnitude and direction of the electric field at each point?

MEASUREMENT

Select a point on the conductive paper where you wish to determine the electric field. Place the probe on the conductive paper at that point and rotate until you have found the direction of the electric field. Record the magnitude and direction of the field at that point by drawing a vector in your lab journal or on a sheet of white paper with a grid pattern similar to that on the conductive paper. At each point, take at least two measurements of magnitude and direction to gain a measure of your uncertainty.

Repeat for as many points as needed to check your prediction. When you have taken enough data, you will have a map of the electric field.

CONCLUSION

How does your map compare to your prediction? How does it compare to the simulation program? Where is the field the strongest? How do you show this in your map? Where is the field the weakest? How do you show this in your map?

PROBLEM #3:
ELECTRIC POTENTIAL DUE TO MULTIPLE CHARGED OBJECTS

You are a member of a team designing a compact particle accelerator in which ions of low-Z atoms will be directed at radio resistant malignant tumors. Charged atomic nuclei will be accelerated when they pass through a charged electrode structure. The team must determine the effect of several electrode configurations on the final speed of various nuclei. The charged electrode configuration will be extremely complicated, so your team has decided to use a computer simulation. The first step is to calculate the electric potential that will affect the nuclei.

Your immediate task is to determine if the simulation can be trusted. You decide to calculate the electric potential caused by a set of charged objects complex enough to test the simulation, but simple enough for direct calculation. The first configuration that you try is a square with two equal negatively charged point objects in opposite corners and a positively charged point object of $\frac{1}{3}$ the magnitude of the negative charges in a third corner. You will calculate the electric potential at the remaining corner of the square and compare your result to that of the computer's simulation of the same configuration. What is the electric potential at the corner of a square made of charged point objects?

EQUIPMENT

You will use the computer program EM Field.

PREDICTION

Two equal negatively charged point objects are in opposite corners of a square. A positively charged point object, with a charge of $\frac{1}{3}$ the magnitude of the negative objects, is located in a third corner of the square. Calculate the electric potential at the fourth corner of the square.

WARM-UP

Read Serway & Jewett: sections 19.2, 19.5, 19.6, 20.1, 20.2, 20.3.

The following questions should help with your prediction.

1. Make a picture of the situation. Label the objects and their charges. Draw and label all relevant distances and angles. Draw appropriate right triangles so that you can use the Pythagorean theorem to find needed distances.

2. What variables affect the potential at the unoccupied corner of the square? For each charged object, write down a formula expressing the electric potential from that object at the point of interest.

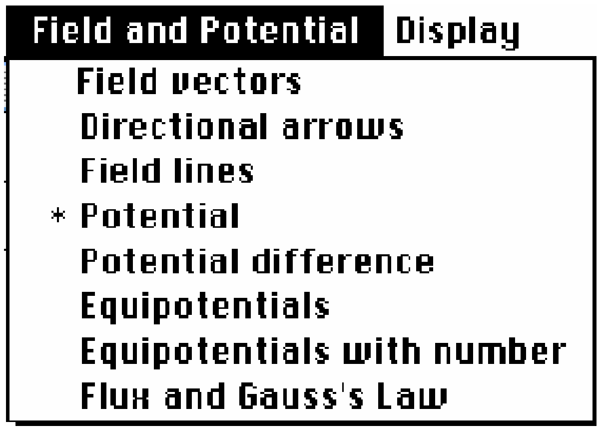
3. Add the electric potentials due to each of the charged objects to find the potential at the unoccupied corner due to all three of them. This "adding" up of different charges is possible by the principle of "Linear Superposition."

EXPLORATION

Before beginning to use the computer simulation, do a quick check to see if the program works the way you think it should.

Open EM Field and click anywhere in the window for the instructions. From the *Sources* pull-down menu, select *3D point charges*. Drag any positive charge to the window of EM Field.

From the *Field and Potential* pull-down menu (as shown to the right), select *Potential*. Move the cursor where you would like to determine the electric potential and click the mouse button.



When using the program quantitatively, use the *show grid* and *constrain to grid* features of the program (from the *display* pull-down menu). To expand the display window to fill the entire screen, click the small box in the top-right corner of the window.

Another useful way of viewing the electric potential is using equipotential surfaces. Select *Equipotentials with number* from the *Field and Potential* pull-down menu. Move the cursor where you would like to determine the electric potential and click the mouse button. How is this different from the *potential* setting?

Try using different magnitudes of charge. What range of charge values allows you to accurately measure the electric potential at a large number of locations on the screen?

Try using negative charges. How does this change the electric potential?

Check to see if you get the correct behavior of the electric potential from a point charge:

- Make a graph of the electric potential as a function of the distance from the center of the charged point object. What features of the graph help you determine if the simulation displays potential correctly, for a point charge?
- Re-graph the same electric potential values versus the inverse distance from the point charge, $\frac{1}{r}$. What shape do you expect for this graph? Why? Does the graph match your expectation? For more on this topic, see *Appendix C*, "How do I linearize my data?"

Now, qualitatively check to see if the program combines the electric potentials from two charged point objects correctly. First examine the potential at several points due to a dipole configuration. Does it behave as you expected? Does it go to zero where you would expect it to? Second, examine the potential at several points due to two identical charges (positive or negative). Does it behave as expected?

You may notice that the potential measurements given by the computer are in a foreign set of units. You will have to translate the computer-generated measurement into an actual electric potential in appropriate units. To do so, you must calibrate the computer simulation program using a charge distribution whose actual electric potential can easily be determined:

- You have already collected a set of electric potentials for different distances from a single charged point object (of different magnitudes).
- Calculate the actual electric potential for this set of charges and distances.
- Graph the set of simulated electric potentials vs. the corresponding calculated electric potentials. Knowing the slope of this curve, you can translate a number the *computer gives* for the electric potential into an *actual* electric potential in the appropriate units. (What are the units of the slope?) Be sure you can explain the translation procedure to your teammates. Record information for translation, as you will need it later.

MEASUREMENT

Place charges on the screen to simulate the situation described in the problem. Measure the electric potential of an object at the point of interest.

ANALYSIS

For the situation in the problem, compare your calculated electric potential to that from the computer simulation.

CONCLUSION

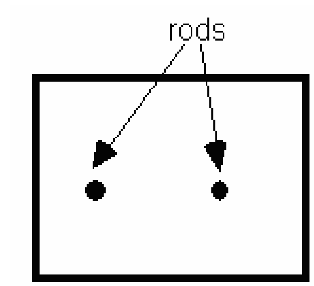
Did your results match your predictions? Explain any differences.

PROBLEM #4:
ELECTRIC FIELD AND POTENTIAL

You work for a team consulting with a company that produces technology for medical education. A school has asked the company to produce cheap, durable equipment that can measure and depict the electric field and the electric potential distribution inside a human body. The equipment will be used in the education of EKG technicians. Because the electric field and electric potential are related, you know that it is not necessary to measure both the field and potential directly. To convince yourself and the company that it is appropriate to measure only the potential distribution, you decide to investigate a method of determining the electric field from the electric potential. You decide to investigate a single dipole first, since many electric fields and electric potentials can be modeled in terms of dipole combinations. Determine the electric field and electric potential near a dipole and how the field and potential are related.

EQUIPMENT

You will be using the conductive paper setup described in Appendix D. There is a coordinate grid drawn on the conductive paper. Two brass rods (electrodes) stand upright with their tips in contact with the conductive paper and connected to opposite terminals of a battery or power supply. The **single-tip probe** is connected to the DC voltage socket of a digital multimeter (DMM) set to read DC volts. The GND socket of the DMM is connected to the ground of the power supply or the cathode of the battery. You will also have the EM Field program.



Overhead view of conductive paper for this problem.

NOTE: The probe is *not* the one used in problem #2.

PREDICTION

Qualitatively sketch equipotential lines for the dipole. Potential differences between adjacent pairs of equipotential lines in the sketch should be approximately equal. Based on the equipotential lines, sketch electric field vectors at several points. Explain your method.

WARM-UP

Read Serway & Jewett: sections 19.2, 19.5, 19.6, 20.1, 20.2, 20.3, 20.4.

1. On a piece of paper, draw a horizontal axis and a vertical axis. Place two charged objects on the horizontal axis so that they create a dipole centered around the vertical axis. (Leave enough space between the objects so that at least five equipotential lines will fit between them.)

2. How is the electric potential due to the two point-like charged objects of a dipole related to the potential due to each of the objects? Write an equation describing the dipole electric potential on your paper. Clearly identify all variables.

3. Calculate the electric potential at the point where the axes intersect, and label the point with its potential. What other points have the same potential? Draw the line connecting those points (an equipotential line). Select another point on the horizontal axis between the two charges, label it with its electric potential, find other points with the same electrical potential, and sketch the equipotential line associated with that point. Repeat for at least three more equipotential lines. (Be sure to keep a constant potential difference between adjacent lines.) You may be able to intuitively see where the equipotentials lie, but better results can be obtained with the equation formed in **(2)**.

4. What symmetry would you expect to see in the equipotential lines? Do your equipotential lines exhibit that symmetry? Since pairs of adjacent lines have equal potential differences, would you expect them to be equally spaced on the paper? Why or why not?

5. What is the relationship between electric potential differences between two points and the electric field? How would you find the direction of the electric field vector at a point on an equipotential line? How would you find the magnitude of the electric field vector at a point on an equipotential line? Qualitatively sketch the electric field vectors at several points on each equipotential line. (The relative lengths of the lines should indicate the relative magnitudes of the electric field at the points.)

EXPLORATION

Set up the conductive paper as instructed in *Appendix D*. For use of the DMM and power supply, see *Appendix D*.

If you use the power supply, set it to provide no more than 15 Volts DC.

Connect the two rods representing a dipole to the battery or power supply. Connect the single-tip probe to the DC voltage socket of the digital multimeter (DMM). Use a wire to connect the GND socket of the DMM to the cathode of the battery or the GND of the power supply.

Turn on the power supply. Be careful to avoid a short circuit. Place the tip of the probe against the paper. The DMM displays a value of voltage. What does it mean? Move the tip to other places. Observe whether the value displayed in DMM changes. What does the change mean?

Try to stabilize the tip on the paper. Can you get a stable value from the DMM? Is there a fluctuation due to the small shaking of your hand? If there is large fluctuation, how will you make your measurement consistently? Estimate the uncertainty in your measurements of electric potential.

Select a point between the two rods of the dipole. Put the tip at this point and read the value from DMM. On your copy of the grid, record the voltage reading for that point. Find more points that produce the same voltage reading, and mark your copy of the grid to indicate their positions. Connect your marks with a smooth curve. What does the curve mean?

Practice the above process and find more similar curves.

MEASUREMENT

Record the voltage reading given by the DMM at the point midway between the two rod-points that form the dipole. As in the exploration, find other points that produce the same reading and connect them with a smooth curve.

Make a voltage reading at a second point, and repeat the process of producing a curve of constant voltage readings. Calculate the difference in voltages between points on this curve and points on the first one.

Repeat the process for at least three more points (curves). Be sure that the voltage difference between adjacent curves is constant.

ANALYSIS

What is the significance of the curves of constant voltage readings you have created? How are they related to the warm-up questions?

Write down the equation that expresses the electric field in terms of spatial variation in the electric potential. Based on the equation, develop a technique to estimate the direction and magnitude of the electric field for a point on a curve of constant voltage readings. (Hint: What are the units of electric field and potential?) What assumptions must you make to estimate electric fields based on the limited amount of data you have collected about voltage in the water tank?

Use your technique to estimate the magnitude of the electric field at several points along curves of equal voltage readings. Create a map of the electric field on your copy of the grid, by drawing arrows to represent the direction and magnitude of the field at each of those points.

CONCLUSION

What parts of your measured map correspond to parts of your predicted map of electric potential and field for a dipole? Can you account for any differences? How do these maps of electric field compare to your dipole results in problems 1 and 2? Can you account for any differences?

Symmetries should be apparent in your map of potential. Can you explain these symmetries with your prediction equation?

Use the <u>EM Field</u> program to simulate a dipole, and use the software to draw equipotential lines (with constant potential difference between adjacent lines). Select several points on the equipotential lines, and show electric field vectors for those points. Print out the result.Compare the simulation result with your measured result.

Is the method used here, deriving the electric field from electric potential, reasonable? How could you improve its accuracy? *Is it possible to determine the electric potential from the electric field? Do you think it would be better or worse (for the team's medical education project) to measure the electric field directly and derive the electric potential, or to measure the electric potential directly and derive the electric field?*

PROBLEM #5:
DEFLECTION OF AN ELECTRON BEAM BY AN ELECTRIC FIELD

As in problem #3, you are a member of a team designing a compact particle accelerator in which ions of low-Z atoms will be directed at radio resistant malignant tumors. Charged atomic nuclei will be accelerated when they pass through a charged electrode structure. The team has moved on to the problem of aiming the atoms that emerge from the accelerator. You plan to add controls to the accelerator that will aim the beam by passing it through a region with an adjustable electric field. You decide to use a cathode ray tube (CRT) to model the particle accelerator and study the plan. In the CRT, electrons are emitted at one end of an evacuated glass tube and are detected by their interaction with a phosphorous screen on the other end. Inside the tube, the electrons pass between two sets of parallel plates: one set oriented horizontally, and another oriented vertically. If an electron beam passes through a perpendicular electric field, how does the deflection of the beam depend on the strength of the perpendicular field?

EQUIPMENT

You will be using the Cathode Ray Tube described in Appendix D. The fluorescent screen has a centimeter grid in front of it so you can measure the position of the beam spot. The applied electric field is created by connecting the internal parallel plates to a battery or power supply. **Note that you will be using the deflection plates as described in Appendix D, "Cathode Ray Tube (CRT) and accessories".**

PREDICTIONS

Calculate how the electric field between the horizontal deflection plates affects the position of the electron beam spot. Use this equation to make a graph of deflection as a function of the strength of the electric field between the plates.

WARM-UP

Read Serway & Jewett: sections 19.2, 19.5, 19.7.
Review Kinematics if neccessary: Read Serway and Jewett: Chapters 3 and 4.

Preamble: *This problem involves kinematics, which many students have forgotten about by this time of the semester. It is suggested that you complete the following problem before starting on the rest of the warm-up questions.* A herd of Holsteins in Montana has been snowbound for several days by an early October snowstorm. Their owner decides to drop bales of hay to the starving cows from his crop duster. If the rancher is flying at an altitude h, with horizontal speed V_{ox}, how soon, in distance and time, before he flies over them should he drop the bales of hay? Ignore crosswinds and air resistance. Answer: horizontal distance = $V_{ox}t = V_{ox}\sqrt{\frac{2h}{g}}$, time = $\sqrt{\frac{2h}{g}}$

1. Draw a picture of the important components of the CRT. Only include one set of the deflection plates shown in Appendix D. Draw a coordinate axis on this picture. Draw the trajectory the

electron would take if there were no electric field between the plates. If there is an electric field between the deflection plates, will there be *regions* where different forces act on the electron? Label these regions. Draw the trajectory the electron would take if there were an electric field between the plates. On the trajectory, draw and label arrows representing the electron's velocity and acceleration for each region. The distance between where these two trajectories hit the CRT screen is the *deflection*.

2. What forces cause electrons to accelerate in each region? On your picture, draw an arrow representing each force. (Are there any forces you can assume to be negligible?) For each region, sketch a motion diagram showing the electron's trajectory and the electron's velocity and acceleration as it enters the region, while it is in the region, and when it leaves the region. Qualitatively describe the shape of the electron's trajectory in each region.

3. The magnitude of the electric field (in Newtons per Coulomb) between two equally charged parallel plates is equal to the voltage between the two plates (in Volts) divided by the distance between the plates (in meters). What is the direction of the electric field between the two accelerating plates? How much energy is transferred to the electron by this accelerating field? Using conservation of energy, write an equation for the electron's velocity as it leaves the electron gun in the CRT. What is the direction of the electron as it leaves the accelerating field? What assumptions have you made?

4. What is the net force exerted on an electron as it travels through the region between the deflecting plates? Use Newton's second law to write an equation for the acceleration of an electron as it travels through this region. Is the electric field constant in the region between the deflecting plates? What does that tell you about the acceleration of the electron in that region?

5. Use your drawing from step 1 and kinematic equations for constant acceleration motion to determine the position and direction of the electron as it enters the region between the deflection plates and when it leaves that region. Write down an equation giving the electron's change in position as it emerges from the deflecting plates (how much it was deflected while traveling between the plates). Write another equation giving the electron's direction.

6. Use your drawing from step 1, the position and direction of the electron as it leaves the deflection plates, and geometry to write down an equation giving the position of the electron when it hits the screen. Use the deflection distance from each region to write an expression for the total deflection during the electron's motion through all regions of the CRT.

7. Examine your equations giving the electron's position at the screen. You want an expression for the total deflection in terms of the accelerating voltage, length of the deflecting plate region, distance from the plates to the screen, separation distance of the plates, and potential difference across the plates. Are there any other variables in your equation? You can solve them if the number of unknowns in your equations is equal to the number of equations. Is it? If it is, solve your equations algebraically for the deflection of an electron. If it is not, write down additional equations that relate some of the unknown quantities in your equations to quantities that you know.

8. Complete your solution by using the actual numbers that describe your situation. Refer to the distances shown on the diagram of the CRT in the Appendix.

   Does your solution make sense? If not, check your work for logic problems or algebra mistakes.

EXPLORATION

WARNING: You will be working with equipment that generates large electric voltages. Improper use can cause painful burns. One unfortunate student in a past year had a hole burned through his finger from improper use of the lab equipment. **To avoid danger, the power should be turned OFF and you should WAIT at least one minute before any wires are disconnected from or connected to the power supply. Never touch the conducting metal of any wire.**

Follow the directions in Appendix D for connecting the power supply to the CRT. Check to see that the connections from the power supply to the high voltage and the filament heater are correct, *before* you switch on the power supply. The electric potential difference between the cathode and anode should be in the range of 250V-500V. After a moment, you should see a spot that you can adjust with the knob labeled "Focus". If your connections are correct and the spot still does not appear, inform your lab instructor.

Before you turn on the electric field between the deflection plates, find the CRT orientation that gives no deflection of the electron beam. In this position the effect of all of the outside forces on the electron is negligible.

Now apply a voltage across one set of deflection plates, noting how the electron beam moves across the screen as the voltage is increased. How will you adjust the voltage level and how will you measure it? Write down the range of voltages for which you can make a good measurement. Repeat this procedure for the perpendicular set of deflection plates.

If you cannot make the electron spot sweep entirely across the screen, try changing the voltage between the anode and the cathode that you originally set somewhere between 250 and 500 volts. This voltage changes the electron's velocity entering the deflection plates. Select a voltage between the anode and cathode that gives you a useful set of measurements for your deflections.

Devise a measuring scheme to record the position of the beam spot. Be sure you have established the zero deflection point of the beam spot.

How will you determine the strength of the electric field between the deflection plates? What quantities will you hold constant for this measurement? How many measurements do you need?

Write down your measurement plan.

MEASUREMENT

Measure the position of the beam spot as you change the electric field applied to the deflection plates. Make sure you take at least 2 measurements at each point for averaging.

Note: Be sure to record your measurements with the appropriate number of significant figures (see Appendix A) and with your estimated uncertainty (see Appendix B). Otherwise, the data is virtually meaningless.

ANALYSIS

Draw a graph of your prediction equation of the deflection of the electron beam as a function of the voltage applied to the deflecting plates.

Draw a graph using your measurements of the deflection of the electron beam as a function of the voltage applied to the deflection plates.

CONCLUSION

How does the graph based on your data compare to the graph based on your prediction? If they are different, explain why.

How does the deflection of the electron beam vary with the applied deflection plate voltage? How does it vary with the applied electric field? State your results in the most general terms supported by your data.

PROBLEM #6:
DEFLECTION OF AN ELECTRON BEAM AND VELOCITY

You are continuing your attempt, from problem #5, to control the direction of charged particles emerging from a particle accelerator, and are still using a cathode ray tube (CRT) as a model. In the CRT, electrons are emitted at one end of an evacuated glass tube and are detected by their interaction with a phosphorous screen on the other end. While inside the tube, the electrons pass between pairs of charged deflecting plates that create an electric field, which changes the path of the electron beam. To refine your model for aiming charged particles with electric fields, you wish to determine how the velocity of the electrons leaving the electron gun region of the CRT affects the position of the beam spot. How does the deflection of the electron beam vary with initial electron velocity?

EQUIPMENT

You will be using the Cathode Ray Tube described in Appendix D. The fluorescent screen has a centimeter grid in front of it so you can measure the position of the beam spot. The applied electric field is created by connecting the internal deflecting plates to a battery pack or power supply.

PREDICTION

Calculate how the deflection of the electron beam spot changes as the initial velocity of the electrons changes.

Use this equation to make a graph of the deflection of the beam spot as a function of the initial velocity of the electrons.

WARM-UP

Read Serway & Jewett: sections 19.2, 19.5, 19.7.
Review Kinematics if neccessary: Read Serway and Jewett: Chapters 3 and 4.

The prediction for this lab requires the derivation of the prediction equation described in the previous lab problem. If you have not yet completed Problem 5, do the warm-up questions for Problem 5 and then follow the steps below.

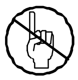
Use conservation of energy to write an equation for the velocity of the electrons as they leave the electron gun in the CRT. This velocity should be determined using the voltage across the accelerating plates in the CRT. The relationship between the initial electron velocity and the accelerating voltage can be used to rewrite your already derived deflection equation in terms of the electron velocity.

Sketch the shape of a graph of your prediction equation's dependence on initial electron velocity for a fixed, non-zero transverse electric field.

Sketch the shape of a graph of your prediction equation's dependence on accelerating voltage for a fixed, non-zero transverse electric field.

Does your solution make sense? If not, check your work for logic problems or algebra mistakes.

EXPLORATION



WARNING: You will be working with equipment that generates large electric voltages. Improper use can cause painful burns. **To avoid danger, the power should be turned OFF and you should WAIT at least one minute before any wires are disconnected from or connected to the power supply. Never touch the conducting metal of any wire.**

Follow the directions in Appendix D for connecting the power supply to the CRT. Check to see that the connections from the power supply to the high voltage and the filament heater are correct, *before* you turn the power supply on. Apply between 250 and 500 Volts across the anode and cathode. After a moment, you should observe a spot on the screen that can be adjusted with the knob labeled "Focus". If your connections are correct and the spot still doesn't appear, inform your lab instructor.

TAKING EXTREME CARE, change the voltage across the accelerating plates, and determine the range of values for which the electrons have enough energy to produce a spot on the screen. Changing this voltage changes the velocity of the electrons as they enter the deflection plates. What is the range of initial electron velocities corresponding to this range of accelerating voltages? Which of these values will give you the largest deflection when you later apply an electric field between the deflection plates?

The electric field between two equally charged parallel plates (in Newtons per Coulomb) is equal to the voltage between the two plates (in Volts) divided by the distance between the plates (in meters).

Before you turn on the electric field between the deflection plates, find the CRT orientation that gives no deflection of the electron beam. In this position the effect of all of the outside forces on the electron is negligible.

Now apply a voltage across one set of deflection plates, noting how the electron beam moves across the screen as the voltage is increased. Find a voltage across the deflection plates that allows the deflection for the entire range of initial electron velocities to be measured as accurately as possible.

Devise a measuring scheme to record the position of the beam spot. Be sure you have established the zero deflection point of the beam spot.

How will you determine the strength of the electric field between the deflection plates? How will you determine the initial velocity of the electrons? What quantities will you hold constant for this measurement? How many measurements do you need?

Write down your measurement plan.

MEASUREMENT

Measure the deflection of the beam spot as you change the initial velocity of the electrons in the beam but keeping the electric field between the deflection plates constant.

Note: Be sure to record your measurements with the appropriate number of significant figures (see Appendix A) and with your estimated uncertainty (see Appendix B).

ANALYSIS

Calculate the initial electron velocity for each accelerating voltage you used. Use a spreadsheet program (such as Excel on your lab workstation computer) to make a graph of your average measurements of the deflection of the electron beam as a function of the initial electron velocity. How do your uncertainties affect your graph?

Use your prediction equation to calculate the predicted values for the deflection of the electron beam as a function of the accelerating voltage. Plot these values on the same graph as your measurements and compare.

Make a graph of your average measurements of the deflection of the electron beam as a function of the accelerating voltage. How do your uncertainties affect your graph?

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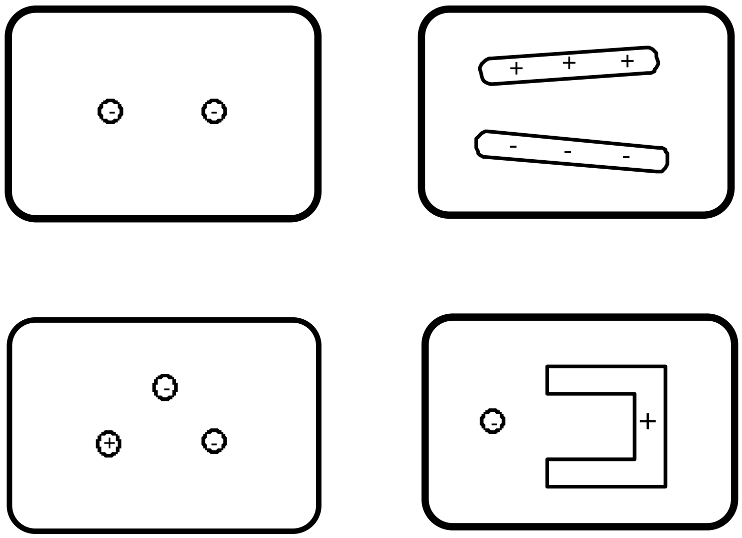
CONCLUSION

Did your data agree with your prediction of how the electron beam would deflect due to the initial electron velocity? If not, why not?

How does the deflection of the electron beam vary with initial electron velocity? How does it vary with accelerating voltage? State your results in the most general terms supported by your data.

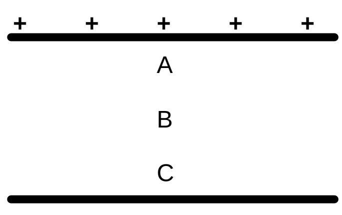
☑ CHECK YOUR UNDERSTANDING

1. For each of the charge configurations below, map the electric field. Assume that each object is made of metal and that the trays are filled with water.



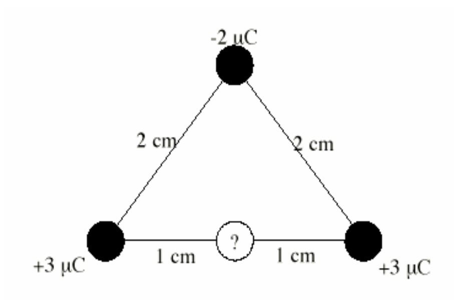
2. For a CRT with the same plates and electron gun as you used in lab, assume that the distance from the center of the Vx plate to the fluorescent screen is 10 cm and the distance from the center of the Vy plate to the screen is 8 cm. If V_{acc} is 300V, Vx = -8V and Vy = 3V, what is the displacement of the electron beam?

3. Assume you have two infinite parallel planes of charge separated by a distance d as shown below. Use the symbols <,>, and = to compare the force on a test charge, q, at points A, B, and C.

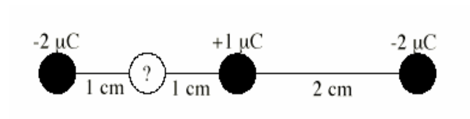


☑ CHECK YOUR UNDERSTANDING

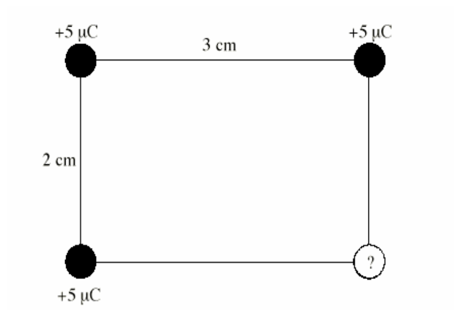
4. For each of the charge configurations below, find the electric field and the electric potential at the point marked with the "?".



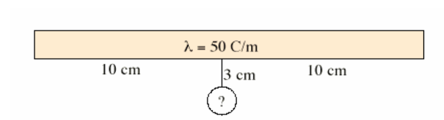
Configuration 1



Configuration 2



Configuration 3



Configuration 4

PHYSICS 1202 LABORATORY REPORT

Laboratory IV

Name and ID#: ______________________________

Date performed: ____________ Day/Time section meets: ______________________

Lab Partners' Names: ______________________________

____

____

Problem # and Title: ______________________________

Lab Instructor's Initials: ________

Grading Checklist	Points
LABORATORY JOURNAL:	
PREDICTIONS (individual predictions and warm-up completed in journal before each lab session)	
LAB PROCEDURE (measurement plan recorded in journal, tables and graphs made in journal as data is collected, observations written in journal)	
PROBLEM REPORT:*	
ORGANIZATION (clear and readable; logical progression from problem statement through conclusions; pictures provided where necessary; correct grammar and spelling; section headings provided; physics stated correctly)	
DATA AND DATA TABLES (clear and readable; units and assigned uncertainties clearly stated)	
RESULTS (results clearly indicated; correct, logical, and well-organized calculations with uncertainties indicated; scales, labels and uncertainties on graphs; physics stated correctly)	
CONCLUSIONS (comparison to prediction & theory discussed with physics stated correctly ; possible sources of uncertainties identified; attention called to experimental problems)	
TOTAL(incorrect or missing statement of physics will result in a maximum of 60% of the total points achieved; incorrect grammar or spelling will result in a maximum of 70% of the total points achieved)	
BONUS POINTS FOR TEAMWORK (as specified by course policy)	

* An "R" in the points column means to <u>rewrite that section only</u> and return it to your lab instructor within two days of the return of the report to you.