Section 1

Static Electricity and Coulomb's Law: Opposites Attract



Learning Outcomes

In this section, you will

- **Produce** electrically charged objects.
- **Describe** the behavior of like charges, and the behavior of unlike charges.
- **Discover** the factors that determine the force between two charged objects.
- Calculate the electrical force using Coulomb's law.
- **Implement** the organizing principle of conservation of charge.
- **Recognize** the similarities and differences between Coulomb's law and Newton's law of gravitation.
- Explain how Coulomb was able to measure Coulomb's constant using a torsion balance.

What Do You Think?

Have you ever seen a tremendous lightning storm? Bolts of lightning ignite the sky as they streak toward and away from Earth. A tiny lightning storm also takes place when you get an electric shock. Think back to the last time you got a shock. Were you inside or outside? Was it winter or summer? What did you touch to get the shock?

• What do you think caused the shock?

Record your ideas about this question in your *Active Physics* log. Be prepared to discuss your responses with your small group and your class.

Investigate

The study of lightning, shocks, and static cling can reveal important physics. In this section, you will investigate what happens when two strips of matte-finish "invisible" tape are charged and brought near each other.

1. Cut two strips of invisible tape about 12 cm long. Fold over a 1-cm section on the end of each strip and press the sticky sides

together to form a tab. Place one strip (sticky side down) on a table and label the tab B, for "bottom." Place the other strip (sticky side down) touching the top of the first strip and label the tab T, for "top." Press the two strips together, rubbing your finger over the strips a few times to smooth out the creases. Hold down the tab of the bottom strip and with one hand, peel off the top strip by pulling up its tab. Then pull the bottom strip off the table by its tab with the other hand.



- 2. Hold both strips apart, allowing them to hang down. Slowly bring the hanging strips toward each other, but do not let them touch.
- **()** Record your observations.
- Solution (Section 2) (Secti
- **S**c) Was the force attractive or repulsive? Explain your answer.

- 3. Design an inquiry investigation between two pairs of tape strips similar to the strips you made in *Step 1*. Label the tapes T1, B1 and T2, B2 and set them up as you did in *Step 2*.
- (1) a) Record your observations of forces when different strips are brought near each other (for example, T1 and T2; T1 and B2).
- b) Is there any evidence so far that the distance between the two strips of tape plays a role in the amount of force exerted on each? Be sure to estimate some approximate distances in your response.
- 4. Continue your inquiry investigation. Recharge the original two strips of tape as in *Step 1*. Place them on the table edge so that they hang freely. Rub a sheet of styrene foam or plastic rod with fur or wool. Slowly move the foam toward the strips.
- **()** Describe what happens.
- (A) b) How does the amount of force exerted in this case compare to the forces observed in *Step 3*? (More, less, or the same? What is your evidence?)
- Sc) What other factor does this suggest as having an impact on the magnitude of the electrical force between two objects?



793



- 5. You have probably heard the phrase "opposites attract." Opposite charges attract and like charges repel.
- A) Using this law of electrostatics, explain the results of your inquiry investigation when pairs of strips (for example, T1 and B1) were placed near each other.

What did your investigation tell you about the relative charges on the different tapes?

- b) Using this law of electrostatics, explain the results of your inquiry investigation when the styrene foam or plastic rod was used.
- 6. Rubbing the foam transfers negative charges (electrons) from the wool to the foam, giving it an overall negative charge and leaving the wool with a shortage of electrons (a positive charge).
- **)** a) Where did the positives on the T tapes come from?
- b) How would that affect the charge on the B tapes? Explain how your observations confirm your idea.
- **S**c) Think of another test to determine that B tapes are negative. Try the test and record your observations.
- 7. Use the charged styrene foam or plastic rod to pick up a tiny piece of paper.
- ▲a) Compare the force of electrical attraction between the styrene foam and the piece of paper with the gravitational force of attraction between Earth and the paper.

8. Recharge the original two strips of tape as in *Step 1*. Place them back on the table edge. Bring your finger close to each tape.

∆a) Describe your observations.

▲ b) Like charges repel, and unlike charges attract. How would you explain the interaction between the charged pieces of tape and your finger? (Hint: The electrons in your finger are able to move about so that some are able to move closer to or further away from each charged tape.)

> Use a diagram to help you explain your observations. Remember, when some electrons leave an area it becomes more positively charged.

- 9. Investigate if it is possible to remove the charge from the charged styrene foam or plastic rod tube by touching it.
- ▲ a) If the charged object had an excess of negative charges, describe how they could have gone from the tube to your finger and then through your body to the ground. (You may have to move your hand around to different places while touching the object.)
- b) Adding or removing electrons to restore a charged object to neutral is called *grounding*. By taking the negative charges from the plastic rod, you grounded it. Describe what happens when a positively charged object is grounded.

Physics Talk

INVISIBLE EFFECTS

Static Charges and Forces

In this section, you noticed that a force was present between the pieces of tape. This force was invisible. You could not see the force directly, but you saw evidence of the force because it moved the tape. Believing in invisible things is tough. But since the force you noticed in the *Investigate* had (and consistently does have) visible and measurable effects, not believing in invisible things might be tougher.

In Benjamin Franklin's time, the kind of experiment you just performed with tape was cutting-edge physics research. People realized that because of the existence of both the force of attraction and the force of repulsion there were two kinds of charge. In the early days of this research, these charges were called vitreous electrical fluid and resinous electrical fluid because of the kinds of materials you had to rub to get these charges. For example, if you rubbed resin (hardened tree sap) with a cloth you got the resinous charge. Franklin was the first person to realize that these two kinds of charges were in fact merely opposites. This discovery made Franklin so famous that he became an ambassador for Pennsylvania to England before the American Revolution, and ambassador to France during the Revolution for the fledging colonies. (The Europeans knew him as a famous physicist.) Franklin showed that if you add the same amount of vitreous and resinous charges, you get zero charge. So, if you called one kind of charge positive, the other had to be negative. Franklin decided which kind of charge would be called negative and which would be positive.

The kinds of charges that Franklin named negative turned out later to be the particles that are now called **electrons**. Electrons were the first parts of an atom to be discovered, back in 1895, more than 100 years after Franklin's explanation. The electrons can be very mobile.

In the *Investigate*, the two strips of tape started out with equal amounts of positive and negative charges. When objects have equal amounts of charge, they are electrically neutral. As you pulled off the top tape, you left some of the electrons from the atoms in the top tape behind to reside on the bottom tape. The tape that lost the electrons, therefore, had a positive charge; the other piece of tape that gained the electrons became negatively charged.



Physics Words

electron: a negatively charged particle of specific charge and mass.

Active Physics



The top tape and the bottom tape attracted each other because positively and negatively charged objects attract (unlike charges attract). In other experiments you performed, you found that positively-charged objects repel positively charged objects and negatively-charged objects repel negatively charged objects (like charges repel). You also found that by touching a charged object with your finger you removed the excess charge from the object. This process of adding or removing excess electrons to achieve electrical neutrality is called **grounding**.

Physics Words

grounding: the process of adding or removing electrons to restore a charged object to neutral.

conservation of charge: the total charge of an isolated system before an event equals the total electric charge after the event. In all these cases, however, only a very little mass has been transferred. Electrons are parts of the atom, but account for only a very tiny part of the mass compared to the rest of the atom. Evidently, the positives (positive charges) that are left behind are very heavy compared to the electrons. You will learn more about the electrons, and about the positives, later in this chapter.

Conservation of Charge



When the top strip of tape is pulled from the bottom strip of tape, the top strip loses electrons, while the bottom strip gains electrons. This situation is a good example of one of the major organizing principles of physics—the **conservation of charge**. In any isolated system, the total amount of charge must remain constant. If a negative charge is removed from one object, that negative charge must go somewhere. For example, if 15 bits of negative charge are removed from the top strip of tape in the *Investigate*, then 15 bits of negative charge are transferred to the bottom strip. There are only a few quantities discovered that nature conserves—charge is one of them.

Perhaps without being aware of it, you used the concept of conservation of charge in your analysis of what you observed. A few simple problems illustrate this conservation law. When two identical metal spheres touch and then separate, they will end up with identical charges. If they did not end up with identical charges, there would be a way to distinguish the metal spheres. One sphere with a charge of –10 touches a neutral, identical sphere. After touching and separating, each sphere has a net charge of –5. The charge was transferred, but the total charge remained the same. Keep in mind that neutral matter already contains enormous amounts of positives and negatives (positive and negative charges), but in equal amounts. Thus, the excess and deficiency are relative to a baseline of starting out neutral.



The conservation of charge between identical metal spheres that touch and then separate can be summarized as follows:

- 1. The total charge of the two spheres before touching is equal to the total charge after touching.
- 2. The charges on the identical spheres must be identical after they touch.
- 3. In solving problems like this, find the total charge before contact. Distribute that total charge of the two spheres equally to both spheres after contact.

Coulomb's Law

You have seen that in physics, scientists often search for an equation that can provide a clearer, more precise description of what they observe. In your experiments, you found that the force between two charged objects could be attractive or repulsive, and the force decreased when the objects moved farther apart. You also found that larger amounts of charge exerted a greater force between the objects. In 1784, Charles Augustin de Coulomb experimentally determined and used precise measurements to show that the force of attraction between two charges is directly proportional to the product of the charges and inversely proportional to the square of the distance between them. This is called Coulomb's law.



Physics Words

Coulomb's law of electrical attraction or repulsion: the force of attraction between two charges is directly proportional to the product of the charges and inversely proportional to the square of the distance between them.



This law can be written using an equation:

$$F = k \frac{q_1 q_2}{d^2}$$

where F is the force in newtons (N),

- q_1 and q_2 are charges in coulombs (C),
- *d* is the distance between the centers of the charges in meters (m), and
- k is Coulomb's constant, always equal to 9×10^9 N \cdot m²/C².

In every problem you solve, k will be $9 \times 10^9 \text{N} \cdot \text{m}^2/\text{C}^2$. That is why it is called a constant. Note that the unit of charge was named a coulomb, in honor of Charles de Coulomb.

Sample Problem

Two small charged spheres are placed 0.2 m apart. The first sphere has a charge of $+3.0 \times 10^{-6}$ C and the second sphere has a charge of -4.0×10^{-6} C. Calculate the force between them.

Strategy: You can use the equation for electric forces to calculate the force between the spheres.

Given:

$$q_1 = +3.0 \times 10^{-6} \text{C}$$

 $q_2 = -4.0 \times 10^{-6} \text{C}$
 $d = 0.2 \text{ m}$

Solution:

$$F = k \frac{q_1 q_2}{d^2}$$

$$F = \frac{(9 \times 10^9 \,\text{N} \cdot \text{m}^2/\text{C}^2)(+3.0 \times 10^{-6} \,\text{C})(-4.0 \times 10^{-6} \,\text{C})}{(0.2 \,\text{m})^2} = -2.7 \,\text{N}$$

The negative sign indicates that the force is attractive.

One coulomb of charge is an enormous amount of charge. A lightning bolt may transfer a coulomb of charge. That is why, in solving problems that have to do with realistic charges, you must use numbers and units like 1×10^{-6} C. Many calculators allow calculations with exponents to be completed with ease.



How does a negatively charged rod pick up a neutral piece of paper? The rod is negatively charged. In the diagram to the right, there are more negatives than positives in the rod. The piece of paper is neutral. There are an equal number of positives and negatives. When the rod is brought close to the paper, the excess negatives on the rod repel



the negatives of the paper. The excess negatives of the rod are attracted to the positives in the paper and repelled by the negatives in the paper. Because the positives are closer, the force of attraction is larger. Coulomb's law informs you that the force gets weaker as the distance gets larger. With a stronger force of attraction on the positive charges and the weaker force of repulsion on the negative charges, the rod can pick up the paper.

Comparing Coulomb's Law and Newton's Law of Universal Gravitation

You found you could actually calculate the force of attraction or repulsion of charges by using Coulomb's law:

$$F = k \frac{q_1 q_2}{d^2}$$

Coulomb's law for electrostatic attraction and repulsion is very similar to **Newton's law of universal gravitation**. Newton's law gives the relationship among gravitational force, masses, and the distance between the masses. This relationship can be summarized by the following equation:

$$F = G \frac{m_1 m_2}{r^2}$$

Where F is the force in newtons (N),

 m_1 and m_2 are masses in kilograms (kg),

r is the distance between the centers of the masses in meters (m),

and G is the gravitational constant, always equal to $6.67 \times 10^{-11} \text{ N} \cdot \text{m}^2/\text{kg}^2$.

Look at the similarities:

- Both laws show forces that decrease in strength with the square of the distance between two objects.
- Both laws show forces that depend on the product of the masses or charges.

Physics Words

Newton's law of universal gravitation: the relationship among gravitational force, masses, and the distance between the masses.

799



• Both laws have constants that set the scale of their intrinsic strength.

Look at the differences:

- Electric forces are attractive and repulsive; gravitational forces are only attractive.
- Charges come in two varieties, + and -. Mass comes in one variety, +.
- The electric force constant k is quite large, while the gravitational force constant G is quite small.

If you look at the gravitational and electrical forces between two electrons, the gravitational force is much smaller. The force is so small that you don't need to take it into account when describing the electric forces between the charges.

The experimental techniques to find the value of k and G are quite similar. In Coulomb's experiment, two spheres were attached to the ends of a rod and the rod was suspended by a wire. These spheres were charged, and similarly charged spheres were brought near the ends of the rods. The repulsive force caused the wire to twist. The twist was a measure of the force, and Coulomb was able to verify his law.

The constant for the strength of the gravitational force was determined in an experiment by Henry Cavendish. Cavendish's setup was similar to Coulomb's, but the

Checking Up 1. If electrons are removed from a neutral object, what kind of charge will the object have? Explain.

- 2. What happens to the force of attraction between two charged objects as the distance between them increases? Explain using Coulomb's law.
- 3. When two charged objects are made to touch each other and then separated, what will be true about the net charge of the two objects after separation? Explain your answer.

attraction between the pairs of spheres was due to their gravitational attraction. This tiny force was measured by the twist in the wire. The symmetry of what appears to be two unrelated forces provides a glimpse into the beauty of the world. Physicists remark on this beauty, which drives them to find out if there are other underlying understandings of the two forces because of that symmetry. This is what physicists are exploring when you hear about their work on unified theories.



800

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Coulomb's Law

Coulomb's law describes the force between a pair of charged objects. You can also use Coulomb's law to find the force among a large number of charges.

Situation 1: Assume that you have three charged objects equally spaced along a line.



To find the net force on object B, you can immediately determine that the force will be toward A. This is because A attracts B (unlike charges attract) and B is repelled from C (like charges repel). Since both forces on B are to the left, B will accelerate toward the left.

You can find the value of the net force by calculating the forces using Coulomb's law and then adding.

Situation 2: Assume that you have three charged objects equally spaced along a line, as in Situation 1, but C has a positive charge.



To find the net force on object B, you can determine that the force will be toward C. A attracts B (unlike charges attract) and B is attracted to C (unlike charges attract).

The force of attraction to C is greater than the force of attraction to A because the charge on C is greater than the charge on A (and the distances are identical). You can find the value of the net force by calculating the forces using Coulomb's law and then adding the negative force (to the left) and the positive force (to the right).

Situation 3: Assume that you have three charged objects where C is twice as far from B as A is from B.



To find the net force on object B, you can immediately determine that the force will be toward A. A attracts B (unlike charges attract) and B is attracted to C (unlike charges attract). Because the force of attraction to A is greater (as it is closer), B will accelerate toward the left.

You can find the value of the net force by calculating the forces using Coulomb's law and then adding the negative force (to the left) and the positive force (to the right).

Situation 4: Assume that you have three charged objects where C is twice as far from B as A is from B.





For what charge of C would the net force on B be zero? Since C is twice as far from B, the charge would have to be four times as large to exert an equal force. That is because the force decreases by the square of the distance. Double the distance, and the force is $\binom{1}{2}^2$ or $\frac{1}{4}$ the strength; triple the distance, and the force is $\binom{1}{3}^2$ or $\frac{1}{9}$ the strength).

- 1. Find the direction of the net force on B in the following situations without any calculations.
 - a) Assume that you have three charged objects equally spaced along a line.



b) Assume that you have three charged objects equally spaced along a line.



c) Assume that you have three charged objects, where C is three times as far from B as A is from B.



d) Assume that you have three charged objects, where C is three times as far from B as A is from B.



The charges do not have to be limited to positions along a line. If the charges are located in fixed positions on a plane, you can also determine the force by adding the forces. However, in this case, the vector addition of forces is a bit more complex than addition of forces along a line.

Situation 5: Assume that you have three charged objects equally spaced as shown in the diagram.



The force on B can be determined to be down and to the left. Object A will attract B to the left. Object C will attract B to the bottom of the page. Both forces will be equal since the charges and distances will be equal. The vector sum of these forces can be determined by the vector addition in the diagram below.



You can find the value of the force by calculating each force using Coulomb's law and then adding the forces using the Pythagorean theorem $(a^2 + b^2 = c^2)$.

The problems can get more complex if the charges and distances are no longer equal.

2. Determine the force (both magnitude and direction) on object B for each of the following charges and distances. Assume that the configuration is that A is to the left of B, and C is below B as shown in Situation 5.

Case Number	Charge on A	Charge on B	Charge on C	Distance Between A and B	Distance Between B and C
1	$+5 imes 10^{-6} \text{C}$	$+5 \times 10^{-6}$ C	$+5 imes 10^{-6}$ C	2 m	2 m
2	$+5 \times 10^{-6}$ C	$+5 \times 10^{-6}$ C	$-5 imes 10^{-6}$ C	2 m	2 m
3	$+5 \times 10^{-6}$ C	$+5 \times 10^{-6}$ C	$-10 imes 10^{-6} C$	2 m	2 m
4	-5×10^{-6} C	-5×10^{-6} C	-5×10^{-6} C	2 m	2 m
5	$+5 \times 10^{-6}$ C	$+5 \times 10^{-6}$ C	-15×10^{-6} C	2 m	2 m

What Do You Think Now?

At the beginning of this section you were asked the following about getting a shock:

• What do you think caused the shock?

Now that you know about electrons, what happens when they are transferred from one object to another object? What is the law of conservation of charge? How is this law related to the transfer of charge between two objects?





What does it mean?

How does Coulomb's law increase your understanding of unlike charges attracting and like charges repelling?

How do you know?

What experiments have you made yourself that show "something" is going on in the world that Coulomb's law attempts to describe? What kinds of measurements did you perform that show both attraction and repulsion?

Why do you believe?

Connects with Other Physics Content	Fits with Big Ideas in Science	Meets Physics Requirements
★ Forces and motion	Models	Good, clear, explanation, no more complex than necessary

★ The electrical force between charged objects is invisible. You can't see the charged particles and you can't see the force. In physics, scientists adopt models that can explain what they observe within nature. They try to derive equations that can accurately explain what they observe and can predict what they will observe in different situations. Forces and motion is one of physics' big ideas. Finding similarities (symmetries) between forces is one of the challenges of modern physics. Compare and contrast the electrostatic force with the gravitational force. A comparison between Coulomb's law for electrostatics and Newton's law of gravitational attraction would be helpful.

Why should you care?

You have seen that charged objects can attract or repel one another. These attractive and repulsive forces will help you create a model for how the atom is constructed and held together. Since your museum exhibit must include distinct features of the atom, you may decide to include something you learned about charges and forces from this section. Describe the aspects of electrical forces you might include in your exhibit and how you will make it engaging.

Reflecting on the Section and the Challenge

You are starting to provide evidence that atoms are composed of electrons and other particles. These particles have electric charge. You will need to provide a description of the interaction between the charges when you provide a description of the atom for your museum display. You may find a way to include in your exhibit the larger concepts of conservation of charge or the ability to actually calculate these forces of attraction and repulsion.

Physics to Go

- 1. Electrons are transferred from a rod to a piece of cloth.
 - a) Which object will become negatively charged?
 - b) Which object will become positively charged?
- 2. A rubber rod is negatively charged after being rubbed by wool. Explain how this happens.
- 3. Two identical spheres are mounted on insulated stands. The first sphere has a charge of -1. The second sphere has a charge of -3. After the spheres touch, what will the charge on each be?
- 4. One of two identical metal spheres has a charge of +1 and the other sphere has a charge of -5. Compare the total charge on the spheres before and after contact.
- 5. Charge A is $+2.0 \times 10^{-6}$ C and charge B is $+3 \times 10^{-6}$ C. The charges are 3 m apart. What is the force between them? Is it attractive or repulsive?
- 6. Charge A is -4.0×10^{-6} C and charge B is $+2 \times 10^{-6}$ C. The charges are 5 m apart. What is the force between them? Is it attractive or repulsive?
- 7. When the air is dry and you walk on a wool carpet with your shoes, you may experience a shock when you touch a doorknob. Explain what is happening in terms of electric charge. (Hint: Your shoes are similar to the rubber rod.)
- 8. Compare and contrast Coulomb's law and Newton's law of gravitational attraction. Provide at least one similarity and one difference.
- 9. Coulomb's law states that the electric force between two charged objects decreases with the square of the distance. Suppose the original force between two objects is 60 N, and the distance between them is tripled, the new force would be $\left(\frac{1}{3}\right)^2$, or nine times weaker. This new force would be 60 N $\times \frac{1}{9} = 6.7$ N

or 7 N. Find the new forces if the original distance was

- a) doubled.
- b) quadrupled.
- c) halved.

d) quartered.

10. Sketch a graph that shows how the electrostatic force defined by Coulomb's law varies with the distance.



- 11. A single electron has a charge of 1.6×10^{-19} C.
 - a) Show why it takes 6.25×10^{18} electrons to equal 1 C.
 - b) If you studied currents in *Electricity for Everyone*, solve this problem: Calculate how many electrons go by when 5 A of current exists for one minute.
- 12. Compare the gravitational force between two electrons to the electric force between them. Which force is stronger, and by how much? The mass of an electron is 9.1×10^{-31} kg.
- 13. How could you depict the invisible electrostatic force in a museum exhibit?

For Questions 14 to 19 choose the best answer from those given.

- 14. If the distance between two charged objects is halved, the force between them will
 - a) double.
 - b) be half as much.
 - c) quadruple.
 - d) stay the same.
- **15.** Two charged identical spheres attract each other. If the charge on one is doubled, the force between them will
 - a) double.
 - b) be half as much.
 - c) quadruple.
 - d) stay the same.
- 16. The force between two charged objects A and B is determined to be 47 N. Which of the following options is possible?
 - I. The charge on A is positive and B is positive.
 - II. The charge on A is negative and B is negative.
 - III. The charge on A is positive and B is negative.
 - IV. The charge on A is negative and B is positive.
 - a) III and IV
 - b) I and II
 - c) III only
 - d) II only

- 17. As two charged objects are brought closer together, the magnitude of the force between them will
 - a) increase.
 - b) decrease.
 - c) stay the same.
 - d) not enough information
- 18. To make a neutral object positively charged you should
 - a) add positives.
 - b) take away positives.
 - c) add negatives.
 - d) take away negatives.
- 19. An unknown object attracts both a "T" tape and a "B" tape. What kind of charge does the object have?
 - a) positive
 - b) negative
 - c) neutral
 - d) not enough information

20. Preparing for the Chapter Challenge

The Museum Director needs an update on your progress. Write a paragraph in your *Active Physics* log reassuring him/her that you are making progress. For example, the Director might walk in and ask, among other questions, "Are forces going to be a part of your exhibit? How could you depict the invisible electrostatic force in a museum exhibit?" What would be your answer?

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/ YES?	n Antt
I BRING A MESSAGE	p://xkc
FROM THE FUTURE!	d.co
I DON'T HAVE MUCH TIME. WHAT IS IT?	∛
THE CONVENTION YOU'RE SETTING FOR ELECTRIC CHARGE IS BACKWARD. THE ONE LEFT ON GLASS BY SILK SHOULD BE THE NEGATIVE CHARGE.	

WE WERE GOINS TO USE THE TIME MACHINE TO PREVENT THE ROBOT APOCALYPSE, BUT THE GUY WHO BUILT IT WAS AN ELECTRICAL ENGINEER.