EXPERIMENT 24

Fields and Equipotentials

I. INTRODUCTION AND OBJECTIVES

When buying groceries, we are often interested in the price per pound. Knowing this, we can determine the price for a given amount of an item. Analogously, it is convenient to know the electric force per unit charge at points in space due to an electric charge configuration or the magnetic force per unit pole or "moving charge." Knowing these, we can easily calculate the electric force or magnetic force an interacting object would experience at different locations.

The electric force per unit charge is called the electric field intensity, or simply the **electric field** (**E**). By determining the electric force on a test charge at various points in the vicinity of a charge configuration, the electric field may be "mapped" or represented graphically by lines of force. The English scientist Michael Faraday (1791–1867) introduced the concept of lines of force as an aid in visualizing the magnitude and direction of an electric field.

Similarly, the magnetic force per unit pole is called the magnetic field intensity, or **magnetic field** (**B**). In this case, the field is mapped out by using the pole of a magnetic compass.

In this experiment, the concept of fields will be investigated and some electric and magnetic field configurations will be determined experimentally.

After performing this experiment and analyzing the data, you should be able to:

1. Describe clearly the concept of a force field.
2. Explain lines of force and the associated physical interpretations.
3. Distinguish between lines of force and equipotentials, and describe their relationships to work.

II. EQUIPMENT NEEDED

A. *Electric Field*

Field mapping board and probes
- Conducting sheets with grids
- Conducting paint
- Connecting wires
- 1.5-V battery (or 10-V dc source)
- Galvanometer [or high resistance voltmeter or multimeter, or vacuum-tube voltmeter (VTVM) with two-point contact field probe*]
- Single-throw switch
- 3 sheets of Cartesian graph paper

B. *Magnetic Field*

- 2 bar magnets and one horseshoe magnet
- Iron filings
- 3 sheets of paper or a glass plate
- Small compass
- 3 sheets of Cartesian graph paper or regular paper

* Leads from the dc input of an oscilloscope work nicely.

III. THEORY

A. *Electric Field*

The magnitude of the electrostatic force between two point charges q_1 and q_2 is given by Coulomb's law:

$$F = \frac{kq_1q_2}{r^2} \tag{24.1}$$

where r is the distance between the charges and the constant $k = 9.0 \times 10^9$ N-m^2/C^2. The direction of the force on a charge may be determined by the law of charges: Like charges repel, and unlike charges attract.

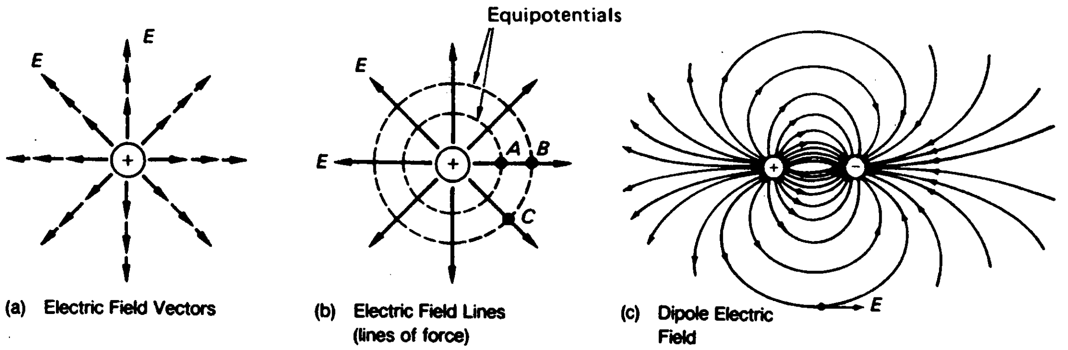
The magnitude E of the **electric field** is defined as the electrical force per unit charge, or $E = F/q_o$ (N/C). By convention, the electric field is determined by using a *positive* t charge q_o. In the case of the electric field associated th a single-source charge q, the magnitude of the electric field a distance r away from the charge is

$$E = \frac{F}{q_o} = \frac{kq_oq}{q_or^2} = \frac{kq}{r^2} \tag{24.2}$$

The direction of the electric field may be determined by the law of charges; that is, in the direction of the force experienced by the positive test charge.

The electric field vectors for several series of radial points from a positive source charge are illustrated in Fig. 24.1a. Notice that the lengths (magnitudes) of the vectors are smaller the greater the distance from the charge. (Why?)

By drawing lines through the points in the direction of the field vectors, we form lines of force (Fig. 24.1b), which give a graphical representation of the electric field. The direction of the electric field at a particular location is tangent to the line of force through that point (Fig. 24.1c). The magnitudes of the electric field are not customarily listed, only the direction of the field lines. However, the closer together the lines of force, the stronger the field.



(a) Electric Field Vectors (b) Electric Field Lines (lines of force) (c) Dipole Electric Field

Figure 24.1 Electric field. (a) Electric field vectors near a positive charge. (b) Lines of force with equipotentials for a positive charge. (c) An electric dipole and its electric field. The direction of the electric field at a particular location is tangent to the line of force through that point, as illustrated on the bottom line of force.

If a positive charge were released in the vicinity of a stationary positive source charge, it would move along a line of force in the direction indicated (away from the source charge). A negative charge would move along the line of force in the opposite direction. Once the electric field for a particular charge configuration is known, we tend to neglect the charge configuration itself, since the effect of the configuration is given by the field.

Since a free charge moves in an electric field by the action of the electric force, we say that work ($W = Fd$) is done by the field in moving charges from one point to another (e.g., from A to B in Fig. 24.1b).

To move a positive charge from B to A would require work supplied by an external force to move the charge against the electric field (force). The work W per charge q_o in moving the charge between two points in an electric field is called the **potential difference** ΔV between the points:

$$\Delta V_{\mathrm{BA}} = V_{\mathrm{B}} - V_{\mathrm{A}} = \frac{W}{q_o} \qquad \textbf{(24.3)}$$

(It can be shown that the potential at a particular point a distance r from the source charge q is $V = -kq/r$. See your textbook.)

If a charge is moved along a path at right angles or perpendicular to the field lines, no work is done ($W = 0$), since there is no force component along the path. Then along such a path (dashed-line paths in Fig. 24.1), $\Delta V = V_{\mathrm{B}} - V_{\mathrm{C}} = W/q_o = 0$, and $V_{\mathrm{C}} = V_{\mathrm{B}}$. Hence, the potential is constant along paths perpendicular to the field lines. Such paths are called **equipotentials.** (In three dimensions, the path is along an equipotential surface.)

An electric field may be mapped experimentally by determining either the field lines (of force) or the equipotential lines. Static electric fields are difficult to measure, and field lines are more easily determined by measuring small electric currents (flow of charges) maintained in a conducting medium between charge configurations in the form of metal electrodes.

The steady-state electric field lines closely resemble the static field that a like configuration of static charges would produce. The current is measured in terms of the voltage (potential) difference by a high-resistance voltmeter or multimeter (or VTVM).

In other instances, equipotentials are determined, and hence the field lines, using a simple galvanometer as a detector. When no current flows between two probe points, as indicated by a zero deflection on the galvanometer, there is no potential difference between the points ($\Delta V = 0$), and the points are on an equipotential.

B. Magnetic Field

As in the electric case, a **magnetic field** was originally defined as the magnetic force per unit pole. The direction of the force at a particular location is that of the force experienced by a north magnetic pole.

Just as we may map the electric field around an electric charge, we may draw magnetic lines of force around a magnet. A single magnetic pole, or magnetic monopole, has never been observed, so the magnetic field is mapped using the north pole (by convention) of a magnetic dipole, for example, the magnetic needle of a compass. The torque on the compass needle resulting from the magnetic force causes the needle to line up with the field, and the north pole of the compass points in the direction of the field (Fig. 24.2). If the compass is moved in the direction indicated by the north pole, the path of the compass traces out a field line.

Another observation is that an electric charge q moving nonparallel to a magnetic field experiences a force. For the special case in which the velocity vector $\mathbf{v}$ of the charge is perpendicular to the magnetic field $\mathbf{B}$, the magnitude of the force is given by

$$F = qvB$$

This gives an expression for the strength (magnitude) of the magnetic field in terms of familiar quantities:

$$B = \frac{F}{qv} \qquad \textbf{(24.4)}$$

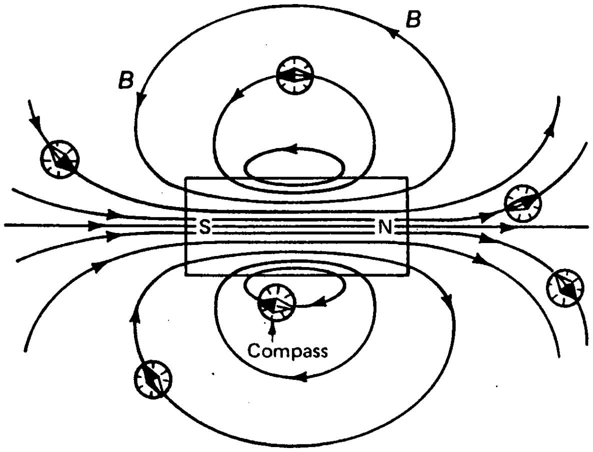


Figure 24.2 Magnetic field. The magnetic force causes a compass needle to line up with the field, and the north pole of the compass points in the direction of the field. If the compass is moved in the direction indicated by the north pole, the path of the compass needle traces out a field line.

where the direction of **B** is perpendicular to the plane of **v** and **F**. Note the SI unit of magnetic field is N/A-m, or tesla (T).*

The magnetic field may then be thought of as the magnetic force "per unit charge" per velocity. The **B** field has the same form as that mapped out using compass-needle poles.

It is instructive for comparative purposes to draw equipotential lines perpendicular to the field lines, as in the electric field case. No work would be done on a magnetic pole (or electric charge) when moved along these equipotential lines. (Why?)

A common method of demonstrating a magnetic field is to sprinkle iron filings over a paper or glass plate covering a magnet (Fig. 24.3). The iron filings become induced magnets and line up with the field as would a compass needle. This method allows one quickly to visualize the magnetic field configuration.

IV. EXPERIMENTAL PROCEDURE

A. Electric Field

1. An electric field mapping setup with a galvanometer is shown in Fig. 24.4a. The apparatus consists of a flat board on which is placed a sheet of carbonized conducting paper imprinted with a grid. The sheet has an electrode configuration of conducting silver paint, which provides an electric field when connected to a voltage source (e.g., a battery).

   The common electrode configurations ordinarily provided are two dots representing point charges of an electric dipole configuration (Fig. 24.1c) and two parallel linear electrodes representing a two-dimensional cross section of a parallel-plate capacitor (on the board in the photo in Fig. 24.4a).

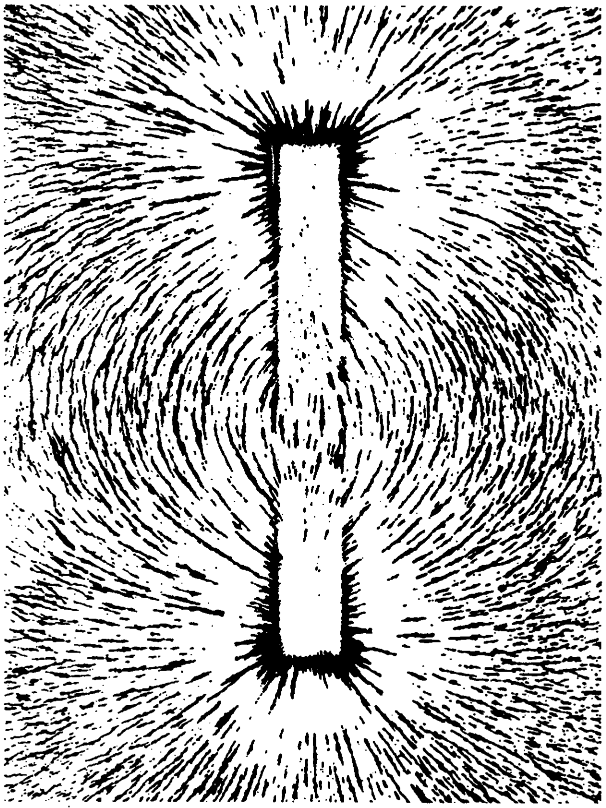


Figure 24.3 Iron filing pattern for a bar magnet. The iron filings become induced magnets and line up with the field, as would a compass needle. (Courtesy of *PSSC Physics*, D. C. Heath and Company with Educational Development Center, Inc., Newton, MA.)

2. Draw the electric dipole configuration on a sheet of graph paper to the same scale and coordinates as those of the painted dipole on the imprinted grid on the conducting sheet. Then place the dipole conducting sheet on the board, and set the contact terminals firmly on the painted electrode connections. If you are using a galvanometer, do procedures 3 through 7. If you are using a voltmeter, do procedures 8 through 12.

GALVANOMETER MEASUREMENTS

3. Connect the probes to the galvanometer as shown in Fig. 24.4a. The probes are used to locate points in the field that are at equipotential. Connect the voltage source (1.5-V battery) to the board terminals. Place a switch in the circuit (not shown in figure) and leave it open until you are ready to take measurements.

   Place the stationary probe on the electric dipole sheet at some general point near the edge of the grid area in the region between the electrodes. The potential

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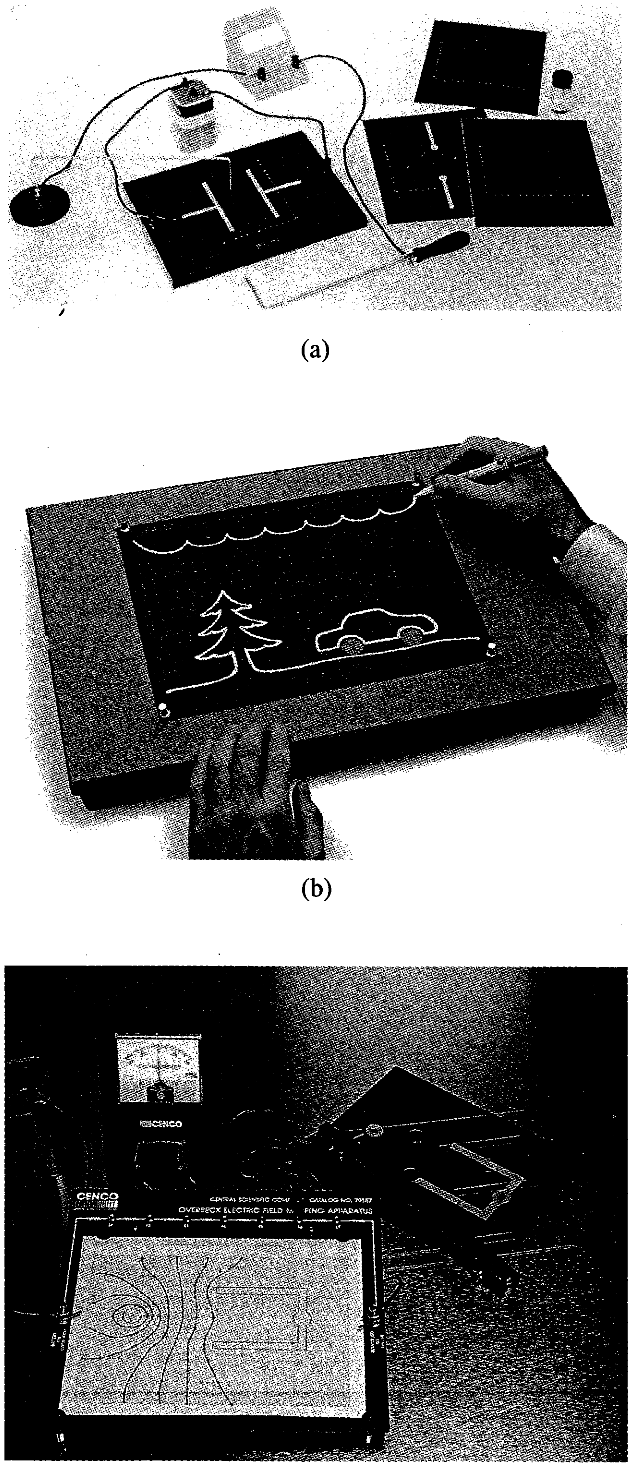
* Other units of magnetic field are the weber/m^2 (Wb/m^2) and the gauss (G). These units are named after early investigators of magnetic phenomena.



(a)

(b)

(c)

Figure 24.4 Electric field mapping apparatus. (a) A parallel-plate capacitor configuration on the board and an electric dipole configuration to the right. (b) A variety of electrode configurations can be drawn with conductive ink on conductive paper. (c) This apparatus uses conductive plates, and the mapping is done on graph paper. [Photos courtesy of (a) Sargent-Welch Scientific Company, (b) PASCO scientific, and (c) Central Scientific Co., Inc.]

at this point will serve as a reference potential. Mark the probe position on your graph-paper map.

The movable probe is then used to determine the location of a series of other points having the same potential. When the movable probe is at a point with the same potential as that of the stationary reference probe, no deflection will be observed on the galvanometer.

The galvanometer is a delicate current-measuring instrument and should be limited to small current values to avoid damage. As a result, the electrodes should not be allowed to make contact with each other. (Why?)

4. Close the switch and place the movable probe on the conducting paper at some location an appreciable distance away from the stationary probe. Move the probe until the galvanometer shows zero deflection (indicating a point of equipotential) and record this point on the graph-paper map.

   Locate a series of 8 or 10 points of the same potential across the general field region, and draw a dashed-line curve through these points on the graph-paper map.

5. Choose a new location for the reference probe 2 to 3 cm from the previous reference position and locate another series of equipotential points. Continue this procedure until you have mapped the field region. Open the switch.

   Draw curves perpendicular to the equipotential lines on the graph-paper map to represent the electric field lines. Do not forget to indicate the field direction on the field lines.

6. Repeat the procedure for the parallel linear (plate) electrode configuration. Be sure to investigate the regions around the ends of the plate electrodes.

7. (*Optional*) Your instructor may wish to have you map the electric field for a nonsymmetrical electrode configuration or a configuration of your own choosing. These can be prepared by painting the desired electrode configuration on a conducting sheet with silver paint.

VOLTMETER MEASUREMENTS

8. For the high resistance voltmeter (or VTVM), the field probe should have two contacts mounted about 2 cm apart. Connect the voltage source (10-V dc) to the board terminals. Place a switch in the circuit (not shown in Fig. 24.4a) and leave it open until you are ready to take measurements.

   Close the switch, and with the zeroed voltmeter set on the 10-V scale, position the negative (−) contact of the field probe near the negative electrode. Using the negative probe point as a pivot, rotate the positive (+) contact around the fixed negative contact until the position with the maximum meter reading is found.

Record the positions of the probe contacts on the graph-paper map. (The sensitivity of the voltmeter may be increased by switching to a lower scale. A mid-scale reading is desirable. Check the zero on the voltmeter frequently, particularly when changing scales.)

9. Using the second probe point as a new negative probe point, repeat the procedure to determine another point of maximum meter reading, and record. Continue this procedure until the positive electrode is approached. Draw a smooth curve through these points on the graph-paper map.

Then starting again at a new position near the negative electrode, repeat these procedures for another field line. Trace out four to six field lines in this manner. Do not forget to indicate the field direction on the lines.

10. Place the negative probe near the center of the field region, and rotate the positive contact until a position is found that gives a *zero* meter reading. Record several of these points on the graph paper with a symbol different from that used for the field lines.

Use the second point as a new pivot point as before, and determine a series of null (zero) points. Draw a dashed-line curve through these equipotential points. Determine three to five equipotential lines in this manner.

11. Repeat this procedure for the parallel linear (plate) electrode configuration. Be sure to investigate the regions around the ends of the plate electrodes.

12. (*Optional*) Your instructor may wish to have you map the electric field for a nonsymmetrical electrode configuration or a configuration of your own choosing. These can be prepared by painting the desired electrode configuration on a conducting sheet with silver paint.

B. Magnetic Field

13. Covering the magnets with sheets of paper (or a glass plate), sprinkle iron filings to obtain an iron filing pattern for each of the arrangements shown in Fig. 24.5.

For the bar magnet arrangements, the magnets should be separated by several centimeters, depending on the pole strengths of the magnets. Experiment with this distance so there is enough space between the ends of the magnets to get a good pattern.

14. Sketch the observed magnetic field patterns on Fig. 24.5 in the Laboratory Report. After the patterns have been sketched, collect the iron filings on a piece of paper and return them to the filing container (recycling them for someone else's later use). Economy in the laboratory is important.

15. Place the magnets for each arrangement on a piece of graph paper or regular paper. Draw an outline of the magnets for each arrangement on the paper. Using a small compass, trace out (marking on the paper) the magnetic field lines as smooth curves. Draw enough field lines so that the pattern of the magnetic field can be clearly seen. Do not forget to indicate the field direction on the lines.

16. Draw dashed-line curves perpendicular to the field lines.

Name ______________________ Section ______________ Date ______________

Lab Partner(s) ____

EXPERIMENT 24

Fields and Equipotentials

Laboratory Report

Attach graphs to Laboratory Report.

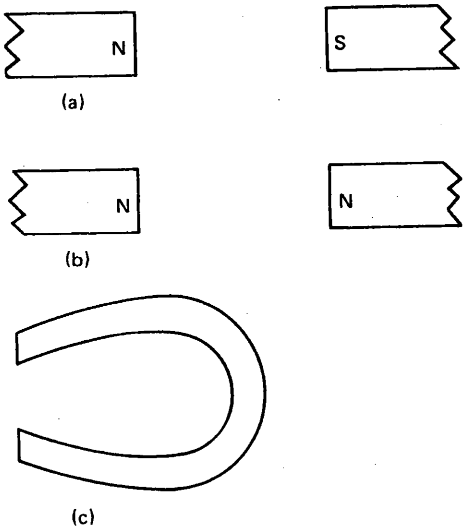


Figure 24.5 See Procedure Section B.

QUESTIONS

1. Directions of the fields are indicated on field lines. Why are no directions indicated on equipotential lines?

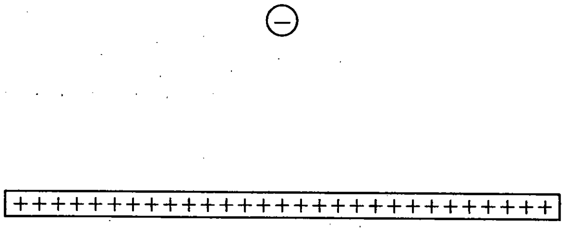
2. For the dipole configuration, in what region(s) does the electric field have the greatest intensity? Explain how you know from your map, and justify.

Don't forget units

(continued)

3. Comment on the electric field of the parallel plates (a) between the plates, and (b) near the edges of the plates.

4. Sketch the electric field for (a) a negative point charge near a positively charged plate, and (b) two positive point charges.



(a)

(b)

5. Compare the electric fields and magnetic fields of the experimental arrangements. Comment on any field similarities and differences.

6. Explain how a gravitational field might be mapped. Sketch the gravitational field for two point masses a short distance apart.