Chapter
Eight

STATIC ELECTRICITY

KEY IDEAS

Electricity is a fundamental property of all matter. There are two types of electric charges: positive and negative. The proton and the electron are, respectively, the fundamental positive and negative charges. If an object has the same number of protons and electrons, it is electrically neutral. Generally, charge is transferred by the gain or loss of electrons.

Electrically charged objects attract or repel each other with a force that is directly proportional to the magnitude of the charges and inversely proportional to the square of the distance between them. The relationship is known as Coulomb's law. Substances that allow charges to move freely through them are called conductors; substances that severely restrict this movement are insulators.

The region of space in which an electric charge is subject to an electric force is known as an electric field. The electric-field concept is an alternative way of explaining how charged objects attract or repel each other. Constructions called field lines are an aid to visualizing the electric fields around various charge configurations.

The work done in moving a unit charge between two points in an electric field is known as the potential difference between these points. Potential difference describes the electric field in terms of energy and work.

The charge that a conductor acquires is proportional to the potential difference across the conductor. The ratio of charge to potential difference is called capacitance. Devices that make use of this property are known as capacitors; they are used to store electric charge for a variety of applications.

KEY OBJECTIVES

At the conclusion of this chapter you will be able to:

- Define the term *electric charge*, and state the SI unit for charge.
- Relate neutral and charged objects to protons and electrons.
- Explain how neutral objects may become charged by contact.
- Solve problems involving elementary charges.
- Define the terms *conductor, insulator,* and *grounding*.

- Describe the difference between charging by induction and charging by conduction.
- Explain how an electroscope operates.
- State the equation for Coulomb's law, and solve problems using the equation.
- Define the term *electric field*, and describe how an electric field is represented by field lines.
- Draw simple field configurations.
- State the equation for measuring electric field intensity, and solve problems using the equation.
- Define the terms *potential difference* and *electric potential*, and state the SI units for measuring these quantities.
- Define the term *electron-volt* and relate it to the joule.
- Relate the electric field strength between oppositely charged parallel plates to the potential difference across them, and use this relationship to solve problems.
- Describe Millikan's oil drop experiment and its contribution to the understanding of electric charge.

🍎 8.1 WHAT IS ELECTRICITY?

We have all experienced the effects of static electricity: A balloon sticks to a wall after being rubbed on a shirt or blouse or a person receives a shock after walking on a carpet and then touching an electrical appliance.

In Chapter 5, we learned that gravitation is a universal attraction between two masses and obeys an *inverse square* law, known as Newton's law of universal gravitation:

$$\mathbf{F}_g = \frac{Gm_1m_2}{d^2}$$

Imagine a force like gravitation that also obeys an inverse square law but is a *billion–billion–billion–billion* times stronger! There are other differences as well. The electric force between two objects depends on their *charges* rather than on their masses. Also, there are two types of **electric charges**, which we call *positive* and *negative*. Like charges (positive–positive and negative–negative) repel each other, and unlike charges (positive–negative) attract.

The phenomenon of electricity was recognized in ancient Greece nearly 5,000 years ago, but it was not understood completely until the twentieth century when the electrical model of the atom was developed.

🍎 indicates that material is part of the New York State core curriculum.

8.2 ELECTRIC CHARGES

The fundamental positive charge is the *proton,* which is found in the nucleus of the atom along with uncharged neutrons. The fundamental negative charge is the *electron,* which is located outside the nucleus. The properties of these three particles are compared in the table below:

Particle	Relative Charge	Charge (C)	Mass (kg)
Proton	+1	$+1.60 \times 10^{-19}$	1.66×10^{-27}
Electron	−1	-1.60×10^{-19}	9.11×10^{-31}
Neutron	0	0.00	1.67×10^{-27}

As we can see, the proton and the electron have equal, but opposite, charges. Therefore, a *neutral* object has the same number of protons and electrons. The proton is nearly 2,000 times more massive than the electron and is tightly bound in the nucleus (along with the neutrons). As a result, ordinary objects, such as balloons, become electrically charged by gaining or losing electrons. If an object gains electrons, the *excess* of electrons gives the object a *negative* charge. If an object loses electrons, the *deficiency* of electrons gives the object a *positive* charge.

It has long been known that a hard rubber rod becomes negatively charged when rubbed with animal fur. How does this occur? Since electrons are transferred in charging, the rubber rod *gains* electrons and so becomes negatively charged. The fur *loses* an equivalent number of electrons and becomes positively charged. This example illustrates the fact that electric charge is *conserved*; it cannot be created or destroyed. The law of conservation of electric charge is a fundamental law of physics, as are the laws of conservation of energy and momentum.

PROBLEM

A glass rod becomes positively charged when it is rubbed with silk. Explain how this occurs.

SOLUTION

The glass rod loses electrons to the silk, which becomes negatively charged.

Since electric charges ultimately come from protons and electrons, charge must be some multiple of the elementary charge. We can write this fact as an equation:

PHYSICS CONCEPTS

$$Q = ne$$

where Q is the charge on the object (in coulombs), n is the number of elementary charges, and e is the elementary charge itself.

PROBLEM
A balloon has acquired a charge of -3.20×10^{-17} coulomb. How many excess electrons does this charge represent?

[redacted]

PROBLEM
How many elementary charges are present in 1.00 coulomb of charge?

SOLUTION
We solve this problem [redacted]

Certain substances, such as sodium chloride (common table salt), consist of positive and negative *ions*—atoms that have lost or gained electrons. In a water solution of sodium chloride, charge is transferred by ions, rather than by free electrons.

8.3 CONDUCTORS AND INSULATORS

Certain materials, for example, metals and solutions of ionic substances, permit charged particles such as electrons or ions to move freely through them; these materials are known as **conductors**. Copper, silver, and a water solution of sodium chloride are examples of electrical conductors. Conductors cannot hold a charge if they are in contact with other materials since the charged particles move easily through them.

Other materials, such as nonmetals, do not readily permit the free movement of charges; these materials are called **insulators**. Rubber, glass, and air are examples of electrical insulators. When an insulator (e.g., a glass rod) is given an electric charge, the charge remains confined to the area where the charge was placed.

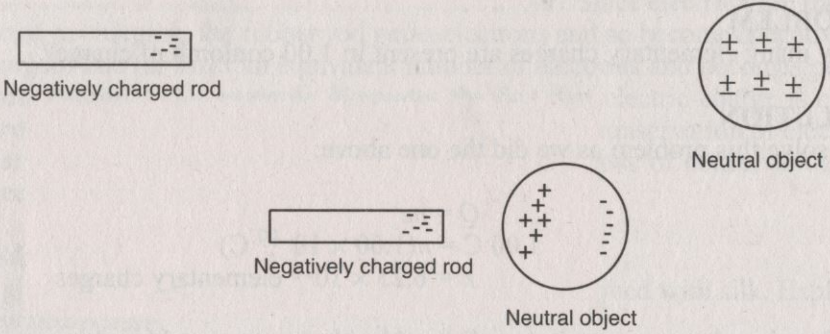
The Earth is an electrical conductor and can accept or donate large numbers of electrons. If a charged object is placed in contact with the Earth, it loses its own charge to the Earth. Because of its large size, the Earth remains essentially neutral.

The process of allowing the flow of charge into the Earth is known as *grounding*. Lightning rods are conductors through which dangerously large buildups of atmospheric charge pass harmlessly into the ground.

Human beings, because of the dissolved salts they contain, are also conductors and can act as "grounds" for electric charge. Touching an exposed electrical wire serves to confirm this shocking point.

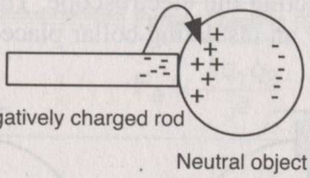
8.4 CHARGING OBJECTS

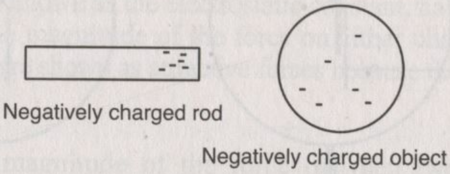
The diagram below represents a negatively charged rod that is brought near a neutral object.



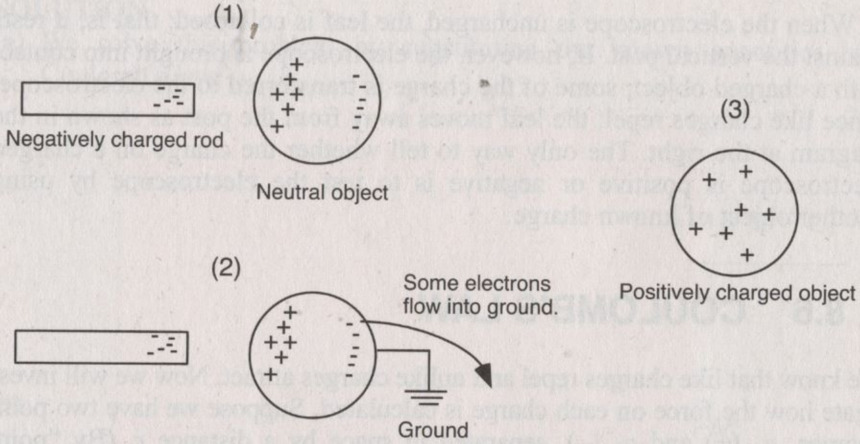
As the rod is brought near the object, the excess electrons in the rod repel the electrons in the object. The result is a *redistribution* of charge within the object. It is still neutral, but some of the charges have been separated, as shown in the lower half of the diagram. This phenomenon is known as *induction*. If the rod were removed, the original distribution of charge would return.

If the rod *touched* the object, some of the excess electrons from the rod would be transferred to the neutral object, giving it a permanent negative charge. This process, known as *charging by conduction,* is shown in the following diagram.





Another way in which an object can be charged is illustrated in the following diagram:

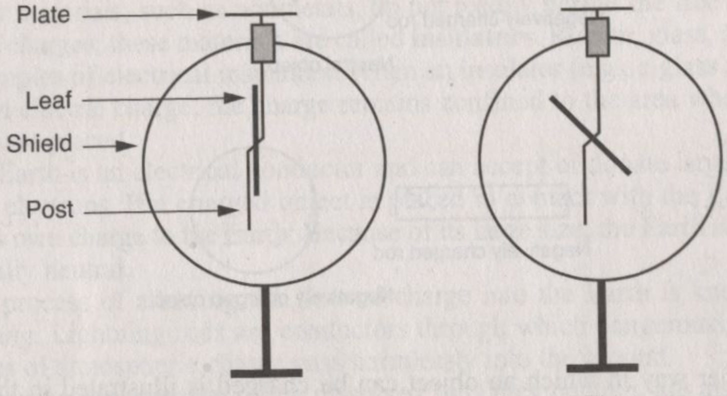


In step (1) the negatively charged rod is brought near the object, causing a redistribution of the object's charges. When the object is grounded in step (2), some of the electrons flow into the ground because they are repelled by the rod. When the ground is removed, the object is then *deficient* in electrons and therefore has acquired a positive charge. This process is known as *charging by induction.*

Note that in all of the examples above, the neutral objects are conductors while the rods are insulators.

8.5 THE ELECTROSCOPE

The *Braun electroscope*, diagramed below, is a device for detecting the presence of electric charge. It consists of a flat plate, a vertical post, and a "leaf," all of which are conductors. In addition, there is a circular shield, which prevents stray charges from affecting the electroscope. The shield is separated from the rest of the device by an insulating collar placed under the plate.

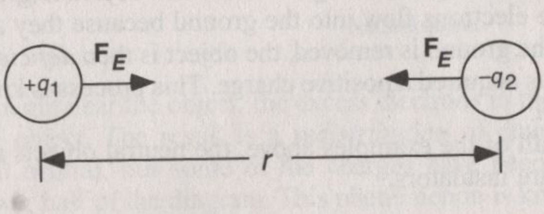


Uncharged Electroscope Charged Electroscope

When the electroscope is uncharged, the leaf is collapsed; that is, it rests against the vertical post. If, however, the electroscope is brought into contact with a charged object, some of the charge is transferred to the electroscope. Since like charges repel, the leaf moves away from the post as shown in the diagram at the right. The only way to tell whether the charge on a charged electroscope is positive or negative is to test the electroscope by using another object of known charge.

8.6 COULOMB'S LAW

We know that like charges repel and unlike charges attract. Now we will investigate how the force on each charge is calculated. Suppose we have two point charges, q_1 (+) and q_2 (–), separated in space by a distance r. (By "point charges" we mean charged objects separated by a distance that is much larger than the size of either object.) This situation is represented in the diagram.



In Section 8.1 we indicated that electric charges obey a law similar to Newton's law of universal gravitation. This law, known as *Coulomb's law*, takes this form:

PHYSICS CONCEPTS

$$F_e = \frac{kq_1q_2}{r^2}$$

Here, q_1 and q_2 represent the two charges, r represents the distance between their centers, and k, known as the electrostatic constant, has the value 9.0×10^9 $N \cdot m^2/C^2$. F_e is the magnitude of the force on either charge. In the diagram above, these forces are shown as attractive forces because the charges are unlike.

PROBLEM

(a) Calculate the magnitude of the force between two positive charges, $q_1 = 3.0 \times 10^{-6}$ coulomb and $q_2 = 6.0 \times 10^{-5}$ coulomb, separated by a distance of 9.0 meters.

(b) Draw a diagram representing this situation.

SOLUTION

(a) We solve this problem by substituting the known quantities into Coulomb's law:

[redacted]

0×10^{-5} C)

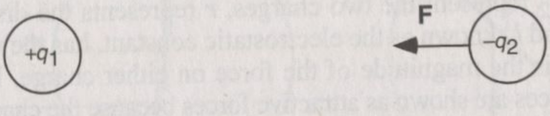
(b)

8.7 THE ELECTRIC FIELD

An **electric field** exists in a region of space if an electric force is exerted on a charged particle. The idea of an electric field was first developed by the great English scientist Michael Faraday and was perfected by other physicists during the nineteenth century.

Before the concept of the electric field was developed, it was assumed that charges affected each other directly. This idea, known as *action at a distance*, is illustrated in the diagram below:

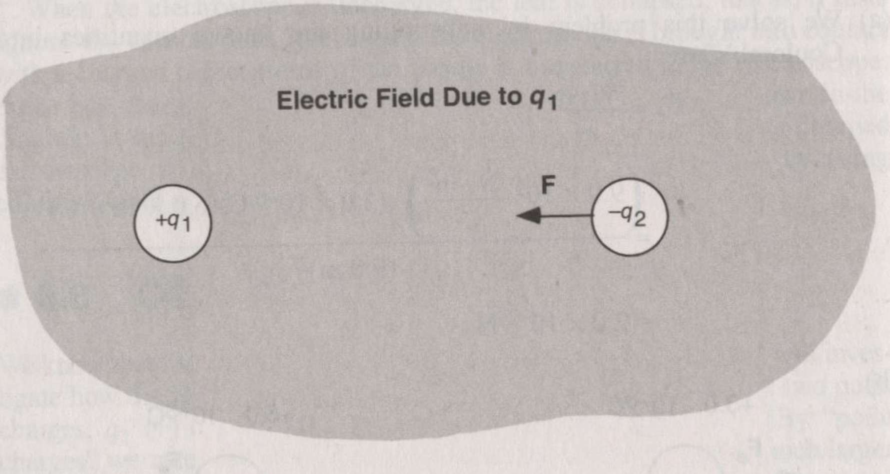
Action at a Distance



The problem with action at a distance is that there is no way to explain how one charge "knows" that another charge is near it.

The electric field concept assumes that one charge (q_1 in the diagram below) somehow changes the space around it. A second charge (q_2) then interacts with the field with the result that a force is exerted on this charge. One type of interaction is represented in the diagram below.

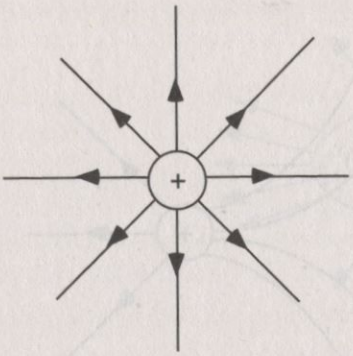
Electric Field Due to q_1

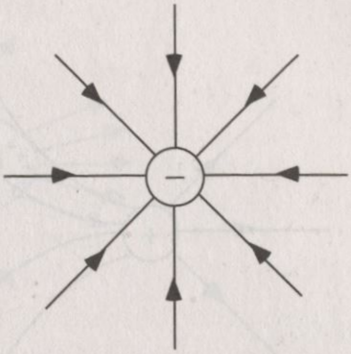


8.8 ELECTRIC FIELD LINES (LINES OF FORCE)

Field lines, also called *lines of force*, are models that we create in order to visualize an electric field. A field line is the path that a very small *positive* charge (known as a *test charge*) takes while in the field; it is drawn as a line (straight or curved) with an arrow to indicate the proper direction. A *negative* charge would move along the same field line but in the opposite direction.

When a sufficient number of field lines have been drawn, the result is a visual representation of the field. The diagrams that follow represent the electric fields in the vicinity of isolated positive and negative charges:

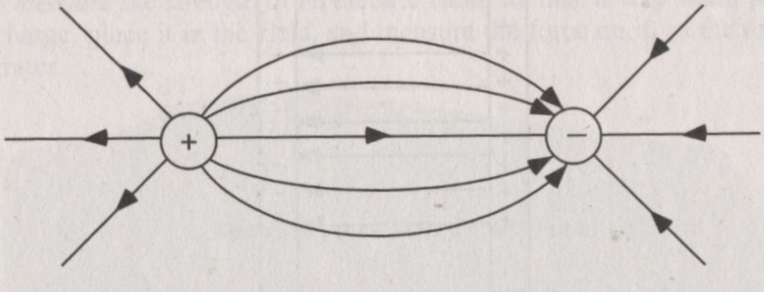




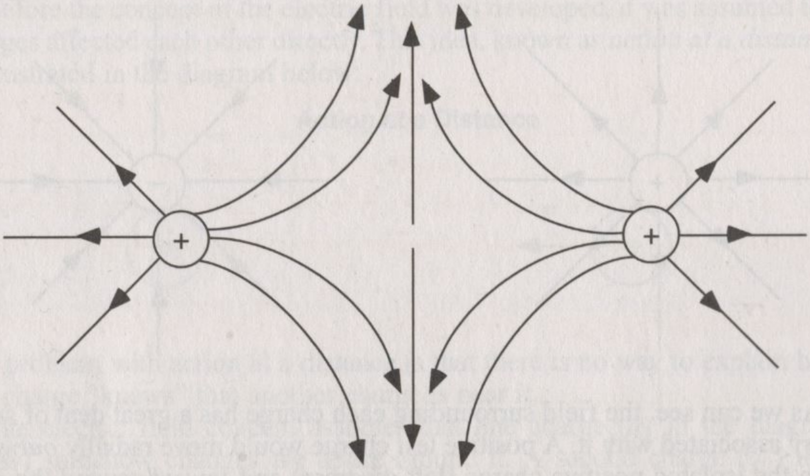
As we can see, the field surrounding each charge has a great deal of *symmetry* associated with it. A positive test charge would move radially *outward* from the isolated positive charge (left diagram) and *inward* toward the isolated negative charge (right diagram). The *number* of lines is an indication of the magnitude of the charge. For example, we might have drawn 16 lines to represent the field of an electric charge 2 times as large as the one shown above.

The *spacing* (or *concentration*) of the field lines indicates the relative *strength* of the electric field. The field is stronger in a region where the lines are more closely spaced and weaker where they are spread farther apart. The diagrams show that each electric field increases in strength as either charge is approached.

Now we will draw the electric field around two equal and opposite charges placed near each other (a configuration known as a *dipole*):

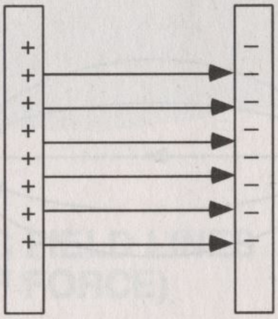


For contrast the electric field in the vicinity of two positive (like) charges is shown in the diagram that follows:



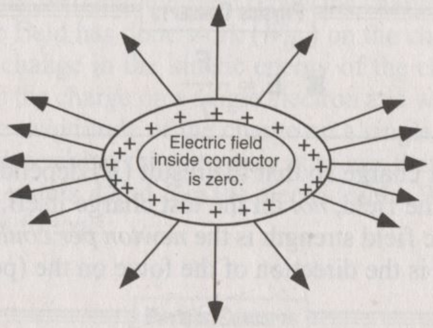
Notice that no field lines pass through the point midway between the charges. If another charge were placed at that point, it would experience no net force; in other words, the field strength is zero at that point. If we had used two *negative* charges, the field lines would have had the same shapes but would have pointed inward toward the charges.

Now let's draw the field lines between two oppositely charged parallel plates. This configuration, known as a *parallel plate capacitor*, is shown in the diagram below. We assume that the plates are very large in size. Actually, this situation can be approximated by placing the plates very close together and considering the field near the center of the plates.



Notice that the field lines are parallel. The result is that the electric field between the plates is uniform; it does not increase or decrease in strength.

Finally, we will consider the electric field in the vicinity of a (positively) charged hollow conductor, as shown in the following diagram:



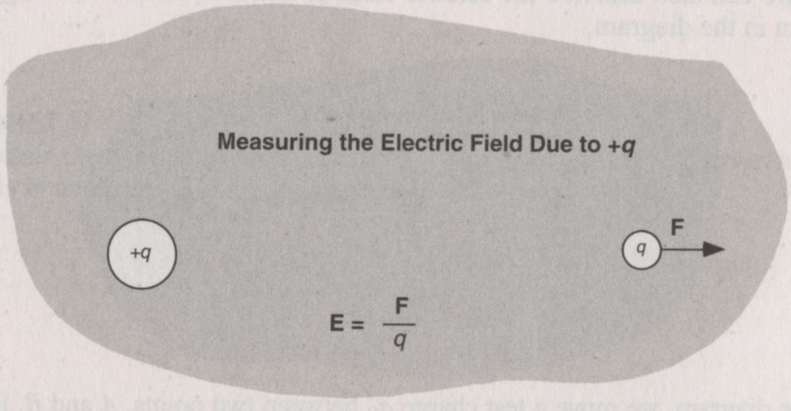
We can see that the field lines are not uniformly distributed: they are more concentrated around the curved parts of the conductor and are less concentrated around the flatter parts. Consequently, pointed objects have a greater buildup of charge. This is the principle upon which the lightning rod operates. The lightning tends to discharge on the pointed rod. Then, since the rod is grounded, any excess charge is passed harmlessly into the earth.

Also note that no electric field exists *inside* the conductor. This statement is true for every hollow conductor, regardless of its shape. As a result, hollow conductors can act as shields against electric charges.

8.9 ELECTRIC FIELD STRENGTH

The electric field is a vector quantity. We can verify this fact by referring to the diagrams in Section 8.8: the arrows point in the direction of the field, and the concentrations of the field lines indicate the magnitude, or strength, of the field.

To *measure* the strength of an electric field, we take a very small positive test charge, place it in the field, and measure the force on it, as the diagram illustrates.



We define the strength of the electric field (**E**) as the ratio of the force (**F**) to the magnitude of the test charge (q):

PHYSICS CONCEPTS

$$\mathbf{E} = \frac{\mathbf{F}}{q}$$

We *divide* by the test charge so that the result (**E**) depends on the charge (or charges) producing the field, *not* on the test charge itself.

The unit of electric field strength is the *newton per coulomb* (N/C), and the direction of the field is the direction of the force on the (positive) test charge.

PROBLEM

A test charge of $+2.0 \times 10^{-6}$ coulomb experiences a force of 2.4×10^{-3} newton [east] when placed in an electric field. Determine the magnitude and the direction of the electric field.

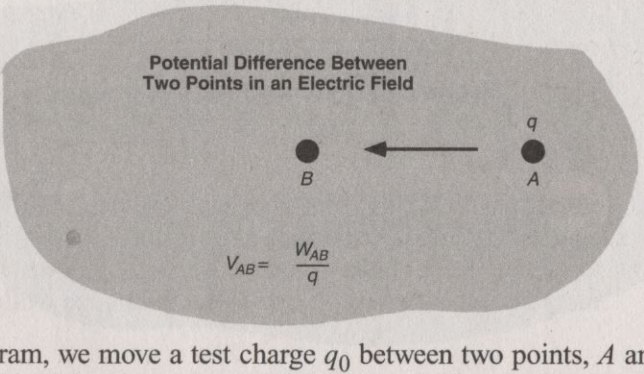
SOLUTION

We solve the problem by using the definition of electric field:

[redacted]

8.10 POTENTIAL DIFFERENCE

We have described the electric field in terms of the force on a charged particle. We can also describe the electric field in terms of work and energy as shown in the diagram.



In the diagram, we move a test charge q_0 between two points, *A* and *B*, in an electric field. If the charge is repelled by the field, we must do work on the charge to move it between the two points. The work we do against the field (W_{AB}) will increase the potential energy of the test charge. If we were to release the test charge at point B so that the field repels the charge back to point A, we can then say that the field has done work (W_{BA}) on the charge where the work is equivalent to the change in the kinetic energy of the charge. Note that this elementary charge is the charge on a single electron and was also subsequently determined to be the magnitude of the charge on a single proton.

Another way of describing this situation is to say that a **potential difference** exists between points A and B in the electric field. We define this potential difference (V) as follows:

PHYSICS CONCEPTS

$$V = \frac{W}{q}$$

Potential difference is a scalar quantity, as is work. The unit of potential difference is the *joule per coulomb* (J/C) called the *volt* (V) in honor of Alessandro Volta, an Italian scientist.

PROBLEM
When a charge of -4×10^{-3} coulomb is moved between two points in an electric field, 0.8 joule of work is done on the charge. Calculate the potential difference between the two points.

[redacted]

PROBLEM
Calculate the work done on an elementary charge that is moved between two points in an electric field with a potential difference of 1 volt.

[redacted]

The very small quantity of work in the problem shown above is frequently used as a unit of energy in atomic and nuclear physics. This unit is known as an **electron-volt** (eV). Some multiples of the electron-volt are shown in the table, where the letter *M* stands for *mega-*; the letter *G* for *giga-*; and the letter *T* for *tera.*

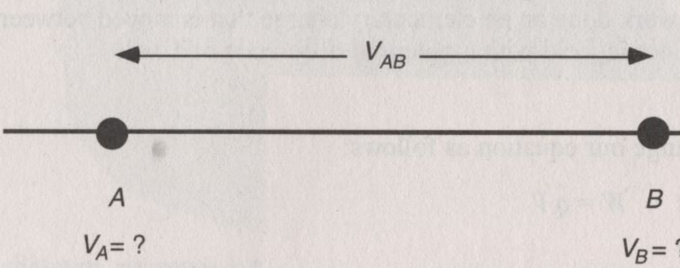
Multiple of eV	Abbreviation
10^6	MeV
10^9	GeV
10^{12}	TeV

PROBLEM
A charge, equal to 2×10^7 elementary charges, is moved through a potential difference of 3000 volts. What is the change in the potential energy of the charge?

[redacted]

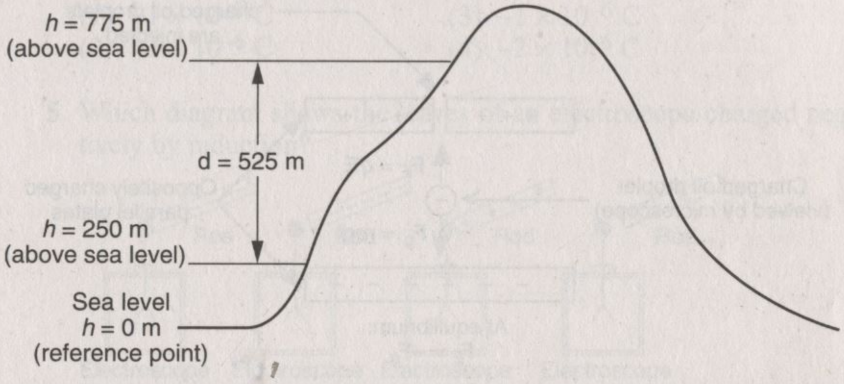
8.11 ELECTRIC POTENTIAL

We know that it is possible to measure the potential difference between two points, *A* and *B*, by dividing the work done on a charge by the magnitude of the charge. Suppose, however, that we wish to know the **electric potential** at just *one* of the points, *A* or *B*. How can we accomplish this?

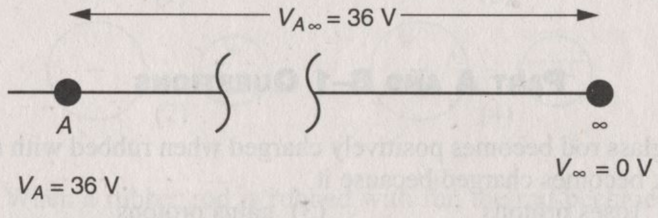


This situation is similar to climbing 525 meters vertically between two points on a hill. It seems only natural to ask how *high* the first and second points are.

The secret is to establish a reference point whose value is zero. With regard to the hill, sea level, with a height of 0 meter, is the reference point, and the height (or altitude) of each point is the distance of that point above sea level. The distance *between* two points is then the *difference* in their altitudes. The diagram below illustrates this concept.



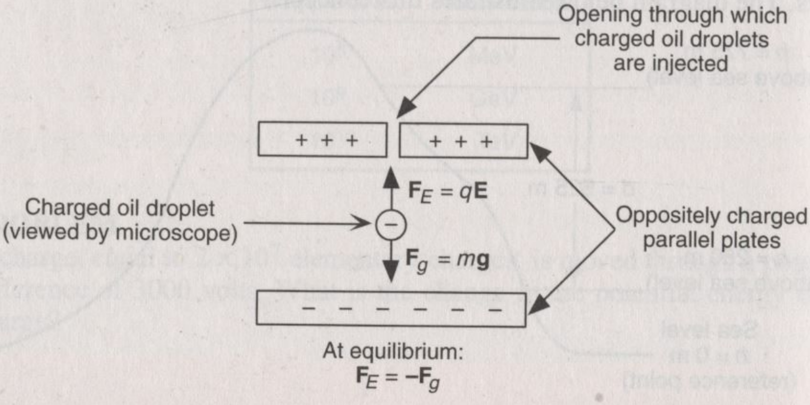
Similarly, to assign electric potentials, we establish a reference point of 0 volt. For an isolated charge, the reference point is taken to be infinitely far from the charge. For other situations, the ground may be taken as a reference point. We then measure the potential difference between the point in question and the reference point, assigning this value as the electric potential of the point. The diagram below, where *A* represents the point in question, illustrates how this is accomplished.



The electric potential at a point is defined as the work needed to move a charge of +1 coulomb from infinity to the point in question.

8.12 THE MILLIKAN OIL DROP EXPERIMENT

Robert Millikan, an American physicist, used a modified pair of charged parallel plates to measure the charges on microscopic oil droplets. The diagram shows how the observation was performed.



The charged droplet was injected through the opening into the uniform field between the parallel plates, where it was observed by a microscope. By changing the potential difference between the plates, the electric field strength was varied until the upward electric force on the droplet was balanced by the weight of the droplet. Millikan was then able to calculate the electric charge on each oil droplet that he observed. By measuring thousands of such charges, he determined that the charges were all multiples of 1.60×10^{-19} coulomb and thus concluded that the smallest charge, the *elementary charge*, is equal to 1.60×10^{-19} coulomb.

[redacted]