TOPIC 4

Electricity and Magnetism

Vocabulary

ammeter	electromagnetic wave	north magnetic pole
ampere	electron	ohm
battery	electronvolt	ohm · meter
cell	electrostatic force	Ohm's law
conductivity	elementary charge	parallel circuit
conductor	equivalent resistance	potential difference
coulomb	induced potential difference	proton
Coulomb's law	joule	resistance
current	law of conservation of charge	resistivity
electric circuit	magnet	resistor
electric field	magnetic field	series circuit
electric field line	magnetic field strength	switch
electric field strength	magnetic field (flux) lines	variable resistor
electrical energy	magnetic force	volt
electrical power	magnetism	voltmeter
electromagnetic induction	neutron	watt

Electrostatics

The study of electric charges at rest, and their electric fields and potentials, is called electrostatics. Charges are said to be "at rest" if there is no net transfer of charge.

Microstructure of Matter The smallest unit of an element is the atom. Atoms are composed of several different subatomic particles—electrons, protons, and neutrons. A typical atom consists of a cloud of electrons surrounding a central dense core known as the nucleus. The nucleus always contains protons and usually contains neutrons. The **electron** is the fundamental negatively charged ($-$) particle of matter. The **proton** is the fundamental positively charged ($+$) particle of matter. The **elementary charge,** e, is equal in magnitude to the charge on an electron ($-e$) or the charge on a proton ($+e$). Although the charge on the proton is equal in magnitude to the charge on the electron, the mass of the proton is much greater than the mass of the electron. **Neutrons,** which are found in the nucleus, are neutral (no charge) subatomic particles that have nearly the same mass as protons. Because they contain equal numbers of protons and electrons, all atoms are electrically neutral.

Charged Objects Protons and neutrons cannot be removed from an atom by ordinary means. Because of this, electrically charged objects are usually formed when neutral objects lose or gain electrons. Electrons are often removed from an atom when energy is imparted to the atom by friction, heat, or light. When an atom gains or loses electrons, it becomes a charged particle known as an ion. An object with an excess of electrons is negatively charged, and an object with a deficiency of electrons is positively charged.

Two objects with the same sign of charge (both positive or both negative) that are located near each other are repelled by an electrical force. A negatively charged object and a positively charged object that are near each other are attracted by an electrical force. As explained in the next section, neutral objects and charged objects can also be attracted to each other.

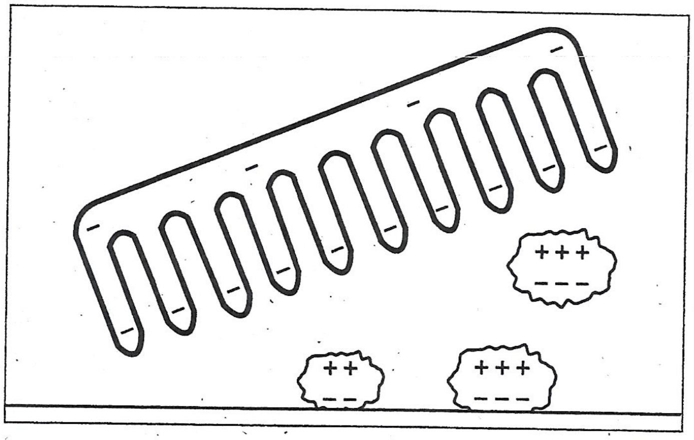


Figure 4-1. Opposite charges attract: The tiny pieces of paper are attracted to the comb. The magnitude of the electrostatic force is greater than the magnitude of Earth's gravitational force acting on the piece of paper being lifted.

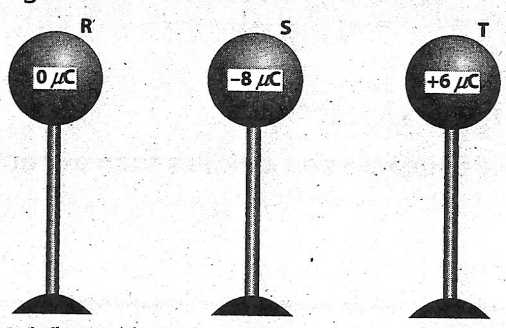
Transfer of Charge If a system consists only of neutral objects, it has a total net charge of zero. If objects in the system are rubbed together, electrons may be transferred between the objects. This, however, does not change the overall charge on the system—the system as a whole remains neutral. If one of the objects loses electrons and becomes positively charged, the object in contact with it acquires the electrons and becomes negatively charged.

If you run a plastic comb through your hair, electrons are transferred from your hair to the comb. Your hair becomes positively charged and the comb becomes negatively charged. If you then bring the comb near neutral pieces of paper on a tabletop, the charges within the paper are rearranged, as shown in Figure 4-1.

Law of Conservation of Charge The statement that in a closed, isolated system, the total charge of the system remains constant is known as the **law of conservation of charge.** Charges within the system may be transferred from one object to another, but charge is neither created nor destroyed.

SAMPLE PROBLEM

The diagram below shows the initial charges and positions of three metal spheres, R, S, and T, on insulating stands.



Sphere R is brought into contact with sphere S and then removed. Then sphere S is brought into contact with sphere T and removed. What is the charge on sphere T after this procedure is completed?

SOLUTION: When spheres R and S are brought into contact, they share the $-8\ \mu C$ charge equally. Thus each sphere possesses $-4\ \mu C$ when they are separated. When spheres S and T are brought into contact, they also share the charge evenly.

$$\frac{-4\ \mu C + 6\ \mu C}{2} = \frac{+2\ \mu C}{2} = +1\ \mu C$$

The final charge on sphere T is $+1\ \mu C$. Note also that charge is conserved; the initial charge of the system equals the final charge of the system.

$$-8\ \mu C + 6\ \mu C = -4\ \mu C + 1\ \mu C + 1\ \mu C = -2\ \mu C$$

Quantity of Charge Electric charge, q, is a scalar quantity. The SI unit of charge is the **coulomb,** C. One coulomb is equal to 6.25×10^{18} elementary charges. The charge on an electron $(-e)$ is -1.6×10^{-19} coulomb, and the charge on a proton $(+e)$ is $+1.6 \times 10^{-19}$ coulomb. The net charge on a charged object is always an integral multiple of e, that is, charge is quantized. For example, an object may have a net charge of 8.0×10^{-19} C (equivalent to $+5e$) or -1.6×10^{-18} C (equivalent to $-10e$), but it cannot have a charge of 2.4×10^{-19} C (equivalent to $\frac{3}{2}e$).

Coulomb's Law The size or magnitude of the **electrostatic force** that one point charge exerts on another point charge is directly proportional to the product of the charges and inversely proportional to the square of the distance between them. This relationship, called **Coulomb's law,** is given by this formula

Ⓡ
$$F_e = \frac{kq_1q_2}{r^2}$$

The electrostatic force F_e is in newtons, q_1 and q_2 are the charges in coulombs, and r is the distance of separation in meters. The electrostatic constant, k, is equal to $8.99 \times 10^9 \text{ N} \cdot \text{m}^2/\text{C}^2$. The electrostatic force is directed along the line joining the charges. The force that q_1 exerts on q_2 is equal in magnitude but opposite in direction to the force that q_2 exerts on q_1. The Coulomb's law formula is valid for charged objects whose dimensions are small compared to the distance separating the objects.

SAMPLE PROBLEM

Calculate the electrostatic force that a small sphere, *A*, possessing a net charge of +2 microcoulombs exerts on another small sphere, *B*, possessing a net charge of −3.0 microcoulombs when the distance between their centers is 10.0 meters.

SOLUTION: Identify the known and unknown values.

Known
$k = 8.99 \times 10^9 \text{ N} \cdot \text{m}^2/\text{C}^2$
$q_1 = +2.0 \times 10^{-6}$ C
$q_2 = -3.0 \times 10^{-6}$ C
$r = 10.0$ m

Unknown
$F_e = ?$ N

1. Write the formula for Coulomb's law.

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

2. Substitute the known values and solve.

$$F_e = \frac{\left(8.99 \times 10^9 \frac{\text{N}\cdot\text{m}^2}{\text{C}^2}\right)(+2.0 \times 10^{-6}\text{C})(-3.0 \times 10^{-6}\text{C})}{(1.00 \times 10^1 \text{ m})^2}$$

$$F_e = \frac{\left(8.99 \times 10^9 \frac{\text{N}\cdot\cancel{\text{m}^2}}{\cancel{\text{C}^2}}\right)(-6.0 \times 10^{-12}\cancel{\text{C}^2})}{1.00 \times 10^2 \cancel{\text{m}^2}}$$

$$F_e = -5.4 \times 10^{-4} \text{ N}$$

The negative sign indicates a force of attraction.

Review Questions

1. What is the charge of a proton?

(1) 9.11×10^{-31} C
(2) 1.67×10^{-27} C
(3) 1.60×10^{-19} C
(4) 6.25×10^{18} C

2. 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^{16} C
(4) 6.25×10^{20} C

3. State *both* the sign and magnitude of the charge on a proton, an electron, and a neutron in terms of *e*, the elementary charge.

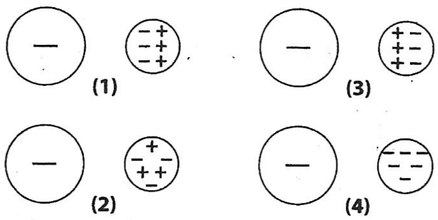
4. The diagram below represents two electrically charged identical-sized metal spheres, *A* and *B*.

$+2.0 \times 10^{-7}$ C $\quad$ $+1.0 \times 10^{-7}$ C

If the spheres are brought into contact, which sphere will have a net gain of electrons?

(1) *A*, only (3) both *A* and *B*
(2) *B*, only (4) neither *A* nor *B*

5. A small, uncharged metal sphere is placed near a large, negatively charged sphere. Which diagram best represents the charge distribution of the smaller sphere?



6. Which net charge could be found on an object?

(1) 8.00×10^{-20} C
(2) 2.40×10^{-19} C
(3) 3.20×10^{-19} C
(4) 6.25×10^{-18} C

7. A positively charged glass rod attracts object *X*. The net charge of object *X*

(1) may be zero or negative
(2) may be zero or positive
(3) must be negative
(4) must be positive

8. 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 electrons
(2) increase of electrons
(3) loss of protons
(4) increase of protons

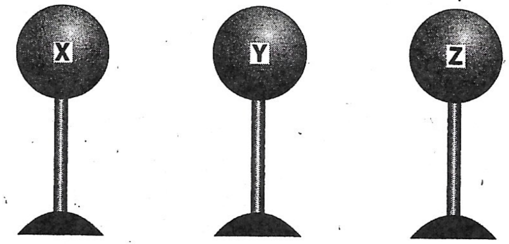
9. A rod and a piece of cloth are rubbed together. If the rod acquires a charge of $+1 \times 10^{-6}$ coulomb, the cloth acquires a charge of

(1) 0 C (3) -1×10^{-6} C
(2) $+1 \times 10^{-6}$ C (4) $+1 \times 10^{+6}$ C

10. Two identical spheres, A and B, carry charges of +6 microcoulombs and −2 microcoulombs, respectively. If these spheres touch, what will be the resulting charge on sphere A?

11. The diagram below shows the initial charges and positions of three identical metal spheres, X, Y, and Z, which have been placed on insulating stands. All three spheres are simultaneously brought into contact with each other and then returned to their original positions.

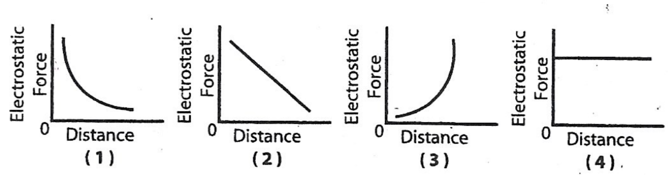
+2 μC $\quad$ +4 μC $\quad$ +6 μC



Which statement best describes the charge of the spheres after this procedure is completed?

(1) All the spheres are neutral.
(2) Each sphere has a net charge of +4 μC.
(3) Each sphere retains the same charge that it had originally.
(4) Sphere Y has a greater charge than sphere X or sphere Z.

12. Two oppositely charged metal spheres are brought toward each other. Which graph best represents the relationship between the magnitude of the electrostatic force one sphere exerts on the other sphere and the distance between their centers?



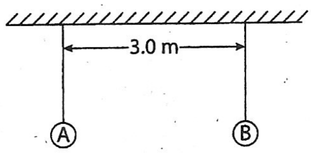
13. The electrostatic force of attraction between two small spheres that are 1.0 meter apart is *F*. If the distance between the spheres is decreased to 0.5 meter, the electrostatic force will be

(1) $\frac{F}{2}$ (3) $\frac{F}{4}$
(2) $2F$ (4) $4F$

14. Two identical small spheres possessing charges q_1 and q_2 are separated by distance *r*. Which change would produce the greatest increase in the magnitude of the electrostatic force that one sphere exerts on the other?

(1) doubling charge q_1
(2) doubling *r*
(3) doubling *r* and charge q_1
(4) doubling *r* and charges q_1 and q_2

15. The diagram below shows two metal spheres suspended by strings and separated by a distance of 3.0 meters. The charge on sphere A is $+5.0 \times 10^{-4}$ coulomb, and the charge on sphere B is $+3.0 \times 10^{-5}$ coulomb.



What forces does sphere *A* exert on sphere *B*?

(1) an attractive gravitational force and a repulsive electrostatic force of 15 N
(2) an attractive gravitational force and a repulsive electrostatic force of 45 N
(3) a repulsive gravitational force and an attractive electrostatic force of 15 N
(4) a repulsive gravitational force and an attractive electrostatic force of 45 N

16. If the charge is doubled on each of two small spheres having a fixed distance between their centers, the magnitude of the electrostatic force that one sphere exerts on the other will be

(1) halved
(2) doubled
(3) quartered
(4) quadrupled

17. A point charge *A* of $+3.0 \times 10^{-7}$ coulomb is placed 2.0×10^{-2} meter from a second point charge *B* of $+4.0 \times 10^{-7}$ coulomb. Calculate the magnitude of the electrostatic force that charge *A* exerts on charge *B*.

SAMPLE PROBLEM

Calculate the magnitude of the electric field strength at a point in a field where an electron experiences a force with a magnitude of 1.0×10^{-15} newton.

SOLUTION: Identify the known and unknown values.

Known	*Unknown*
$F_e = 1.0 \times 10^{-15}$ N	$E = ?$ N/C
$q = 1.60 \times 10^{-19}$ C	

1. Write the formula the defines electric field strength.

$$E = \frac{F_e}{q}$$

2. Substitute the known values and solve.

$$E = \frac{1.0 \times 10^{-15}\ \text{N}}{1.60 \times 10^{-19}\ \text{C}} = 6.3 \times 10^{3}\ \text{N/C}$$

Electric Fields

An **electric field** is the region around a charged particle through which a force is exerted on another charged particle. An **electric field line** is the imaginary line along which a positive test charge would move in an electric field. The direction of an electric field is the direction of the force on a stationary positive test charge located at any point on a field line. On a curved field line, the direction of the field at any point is the tangent drawn to the field line at that point. Electric field lines begin on positive charges (or at infinity) and end on negative charges (or infinity). Field lines never intersect.

Electric field strength, *E*, is the force on a stationary positive test charge per unit charge in an electric field. It is given by this formula

$$E = \frac{F_e}{q}$$ Ⓡ

The electrostatic force F_e is in newtons, the charge q is in coulombs, and the electric field strength E is in newtons per coulomb. Because it has both magnitude and direction, electric field strength is a vector quantity.

Field Around a Point Charge or Sphere Field lines extend radially outward from a positive point charge and radially inward toward a negative point charge. On a sphere, charge is distributed uniformly, and electric field lines are normal (perpendicular) to the surface. According to Coulomb's law, the electric field strength around a point charge or charged sphere varies inversely with the square of the distance from the point charge or sphere. The electric field strength within a hollow, charged conducting sphere is zero.

Field Between Two Oppositely Charged Parallel Plates If the distance separating two oppositely charged parallel plates is small compared to their area, the electric field between the plates is uniform. The electric field lines are parallel to each other, so the field strength is the same at every point between the plates. Figure 4-2 shows the electric fields surrounding charged objects.

The magnitude of the electric force on an electron or a proton located at any point between two given oppositely charged parallel plates is the same. The electric force acting on either of these charged particles causes it to accelerate toward the plate of opposite sign. That is, the particle's speed increases as it approaches the plate of opposite sign.

Potential Difference If the direction of an electric field is such that it opposes the motion of a charged particle, work must be done to move the particle in that direction. The **potential difference** between two points in an electric field is the work done (or change in potential energy) per unit charge as a charged particle is moved between the points. Potential difference is a scalar quantity given by this formula.

R

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

The work W is in joules, the charge q is in coulombs, and the potential difference V is in joules per coulomb. If one joule of work is done to move one coulomb of charge between two points in an electric field, a potential difference of one **volt** is said to exist between the two points. That is, 1 joule/coulomb = 1 volt. The volt, V, is the derived SI unit for potential difference.

If an elementary charge is moved against an electric field through a potential difference of one volt, the work done on the charge is calculated as shown below.

$$W = Vq = (1.00 \text{ V})(1.60 \times 10^{-19} \text{ C}) = 1.60 \times 10^{-19} \text{ J}$$

This amount of work (1.60×10^{-19} J), or gain in potential energy, is called the **electronvolt**, eV. That is, 1.00 eV = 1.60×10^{-19} J.

SAMPLE PROBLEM

Moving a point charge of 3.2×10^{-19} coulomb between points A and B in an electric field requires 4.8×10^{-18} joule of energy. Calculate the potential difference between these points.

SOLUTION: Identify the known and unknown values.

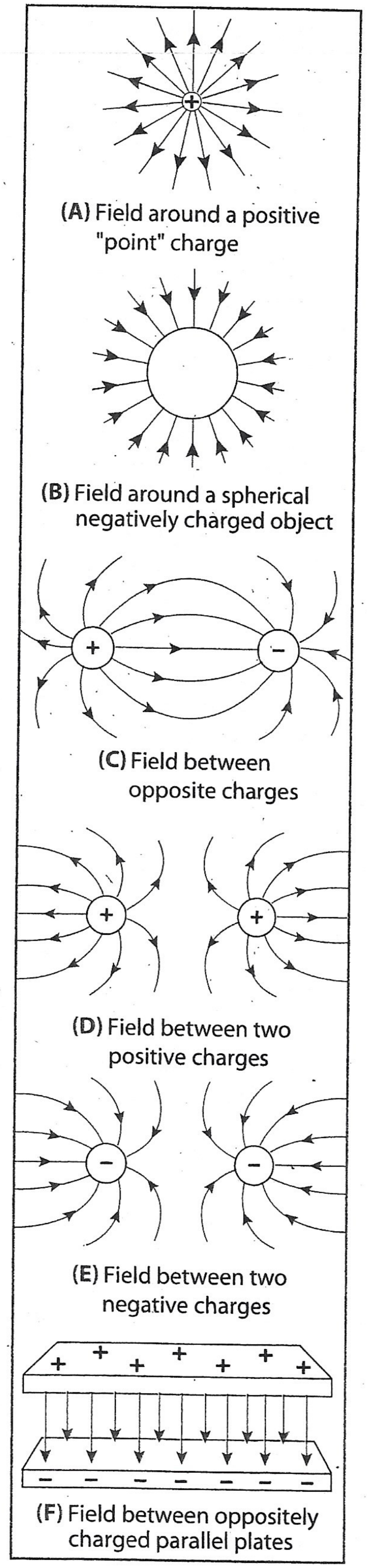
<u>Known</u>	<u>Unknown</u>
$q = 3.2 \times 10^{-19}$ C	$V = ?$ V
$W = 4.8 \times 10^{-18}$ J	

1. Write the formula that defines potential difference.

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

2. Substitute the known values and solve.

$$V = \frac{4.8 \times 10^{-18} \text{ J}}{3.2 \times 10^{-19} \text{ C}} = 15 \text{ V}$$



(A) Field around a positive "point" charge

(B) Field around a spherical negatively charged object

(C) Field between opposite charges

(D) Field between two positive charges

(E) Field between two negative charges

(F) Field between oppositely charged parallel plates

Figure 4-2. Fields surrounding charged objects