15 Electrostatics

15-1 Electrostatic Force

Vocabulary **Electrostatics:** The study of electric charges, forces, and fields.

The symbol for electric charge is the letter "q" and the SI unit for charge is the **coulomb (C).** The coulumb is a very large unit.

$1\ \text{C} = 6.25 \times 10^{18}$ electrons or
1 electron has a charge of 1.60×10^{-19} C.

Electrons surrounding the nucleus of an atom carry a negative charge. Protons, found inside the nucleus of the atom, carry a positive charge of 1.60×10^{-19} C, while neutrons (which also reside in the nucleus) are neutral. It is important to remember that only electrons are free to move in a substance. Protons and neutrons usually do not move.

When two objects with like charges, positive or negative, are brought near each other, they experience a repulsive force. When objects with opposite charges, one negative and one positive, are brought side by side, they experience an attractive force. These forces can be described with Coulomb's law.

Vocabulary **Coulomb's Law:** Two charged objects attract each other with a force that is proportional to the charge on the objects and inversely proportional to the square of the distance between them.

$$F \propto \frac{q_1 q_2}{d^2}$$

This equation looks very similar to Newton's law of universal gravitation. As before, the sign $\propto$ means "proportional to." To make an equation out of this proportionality, insert a quantity called the **electrostatic constant, k.**

$$k = 9.0 \times 10^9\ \text{N} \cdot \text{m}^2/\text{C}^2$$

The magnitude of Coulomb's law can now be written as an equation.

$$\textbf{electrostatic force} = \frac{\textbf{(electrostatic constant)(charge 1)(charge 2)}}{\textbf{(distance)}^2} \quad \text{or} \quad F = \frac{kq_1 q_2}{d^2}$$

Like all other forces, the electrostatic force between two charged objects is measured in newtons.

Solved Examples

Example 1: Anthea rubs two latex balloons against her hair, causing the balloons to become charged negatively with 2.0×10^{-6} C. She holds them a distance of 0.70 m apart. a) What is the electric force between the two balloons? b) Is it one of attraction or repulsion?

Solution: It is not necessary to carry the sign of the charge throughout the entire exercise. However, when determining the direction of your final answer, it is important to remember the charge on each object.

Given: $q_1 = 2.0 \times 10^{-6}$ C
$q_2 = 2.0 \times 10^{-6}$ C
$d = 0.70$ m
$k = 9.0 \times 10^9\ \mathrm{N \cdot m^2/C^2}$

Unknown: $F = ?$
Original equation: $F = \dfrac{kq_1q_2}{d^2}$

Solve: $$F = \frac{kq_1q_2}{d^2} = \frac{(9.0 \times 10^9\ \mathrm{N \cdot m^2/C^2})(2.0 \times 10^{-6}\ \mathrm{C})(2.0 \times 10^{-6}\ \mathrm{C})}{(0.70\ \mathrm{m})^2} = \mathbf{0.073\ N}$$

b) Because both balloons are negatively charged, they will repel each other.

Example 2: Two pieces of puffed rice become equally charged as they are poured out of the box and into Kirk's cereal bowl. If the force between the puffed rice pieces is 4×10^{-23} N when the pieces are 0.03 m apart, what is the charge on each of the pieces?

Solution: Because both charges are the same, solve for both q's together. Then find the square root of that value to determine one of the charges.

Given: $F = 4 \times 10^{-23}$ N
$d = 0.03$ m
$k = 9.0 \times 10^9\ \mathrm{N \cdot m^2/C^2}$

Unknown: $q = ?$
Original equation: $F = \dfrac{kq_1q_2}{d^2}$

Solve: $$q_1q_2 = \frac{Fd^2}{k} = \frac{(4 \times 10^{-23}\ \mathrm{N})(0.03\ \mathrm{m})^2}{9.0 \times 10^9\ \mathrm{N \cdot m^2/C^2}} = 4 \times 10^{-36}\ \mathrm{C^2}$$

This is the square of the charge on the pieces of puffed rice. To find the charge on one piece of puffed rice, take the square root of this number.

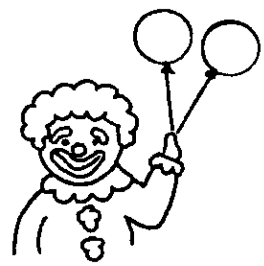
$$q = \sqrt{4 \times 10^{-36}\ \mathrm{C^2}} = \mathbf{2 \times 10^{-18}\ C}$$

Practice Exercises

Exercise 1: When sugar is poured from the box into the sugar bowl, the rubbing of sugar grains creates a static electric charge that repels the grains, and causes sugar to go flying out in all directions. If each of two sugar grains acquires a charge of 3.0×10^{-11} C at a separation of 8.0×10^{-5} m, with what force will they repel each other?

Answer: ____________________

Exercise 2: Boppo the clown carries two mylar balloons that rub against a circus elephant, causing the balloons to separate. Each balloon acquires 2.0×10^{-7} C of charge. How large is the electric force between them when they are separated by a distance of 0.50 m?



Answer: ____________________

Exercise 3: Inez uses hairspray on her hair each morning before going to school. The spray spreads out before reaching her hair partly because of the electrostatic charge on the hairspray droplets. If two drops of hairspray repel each other with a force of 9.0×10^{-9} N at a distance of 0.070 cm, what is the charge on each of the equally-charged drops of hairspray?

Answer: ____________________

Exercise 4: Bonnie is dusting the house and raises a cloud of dust particles as she wipes across a table. If two 4.0×10^{-14}-C pieces of dust exert an electrostatic force of 2.0×10^{-12} N on each other, how far apart are the dust particles at that time?

Answer: ____________________

Exercise 5: Each of two hot-air balloons acquires a charge of 3.0×10^{-5} C on its surface as it travels through the air. How far apart are the balloons if the electrostatic force between them is 8.1×10^{-2} N?

Answer: ____________________

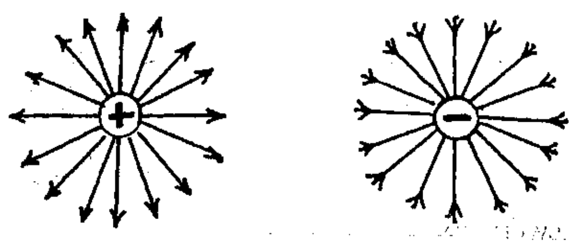
15-2 Electric Field

Vocabulary **Electric Field:** An area of influence around a charged object. The magnitude of the field is proportional to the amount of electrical force exerted on a positive test charge placed at a given point in the field.

$$\textbf{electric field} = \frac{\textbf{electric force}}{\textbf{test charge}} \quad \text{or} \quad E = \frac{F}{q_0}$$

The SI unit of electric field is the **newton per coulomb (N/C).**

The electric field around a charged object is a vector and can be represented with electric field lines that point in the direction of the force exerted on a unit of positive charge. In other words, electric field lines point away from a positive charge and toward a negative charge, as shown in the diagram.



For a point charge (or other spherical charge distribution), the magnitude of the electric field can be written as

$$E = \frac{F}{q_o} = \frac{kq_oq}{q_od^2} = \frac{kq}{d^2}$$

where q is the charge on the surface of the object, and d is the distance between the center of the charged object and a small positive test charge, q_o, placed in the field.

Solved Examples

Example 3: Deepika pulls her wool sweater over her head, which charges her body as the sweater rubs against her cotton shirt. What is the electric field at a location where a 1.60×10^{-19} C-piece of lint experiences a force of 3.2×10^{-9} N as it floats near Deepika? b) What will happen if Deepika now touches a conductor such as a door knob?

a. *Given:* $q_o = 1.60 \times 10^{-19}$ C
$F = 3.2 \times 10^{-9}$ N

Unknown: $E = ?$
Original equation: $F = q_oE$

Solved: $E = \frac{F}{q_o} = \frac{3.2 \times 10^{-9}\text{ N}}{1.60 \times 10^{-19}\text{ C}} = \mathbf{2.0 \times 10^{10}\ N/C}$

b. She will reduce her charge in a process called **grounding,** in which excess electrons flow from her body into the ground and spread evenly over the surface of Earth.

Example 4: A fly accumulates 3.0×10^{-10} C of positive charge as it flies through the air. What is the magnitude and direction of the electric field at a location 2.0 cm away from the fly?

Solution: First, convert cm to m. 2.0 cm = 0.020 m

Given: $k = 9.0 \times 10^9\ \text{N} \cdot \text{m}^2/\text{C}^2$
$q = 3.0 \times 10^{-10}$ C
$d = 0.020$ m

Unknown: $E = ?$
Original equation: $E = \frac{kq}{d^2}$

Solve: $E = \frac{kq}{d^2} = \frac{(9.0 \times 10^9\ \text{N} \cdot \text{m}^2/\text{C}^2)(3.0 \times 10^{-10}\ \text{C})}{(0.020\ \text{m})^2} =$ **6800 N/C away from the fly**

Practice Exercises

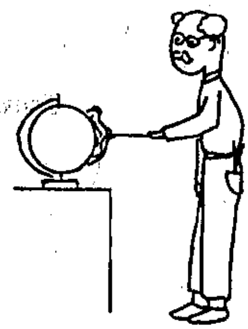
Exercise 6: Mr. Patel is photocopying lab sheets for his first period class. A particle of toner carrying a charge of 4.0×10^{-9} C in the copying machine experiences an electric field of 1.2×10^{6} N/C as it's pulled toward the paper. What is the electric force acting on the toner particle?

Answer: ____________________

Exercise 7: As Courtney switches on the TV set to watch her favorite cartoon, the electron beam in the TV tube is steered across the screen by the field between two charged plates. If the electron experiences a force of 3.0×10^{-6} N, how large is the field between the deflection plates?

Answer: ____________________

Exercise 8: Gordon the night custodian dusts off a classroom globe with a feather duster, causing the globe to acquire a charge of -8.0×10^{-9} C. What is the magnitude and direction of the electric field at a point 0.40 m from the center of the charged globe?



Answer: ____________________

Exercise 9: April is decorating a tree in her backyard with plastic eggs in preparation for Easter. She hangs two eggs side by side so that their centers are 0.40 m apart. April rubs the eggs to shine them up, and in doing so places a charge on each egg. The egg on the left acquires a charge of 6.0×10^{-6} C while the egg on the right is charged with 4.0×10^{-6} C. What is the electric field at a point 0.15 m to the right of the egg on the left?

Answer: ______________________

15-3 Electrical Potential Difference

Vocabulary **Potential Difference:** The work done to move a positive test charge from one location to another.

$$\textbf{potential difference} = \frac{\textbf{work}}{\textbf{test charge}} \quad \text{or} \quad V = \frac{W}{q_0}$$

The SI unit for potential difference is the **volt (V)**, which equals a **joule per coulomb (J/C).**

Remember, the term "work" can be replaced with the term "energy," because to store energy in, or give energy to, an object, work must be done. Therefore, potential difference can also be defined as the electrical potential energy per unit test charge. **Voltage** is often used to mean potential difference.

The field that exists between two charged parallel plates is uniform except near the plate edges, and depends upon the potential difference between the plates and the plate separation.

$$\textbf{electric field} = \frac{\textbf{potential difference}}{\textbf{separation between plates}} \quad \text{or} \quad E = \frac{V}{\Delta d}$$

Here, the unit for electric field is the volt/meter. It was noted earlier that the unit for electric field is the newton/coulomb. This means that a volt/meter must equal a newton/coulomb.

$$\frac{\text{volt}}{\text{meter}} = \frac{\text{joule/coulomb}}{\text{meter}} = \frac{\text{newton}\cdot\text{meter}}{\text{coulomb}\cdot\text{meter}} = \frac{\text{newton}}{\text{coulomb}}$$

Solved Examples

Example 5: An electron in Tammie's TV is accelerated toward the screen across a potential difference of 22 000 V. How much kinetic energy does the electron lose when it strikes the TV screen?

Given: $q_o = 1.60 \times 10^{-19}$ C
$V = 22\,000$ V

Unknown: $W = ?$
Original equation: $V = \frac{W}{q_o}$

Solve: $W = q_o V = (1.60 \times 10^{-19}\ \text{C})(22\,000\ \text{V}) = \mathbf{3.5 \times 10^{-15}\ J}$

Example 6: Amir shuffles his feet across the living room rug, building up a charge on his body. A spark will jump when there is a potential difference of 9000 V between the door and the palm of Amir's hand. This happens when his hand is 0.3 cm from the door. At this point, what is the electric field between Amir's hand and the door?

Solution: First, convert cm to m. 0.3 cm = 0.003 m

Given: $V = 9000$ V
$\Delta d = 0.003$ m

Unknown: $E = ?$
Original equation: $V = E\Delta d$

Solve: $E = \frac{V}{\Delta d} = \frac{9000\ \text{V}}{0.003\ \text{m}} = \mathbf{3 \times 10^6\ V/m}$

Practice Exercises

Exercise 10: James recharges his dead 12.0-V car battery by sending 28 000 C of charge through the terminals. How much electrical potential energy must James store in the car battery to make it fully charged?

Answer: ______________________

Exercise 11: If an electron loses 1.4×10^{-15} J of energy in traveling from the cathode to the screen of Jeffrey's personal computer, across what potential difference must it travel?

Answer: ____________________

Exercise 12: A "bug zapper" kills bugs that inadvertently stray between the charged plates of the device. The bug causes sudden dielectric breakdown of the air between the plates. If two plates in a bug zapper are separated by 5.0 cm and the field between them is a uniform 2.8×10^6 V/m, what is the potential difference that kills the unsuspecting bugs?

Answer: ____________________

Exercise 13: While getting out of a car, Victor builds up a charge on his body as he slides across the cloth car seats. When he attempts to shut the car door, his hand discharges 12 000 V through a uniform electric field of 3.0×10^6 V/m. How far is his hand from the door at the time the spark jumps?

Answer: ____________________

Exercise 14: A lightning bolt from a cloud hits a tree after traveling 200 m to the ground through an electric field of 2.0×10^6 V/m. a) What is the potential difference between the cloud and the tree just before the lightning bolt strikes? b) If you are in an open field during a lightning storm and the only thing you see nearby is a tall tree, is it a good idea to stand under the tree for protection from the lightning? Why or why not?

Answer: **a.** ____________________

Answer: **b.** ____________________

Additional Exercises

A-1: A raindrop acquires a negative charge of 3.0×10^{-18} C as it falls. What is the force of attraction when the raindrop is 6.0 cm from the bulb on the end of a car antenna that holds a charge of 2.0×10^{-6} C?

A-2: In a grain elevator on Farmer Judd's farm, pieces of grain become electrically charged while falling through the elevator. If one piece of grain is charged with 5.0×10^{-16} C while another holds 2.0×10^{-16} C of charge, what is the electrostatic force between them when they are separated by 0.050 m?

A-3: Rocco, an auto body painter, applies paint to automobiles by electrically charging the car's outer surface and oppositely charging the paint particles that he sprays onto the car. This causes the paint to adhere tightly to the car's surface. If two paint particles of equal charge experience a force of 4.0×10^{-8} N between them at a separation of 0.020 cm, what is the charge on each?

A-4: After unpacking a shipment of laboratory glasswear, Mrs. Payne dumps the box of Styrofoam packing chips into a recycling bin. The chips rub together and two chips 0.015 m apart repel each other with a force of 6.0×10^{-3} N. What is the charge on each of the chips?

A-5: Wiz the cat is batting at two Ping-Pong balls hanging from insulating threads with their sides just barely touching. Each ball acquires a positive charge of 3.5×10^{-9} C from Wiz's fur and they swing apart. a) If a force of 6.0×10^{-5} N acts on one of the balls, how far apart are they from each other? b) Is the force between them one of attraction or repulsion?

A-6: A droplet of ink in an ink-jet printer carrying a charge of 8.0×10^{-13} C is deflected onto the paper by a force of 3.2×10^{-4} N. How strong is the field that causes this force?

A-7: In the human body, nerve cells work by pumping sodium ions out of a cell in order to maintain a potential difference across the cell wall. If a sodium ion carries a charge of 1.60×10^{-19} C as it is pumped with an electrical force of 2.0×10^{-12} N, what is the electric field between the inside and outside of the nerve cell?

A-8: Each of two Van de Graaff generators, whose centers are separated from one another by 0.50 m, becomes charged after they are switched on. One Van de Graaff generator holds $+3.0 \times 10^{-2}$ C while the other holds -2.0×10^{-2} C. What is the magnitude and direction of the electric field halfway between them?

A-9: Willa the witch dusts her crystal ball with her silk scarf, causing the ball to become charged with 5.0×10^{-9} C. Willa then stares into the crystal ball and the wart on the end of her nose experiences an electric field strength of 2200 N/C. How far is the tip of her nose from the center of the crystal ball?

A-10: The Millikan oil drop experiment of 1909 allowed Robert A. Millikan to determine the charge of an electron. In the experiment, an oil drop is suspended between two charged plates by an electric force that equals the gravitational force acting on the 1.1×10^{-14}-kg drop. a) What is the charge on the drop if it remains stationary in an electric field of 1.72×10^5 N/C? b) How many extra electrons are there on this particular oil drop?

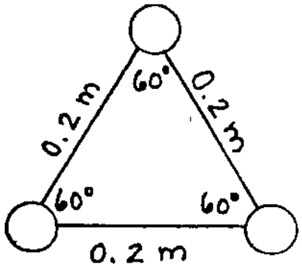
A-11: In eighteenth-century Europe, it was common practice to ring the church bells in an attempt to ward off lightning. However, during one 33-year period, nearly 400 church steeples were struck while the bells were being rung. If a bolt of lightning discharges 30.0 C of charge from a cloud to a steeple across a potential difference of 15 000 V, how much energy is lost by the cloud and gained by the steeple?

A-12: In Exercise A-7, how thick is the wall of the nerve cell if there is a potential difference of 0.089 between the inside and outside of the cell?

A-13: Ulrich stands next to the Van de Graaff generator and gets a shock as he holds his knuckle 0.2 m from the machine. In order for a spark to jump, the electric field strength must be 3×10^6 V/m. At this distance, what is the potential difference between Ulrich and the generator?

Challenge Exercises for Further Study

B-1: Three glass Christmas balls become electrically charged when Noel removes them from the packaging material in their box. Noel hangs the balls on the tree as shown. If each ornament has acquired a charge of 2.0×10^{-10} C, what is the magnitude and direction of the force experienced by the ball at the top?



B-2: In a TV picture tube, electrons are accelerated from rest up to very high speeds through a potential difference of 22 000 V. At what speed will an electron be moving just as it strikes the TV screen? (In reality you would have to consider the effects of relativity in order to solve this exercise properly; however, ignore such relativistic effects here.)

B-3: A lightning bolt discharges into New Hampshire's Lake Winnipesaukee after passing through a potential difference of 9.00×10^7 V. What is the minimum amount of charge the lightning bolt could be carrying, if it were to vaporize 1000. kg of water in the lake that was originally at a temperature of 20.0 °C?