UNIT 3

Electricity and Magnetism

STATIC ELECTRICITY

Static electricity involves the phenomena associated with charges at rest. The term "at rest" means that there is no net flow of charge in any direction. There are many familiar effects of static electricity. For example, a person shuffling across a carpeted floor and then touching a metal doorknob can expect to experience a shock.

The behavior of objects that have a static charge can be demonstrated with pith balls. If a rubber rod or a glass rod is rubbed against fur or silk fabric and then brought near a light, suspended pith ball, the ball approaches the rod, makes contact with it, and then moves away from it. After that, the ball remains as far from the rod as possible. A pith ball touched by a stroked rubber rod and a pith ball touched by a stroked glass rod experience a force of attraction and move toward one another. On the other hand, two pith balls touched by the same type of stroked rod experience a force of repulsion and move away from one another.

Structure of the Atom.

The study of such phenomena indicates that all matter is electrical in nature. The basic unit of matter is the **atom** (Figure 3-1). Every atom consists of three types of particles: **protons**, **neutrons**, and **electrons**. Each electron carries a negative charge and each proton carries a positive charge. Neutrons carry no charge. The amount of negative charge on an electron is the same as the amount of positive charge on a proton. Therefore, an atom with an equal number of protons and electrons has no net charge.

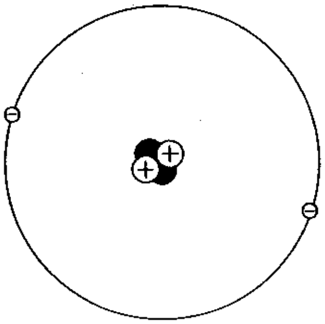


Figure 3-1. Model of an atom.

Protons and neutrons are located at the center of the atom, in the **nucleus**, which occupies a tiny fraction of the volume of the atom. Protons and neutrons are hundreds of times more massive than electrons and are held tightly together by strong nuclear forces. Electrons orbit the nucleus at various distances. The outermost electrons are often loosely bound to the nucleus by electrical forces and can be removed from the atom.

An object becomes charged if it either loses or gains electrons. An object that loses electrons and is left with fewer electrons than protons has a net positive charge. An object that gains electrons and has more electrons than protons has a net negative charge.

Electrons can only be transferred intact (fragments of electrons do not exist). As a result, any deficiency or excess of charge must consist of a whole-number multiple of the charge on one electron or proton. The charge on one electron is known as one **negative elementary charge**. The charge on one proton is referred to as one **positive elementary charge**.

The unit of charge is the **coulomb** (C). One coulomb is equal to the charge carried by 6.25×10^{18} electrons. Therefore the charge on one electron is equal to $1/6.25 \times 10^{18}$ C, or 1.6×10^{-19} C.

The Fundamentals of Electricity.

From the observation of charged objects, the fundamental principles governing all electrical phenomena emerge:

1. There are two kinds of electric charge: positive charge and negative charge.

2. Just as gravitational force exists between masses, there is an electrical force between charges. Unlike gravitational force, which is one of attraction only, charges can be attracted to or repelled by other charges. A positive charge will repel another positive charge, and a negative charge will repel another negative charge. A positive charge and a negative charge will attract one another. In other words, *like charges repel and unlike charges attract*.

3. All ordinary objects are electrically neutral, that is, they contain equal amounts of positive and negative charge.

Although both types of charge exist all around us, we are generally unaware of them because the electric forces they exert balance each other. For example, between two neutral objects there are forces of attraction between unlike charges balanced by equally strong forces of repulsion between like types of charge. Thus, the net force exerted on either object is equal to zero.

TRANSFER OF CHARGE

Charging by Contact.

An exchange of electrons, or transfer of charge, causes the phenomenon associated with the rubber and glass rods and the pith balls.

Electrons are bound more tightly in some materials than in others. Two dissimilar, neutral objects may become charged by rubbing against each other. For example, rubber tends to hold onto electrons more firmly than fur. Hence, when a rubber rod is rubbed against a piece of fur, electrons transfer from the fur to the rubber rod. The fur loses electrons and becomes positively charged. The rubber rod gains electrons and acquires a net negative charge. The magnitudes of the charges on the fur and the rod are equal and their signs are opposite.

If the rubber rod is then brought near a suspended pith ball, the negative charge on the rod repels electrons in the pith ball, forcing them to move to the far side of the ball. As a whole, the ball remains neutral, but the redistribution of electrons causes the ball to become **electrically polarized**. The side of the ball closest to the rod becomes positively charged and the side of the ball farthest from the rod becomes negatively charged (Figure 3-2).

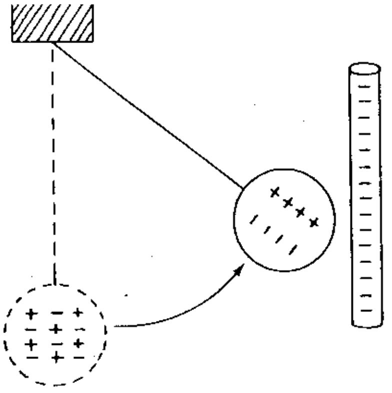


Figure 3-2. A negatively charged rod polarizes the pith ball.

The rod's excess electrons attract the protons on the near side of the ball and repel the electrons on the far side. The force of attraction is stronger (owing to the shorter distance between the rod and the ball's positively charged near side), and so the ball moves toward the rod. When the ball touches the rod, some of the rod's excess electrons transfer to the pith ball. The ball gains electrons and becomes negatively charged. This method of charge transfer is called **charging by contact**. The ball and the rubber rod are now both negatively charged and they repel each other. The ball moves (and remains) as far away from the rod as possible (Figure 3-3).

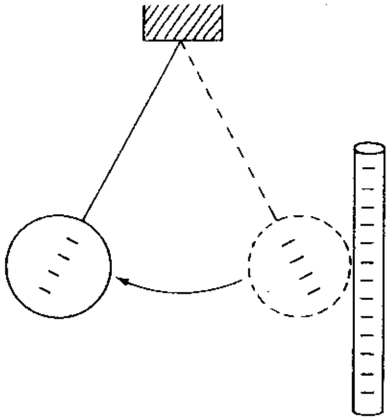


Figure 3-3. When the pith ball touches the rod it becomes negatively charged.

When a glass rod is rubbed against a silk cloth, electrons transfer from the glass rod to the silk. The glass rod loses electrons and becomes positively charged. Like the charged rubber rod, the charged glass rod also polarizes a pith ball, but in the opposite way. The ball's electrons are attracted to the positively charged glass rod and move to the side of the ball closest to it. When the ball touches the rod, some of the ball's electrons transfer to the rod, leaving the ball with more protons than electrons. (The rod remains positively charged because it gains only a few electrons.) At this point, both the ball and the glass rod are positively charged, and the force of repulsion keeps them apart.

Two pith balls that have made contact with a charged rubber rod will repel each other because they have both gained electrons and acquired a negative charge. Two pith balls that have made contact with a charged glass rod will repel each other because they have both lost electrons and become positively charged. Finally, two pith balls that have touched different rods (rubber or glass) attract each other because they become oppositely charged (Figure 3-4).

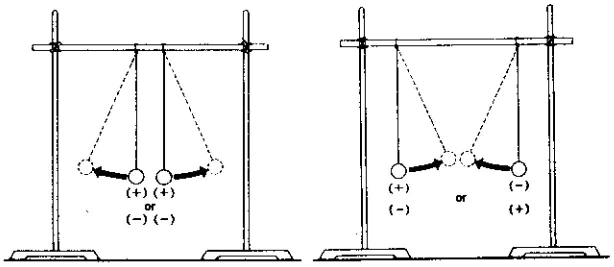


Figure 3-4. Two similarly charged pith balls repel each other and two oppositely charged pith balls attract each other.

Charging by Induction.

A charged object may induce an opposite charge in a neutral object without touching it. First, the neutral object must be **grounded**—that is, it must be connected to an object so large that it can either accept or give up a significant number of electrons without becoming noticeably charged. (The earth is often used as a ground.) Once the neutral object is grounded, a charged rod is brought near it without touching it, as in Figure 3-5. If the rod is negatively charged, it repels the electrons of the neutral object, forcing them to transfer to the ground. If the object is then disconnected from the ground

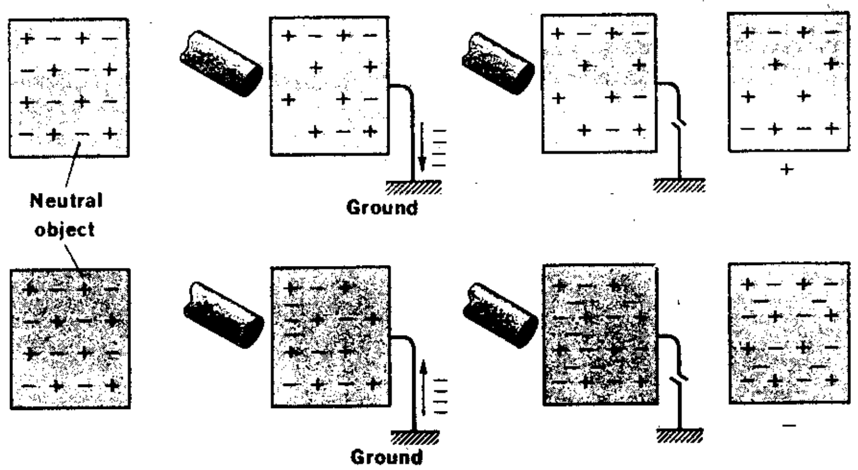


Figure 3-5. Charging by induction.

while the negatively charged rod is nearby, the object will be left with a net positive charge. On the other hand, if the rod is positively charged, it attracts electrons which transfer from the ground into the neutral object. If the object is then disconnected from the ground while the positively charged rod is nearby, the object is left with a net negative charge. In both cases, the charge acquired by the previously neutral object is *opposite* to that of the rod used to charge it.

Conservation of Charge. In all cases of charge transfer, the **law of conservation of charge** applies. Charge is never created or destroyed. A gain of charge in one place must correspond to a loss of that type of charge in another place.

Detection of Charge. The presence of excess charge on an object can be detected by bringing the object near an **electroscope**, a device that consists of a metal knob attached to two light metallic leaves (Figure 3-6). If either a positively or a negatively charged object is brought near the knob of the electroscope, the electrons within the electroscope are forced to rearrange themselves, and the electroscope becomes polarized. Each leaf acquires the same type of charge as the charged object, and the leaves diverge.

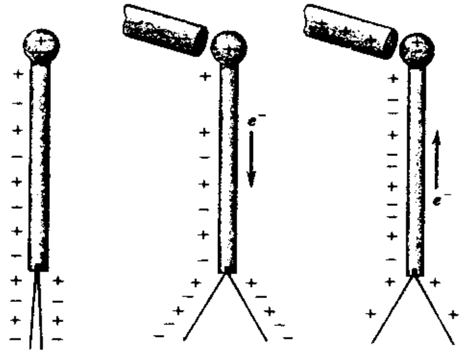


Figure 3-6. Detection of charges using a neutral electroscope.

A neutral electroscope cannot be used to distinguish between a positively charged object and a negatively charged object. However, an electroscope can be charged (either by contact or by induction) and then used to detect both the presence and the type of charge brought near it.

The leaves of a charged electroscope are separated due to the charge on the leaves (Figure 3-7). If an object brought near the knob of the charged electroscope has the same type of charge as the electroscope, the leaves will diverge even more. If the object brought near the charged electroscope is oppositely charged, the leaves will converge to a vertical position.

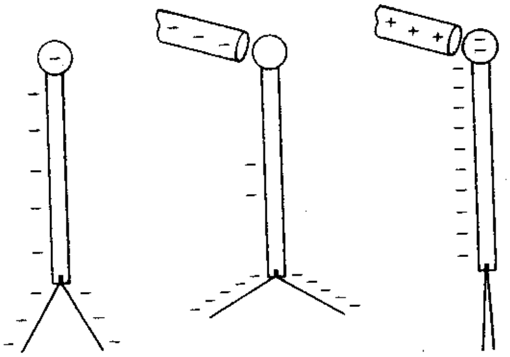


Figure 3-7. Identification of charges using a charged electroscope.

Coulomb's Law.

Experiments performed by Charles Coulomb demonstrate that for two charged objects that are much smaller than the distance between them (**point charges**), the electric force between the charges is directly proportional to the product of the amounts of charge and inversely proportional to the square of the distance between them. This relationship is known as **Coulomb's law**. Doubling the distance between two charges results in a force that is one-fourth as strong. Tripling the distance between the charges results in a force that is one-ninth as strong.

As indicated by Newton's third law of motion, the force exerted by one charge on a second charge is equal in magnitude and opposite in direction to the force exerted by the second charge on the first.

Coulomb's law can be expressed as

$$\mathbf{F} = \frac{kq_1q_2}{d^2}$$

where **F** is the force exerted by either charge on the other, in newtons; q_1 and q_2 are the amounts of charge, in coulombs; d is the distance between the charges, in meters; and k, the **electrostatic constant**, is equal to 9.0×10^9 N·m²/C².

Sample Problems

1. How strong is the repulsive force exerted on two point charges that each carry 1.0×10^{-6} C of negative charge and are 0.3 m apart?

Solution:

$$\mathbf{F} = \frac{kq_1q_2}{d^2}$$

$$= \frac{(9.0 \times 10^9\ \mathrm{N{\cdot}m^2/C^2})(1.0 \times 10^{-6}\ \mathrm{C})(1.0 \times 10^{-6}\ \mathrm{C})}{(0.3\ \mathrm{m})^2}$$

$$= \frac{9.0 \times 10^{-3}\ \mathrm{N{\cdot}m^2}}{9.0 \times 10^{-2}\ \mathrm{m^2}} = 0.1\ \mathrm{N}$$

2. Two identical point charges separated by 25 m exert a repulsive force on each other of 25 N. What is the magnitude of the charge on each object?

Solution:

$$\mathbf{F} = \frac{kq_1q_2}{d^2} \quad \text{and} \quad q_1 = q_2$$

$$25\ \mathrm{N} = \frac{(9.0 \times 10^9\ \mathrm{N{\cdot}m^2/C^2})(q^2)}{(25\ \mathrm{m})^2}$$

$$q^2 = \frac{(25\ \mathrm{N})(25\ \mathrm{m})^2}{(9.0 \times 10^9\ \mathrm{N{\cdot}m^2/C^2})}$$

$$= 1.7 \times 10^{-6}$$

$$q = 1.3 \times 10^{-3}\ \mathrm{C}$$

QUESTIONS

1. After two neutral solids, *A* and *B*, were rubbed together, solid *A* acquired a net negative charge. Solid *B*, therefore, experienced a net (1) loss of protons (2) increase of protons (3) loss of electrons (4) increase of electrons

2. A pith ball may become charged by losing or gaining (1) electrons, only (2) protons, only (3) protons and electrons (4) neutrons and protons

3. When a rubber rod is rubbed with fur, the rod becomes negatively charged due to the transfer of (1) electrons to the fur (2) protons to the fur (3) electrons to the rod (4) protons to the rod

4. How many electrons will a neutral atom of carbon have if the carbon nucleus has 6 protons and 8 neutrons? (1) 6 (2) 2 (3) 8 (4) 14

5. A neutral atom could be composed of (1) 4 electrons, 5 protons, 6 neutrons (2) 5 electrons, 5 protons, 6 neutrons (3) 6 electrons, 3 protons, 6 neutrons (4) 0 electrons, 5 protons, 5 neutrons

6. The ratio of the magnitude of charge on an electron to the magnitude of charge on a proton is (1) 1:2 (2) 1:1 (3) 1:6.25 × 10^{18} (4) 1:1,840

7. How many electrons are contained in a charge of 8.0×10^{-19} coulomb? (1) 5 (2) 2 (3) 8 (4) 4

8. Which is equivalent to three elementary charges? (1) 2.4×10^{-19} C (2) 2.0×10^{-19} C (3) 4.8×10^{-19} C (4) 5.4×10^{-19} C

9. A charge of 100 elementary charges is equivalent to (1) 1.60×10^{-21} C (2) 1.60×10^{-17} C (3) 6.25×10^{18} C (4) 6.25×10^{20} C

10. The coulomb is a unit of electrical (1) charge (2) current (3) potential (4) resistance

11. A sphere has a negative charge of 6.4×10^{-7} coulomb. Approximately how many electrons must be removed to make the sphere neutral? (1) 1.6×10^{-8} (2) 9.8×10^5 (3) 6.4×10^{26} (4) 4.0×10^{12}

12. After a neutral object loses 2 electrons, it will have a net charge of (1) −2 elementary charges (2) +2 elementary charges (3) -3.2×10^{-19} elementary charge (4) $+3.2 \times 10^{-19}$ elementary charge

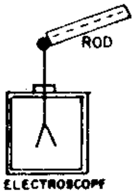
13. Metal sphere *A* has a charge of −2 units and an identical sphere *B* has a charge of −4 units. If the two spheres are brought together and then separated, the charge on sphere *A* will be (1) 0 units (2) −2 units (3) −3 units (4) +4 units

14. If a positively charged rod touches a neutral metal sphere, the number of electrons on the rod will (1) decrease (2) increase (3) remain the same

15. In the charging of a solid, charge transfer is accomplished by the displacement of (1) electrons, only (2) protons, only (3) both electrons and protons (4) neither electrons nor protons

16. A rod and a piece of cloth are rubbed together. If the rod acquires a charge of $+1 \times 10^{-6}$ coulomb, the cloth acquires a charge of (1) 0 C (2) $+1 \times 10^{-6}$ C (3) -1×10^{-6} C (4) $+1 \times 10^{6}$ C

17. Which of the following diagrams shows the leaves of the electroscope charged negatively by induction?



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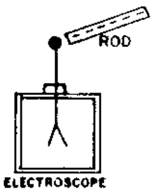

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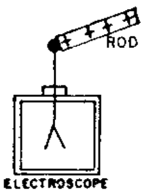

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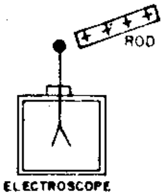

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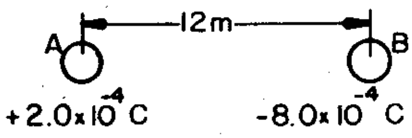
Base your answers to questions 18 through 20 on the following diagram, which represents a system consisting of two charged metal spheres with equal radii.

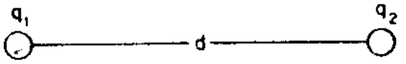


18. What is the magnitude of the electrostatic force exerted on sphere *A*? (1) 1.1×10^{-9} N (2) 1.3×10^{-8} N (3) 120 N (4) 10. N

19. Compared to the force exerted on sphere *B* at a separation of 12 meters, the force exerted on sphere *B* at a separation of 6.0 meters would be (1) $\frac{1}{2}$ as great (2) 2 times as great (3) $\frac{1}{4}$ as great (4) 4 times as great

20. If the two spheres were touched together and then separated, the charge on sphere *A* would be (1) -6.0×10^{-4} C (2) 2.0×10^{-4} C (3) -3.0×10^{-4} C (4) -8.0×10^{-4} C

21. The diagram represents two charges at a separation of *d*. Which would produce the greatest increase in the force between the two charges? (1) doubling charge q_1, only (2) doubling *d*, only (3) doubling charge q_1 and *d*, only (4) doubling both charges and *d*



22. The electrostatic force of attraction between two small spheres that are 1.0 meter apart is *F*. If the distance between the spheres is decreased to 0.5 meter, the electrostatic force will then be (1) *F*/2 (2) 2*F* (3) *F*/4 (4) 4*F*

23. If the charge on one of two small charged spheres is doubled while the distance between them remains the same, the electrostatic force between the spheres will be (1) halved (2) doubled (3) tripled (4) unchanged

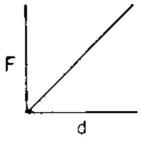
24. Charge *A* is $+2.0 \times 10^{-6}$ coulomb and charge *B* is $+1.0 \times 10^{-6}$ coulomb. If the force that *A* exerts on *B* is 1.0×10^{-2} newton, the force that *B* exerts on *A* is (1) 1.0×10^{-2} N (2) 2.0×10^{-2} N (3) 3.0×10^{-2} N (4) 5.0×10^{-1} N

Base your answers to questions 25 through 27 on the following diagram, which shows two *identical* metal spheres. Sphere *A* has a charge of +12 coulombs and sphere *B* is a neutral sphere.

25. When sphere *A* and *B* are in contact, the total charge of the system is (1) neutral (2) +6 C (3) +12 C (4) −24 C

26. When spheres *A* and *B* are separated, the charge on *A* will be (1) +12 C (2) $\frac{1}{4}$ the original amount (3) $\frac{1}{2}$ the original amount (4) 4 times the original amount

27. After spheres *A* and *B* are separated, which graph best represents the relationship of the force between the spheres and their separation?



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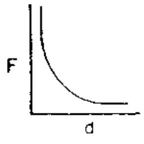

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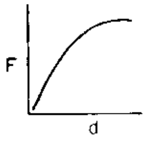

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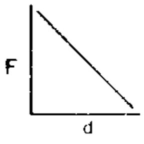

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ELECTRIC FIELDS

A charge in empty space experiences no electric forces, but a charge near another charge does. The reason for this difference is that a charge creates an **electric field** that permeates the surrounding space and affects other nearby charges.

As long as no other charge is present, an electric field does nothing. When another charge (referred to as a **test charge**) is introduced into the field, the field exerts a force on it. The presence of an electric field can be detected by its effect on a charged object introduced into the region.

Electric Field Intensity.

Fields, like forces, are vector quantities: they have magnitude and direction. The magnitude of an electric field is referred to as its **intensity**. The intensity of an electric field at a particular point is defined as the magnitude of the force that the field exerts on a test charge of one coulomb at that point. The direction of the electric field at any given point is defined as the direction of the force that the field exerts on a positive test charge at that point. The intensity and direction of an electric field are different at different positions in the vicinity of a charge, and therefore, the magnitude and direction of the electric force also vary from point to point.

The electric field intensity **E** at a particular point is given by the relationship

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

where **F** is the force, in newtons, exerted on a test charge *q*, in coulombs. The unit for electric field intensity is the newton/coulomb (N/C).

If the electric field intensity at a particular point is known, the force exerted on any amount of charge at that point is provided by the formula

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

Sample Problems

1. What is the intensity of an electric field at a point where a 0.50 C charge experiences a force of 20. N?

Solution:

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

$$= \frac{20.\ \text{N}}{0.50\ \text{C}} = 40.\ \text{N/C}$$

2. If one elementary unit of charge is placed at that point, how strong a force will it experience?

Solution:

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

$$= (40.\ \text{N/C})(1.6 \times 10^{-19}\ \text{C})$$

$$= 6.4 \times 10^{-18}\ \text{N}$$