Experiment 1: Equipotential Lines and Electric Fields

OBJECTIVES

1. To develop an understanding of electric potential and electric fields
2. To better understand the relationship between equipotentials and electric fields
3. To become familiar with the effect of conductors on equipotentials and E fields

INTRODUCTION

Thus far in class we have talked about fields, both gravitational and electric, and how we can use them to understand how objects can interact at a distance. A charge, for example, creates an electric field around it, which can then exert a force on a second charge which enters that field. In this lab we will study another way of thinking about this interaction through electric potentials.

The Details: Electric Potential (Voltage)

Before discussing electric potential, it is useful to recall the more intuitive concept of potential energy, in particular gravitational potential energy. This energy is associated with a mass’s position in a gravitational field (its height). The potential energy difference between being at two points is defined as the amount of work that must be done to move between them. This then sets the relationship between potential energy and force (and hence field):

\[ \Delta U = U_B - U_A = -\int_A^B \vec{F} \cdot d\vec{s} \quad \Rightarrow \quad (\text{in 1D}) \quad F = -\frac{dU}{dz} \quad (1) \]

We earlier defined fields by breaking a two particle interaction, force, into two single particle interactions, the creation of a field and the “feeling” of that field. In the same way, we can define a potential which is created by a particle (gravitational potential is created by mass, electric potential by charge) and which then gives to other particles a potential energy. So, we define electric potential, \( V \), and given the potential can calculate the field:

\[ \Delta V = V_B - V_A = -\int_A^B \vec{E} \cdot d\vec{s} \quad \Rightarrow \quad (\text{in 1D}) \quad E = -\frac{dV}{dz}. \quad (2) \]

Noting the similarity between (1) and (2) and recalling that \( F = qE \), the potential energy of a charge in this electric potential must be simply given by \( U = qV \).
When thinking about potential it is convenient to think of it as “height” (for gravitational potential in a uniform field, this is nearly precise, since $U = mgh$ and thus the gravitational potential $V = gh$). Electric potential is measured in Volts, and the word “voltage” is often used interchangeably with “potential.” You are probably familiar with this terminology from batteries, which maintain fixed potential differences between their two ends (e.g. 9 V in 9 volt batteries, 1.5 V in AAA-D batteries).

**Equipotentials and Electric Fields**

When trying to picture a potential landscape, a map of equipotential curves – curves along which the potential is equal – can be very helpful. For gravitational potentials these maps are called topographic maps. An example is shown in Fig. 1b.

![Figure 1: Equipotentials. A potential landscape (pictured in 3D in (a)) can be represented by a series of equipotential lines (b), creating a topographic map of the landscape. The potential (“height”) is constant along each of the curves.](image)

Now consider the relationship between equipotentials and fields. At any point in the potential landscape, the field points in the direction that a mass would feel a force if placed there (or that a positive charge would feel a force for electric potentials and fields). So, place a ball at the top of the hill (near the center of the left set of circles in the topographic map of Fig. 1b). Which way does it roll? Downhill! But what direction is that? Perpendicular to the equipotential lines. Why? Equipotential lines are lines of constant height, so moving along them at all does not achieve the objective of going downhill. So the force (and hence field) must point across them, pushing the object downhill. But why exactly perpendicular? Work done on an object changes its potential, so it can take no work to move along an equipotential line. Work is given by the dot product of force and displacement. For this to be zero, the force must be perpendicular to the displacement, that is, force (and hence fields) must be perpendicular to equipotentials.

**Note: Potential vs. Potential Difference**

Note that in equation (2) we only defined $\Delta V$, the potential difference between two points, and not the potential $V$. This is because potential is like height – the location we choose to call “zero” is completely arbitrary. In this lab we will choose one location to call zero (the “ground”), and measure potentials relative to the potential at that location.
APPARATUS

1. Conducting Paper Landscapes

To get a better feeling for what equipotential curves look like and how they are related to electric field lines, we will measure sets of equipotential curves for several different potential landscapes. These landscapes are created on special paper (on which you can measure electric potentials) by fixing a potential difference between two conducting shapes on the paper. For reasons that we will discuss later, these conducting shapes are themselves equipotential surfaces, and their shape and relative position determines the electric field and potential everywhere in the landscape. One purpose of this lab is to develop an intuition for how this works. There are four landscapes to choose from (Fig. 2), and you will measure equipotentials on two of them (one from Fig. 1a, b and one from Fig. 1c, d).

![Figure 2 Conducting Paper Landscapes](image)

Figure 2 Conducting Paper Landscapes. Each of the four landscapes – the “standard” (a) dipole and (b) parallel plates, and the “non-standard” (c) bent plate and (d) filled plates – consists of two conductors which will be connected to the positive (red) and ground (blue) terminals of a battery. In (d) there is an additional conductor which is free to float to whatever potential is required. The pads are painted on conducting paper with a 1 cm grid.

2. Logger Pro Interface

In this lab we will use the Logger Pro software and LabPro interface both to create the potential landscapes (by outputting a constant 4 V potential, much like a battery) and to measure the potential at various locations in that landscape using a voltage sensor.
3. Voltage Sensor

In order to measure the potential as a function of position we will use the Vernier Differential Voltage probe, plugged into channel 1 of the Lab Pro interface. When recording the “potential,” you will really be measuring the potential difference between the two leads, (red minus black) and hence you should have the black lead connected to the output ground (what value of potential does this then assign to the output ground?)

GENERALIZED PROCEDURE

For each of the two landscapes that you choose, you will find at least four equipotential contours by searching for points in the landscape at the same potential using the voltage sensor. After recording these curves, you will draw several electric field lines, making use of the fact that they are everywhere perpendicular to equipotential contours.

END OF PRE-LAB READING
IN-LAB ACTIVITIES

EXPERIMENTAL SETUP

1. Open the Logger Pro document 802_Exp_01_2010.cml.

2. Plug the Vernier Differential Voltage probe into channel 1 and the Vernier +/- 10V Voltage probe into channel 4. Navigate to the Experiment menu, select “Set Up Sensors,” and select “Show All Interfaces.” Click on the sensor icon in the CH 4 box and select “Analog Out.”

   Set the waveform to DC Output and the amplitude to 4V (the maximum allowed voltage). If you wish, zero the Differential Voltage probe by clicking “Zero” under the Experiment menu and selecting only this sensor (it is not necessary to zero the sensor as the purpose of this experiment is to obtain qualitative information about the equipotential lines, rather than exact data). One member of the group will hold these wires to the two conductors while another maps out the equipotentials.

3. Within the Experimental menu, select “Data Collection” and toggle “Continuous Data Collection.”

4. To ensure easy measurement, make sure your graph axes extend from 0-4V (set these parameters with “Graph Options” under the Options menu).
MEASUREMENTS

Part 1: “Standard” Configuration

1. Choose one of the two “standard” conducting paper landscapes (the dipole or parallel plate configuration).

2. Use the voltage connectors to make contacts to the two conducting pads. The +/-10V Voltage probe (CH 4) is the voltage source (since you set it to a DC Output of 4V), thus you should use the leads of this probe.

3. Connect the black lead of the other voltage probe (CH 1) to the black lead of the CH 4 probe.

4. Press the “Collect” button (alternatively, the space bar) to begin recording the potential of the red lead (relative to the black lead=ground). See below.

5. Measure the potential of both conducting pads to confirm that they are properly connected (one should be at +4 V, the other at 0 V), and that they are indeed equipotential objects (we will explain why next week).

6. Now, try to find some location on the paper that is at about +1 V (don’t worry about being too precise). Hold the lead steadily in the location you intend to measure, as the voltage varies with movement. Mark this point on the plot on the next page. **Do NOT write on the conducting paper!**

7. Find another 1 V point, about 1 cm away. Continue until you have closed the curve or left the page. Sketch and label this equipotential curve.

8. Repeat this process to find equipotentials at 2 V, 3 V, and 4 V. Work pretty fast; it’s more important to think about what these lines mean than it is to draw them perfectly. Think about what you are doing – are there symmetries that you can exploit to make this task easier?
Figure 3: Measuring Potential. A counter-example of measuring equipotential lines, here the potential was measured increasingly far away from one of the conducting pads. Note that accurate measurement requires holding the lead of the voltage probe at a constant position for up to several seconds.
“Standard” Configurations
**Question 1:**
Sketch in a set of electric field lines (~ ten) on your plot of equipotentials on the previous page. Where do the field lines begin and end? If they are equally spaced at their beginning, are they equally spaced at the end? Along the way? Why?

**Question 2:**
What, approximately, is the potential midway between the two conductors? REMINDER (just this once): Whenever you are asked for a numerical value DO NOT FORGET UNITS!

**Question 3:**
What, approximately, is the strength of the electric field midway between the two conductors? You may find it easier to answer this question if you just measure the potential at a few points near the center.

**Part 2: “Non-Standard” Configuration**
1. Choose one of the two “non-standard” conducting paper landscapes (the bent plate or filled plates configuration)
2. Use the voltage connectors to make contacts to the two conducting pads (for the filled plates, the center pad does not have a connection to it)
3. Press the “Collect” button (alternatively, the space bar) to begin recording the potential of the red lead (relative to the black lead=ground).
4. Confirm that everything is properly connected by measuring the potential on the two connected pads, then record a set of equipotential curves following the same procedure of part 1.
“Non-Standard” Configurations
**Question 4:**

Sketch in a set of electric field lines on your plot of equipotentials on the previous page. Where is the electric field the strongest? What, approximately, is its magnitude?

**Further Questions (for experimentation, thought, future exam questions…)**

- What changes if you switch which conducting pad is at +5 V and which is ground?
- What if you forget to connect the ground lead?
- If you rest your hand on the paper while making measurements, does it affect the readings? Why or why not?
- If you wanted to push a charge along one of the field lines from one conductor to the other, how does the choice of field line affect the amount of work required?
- The potential is everywhere the same on an equipotential line. Is the electric field everywhere the same on an electric field line?