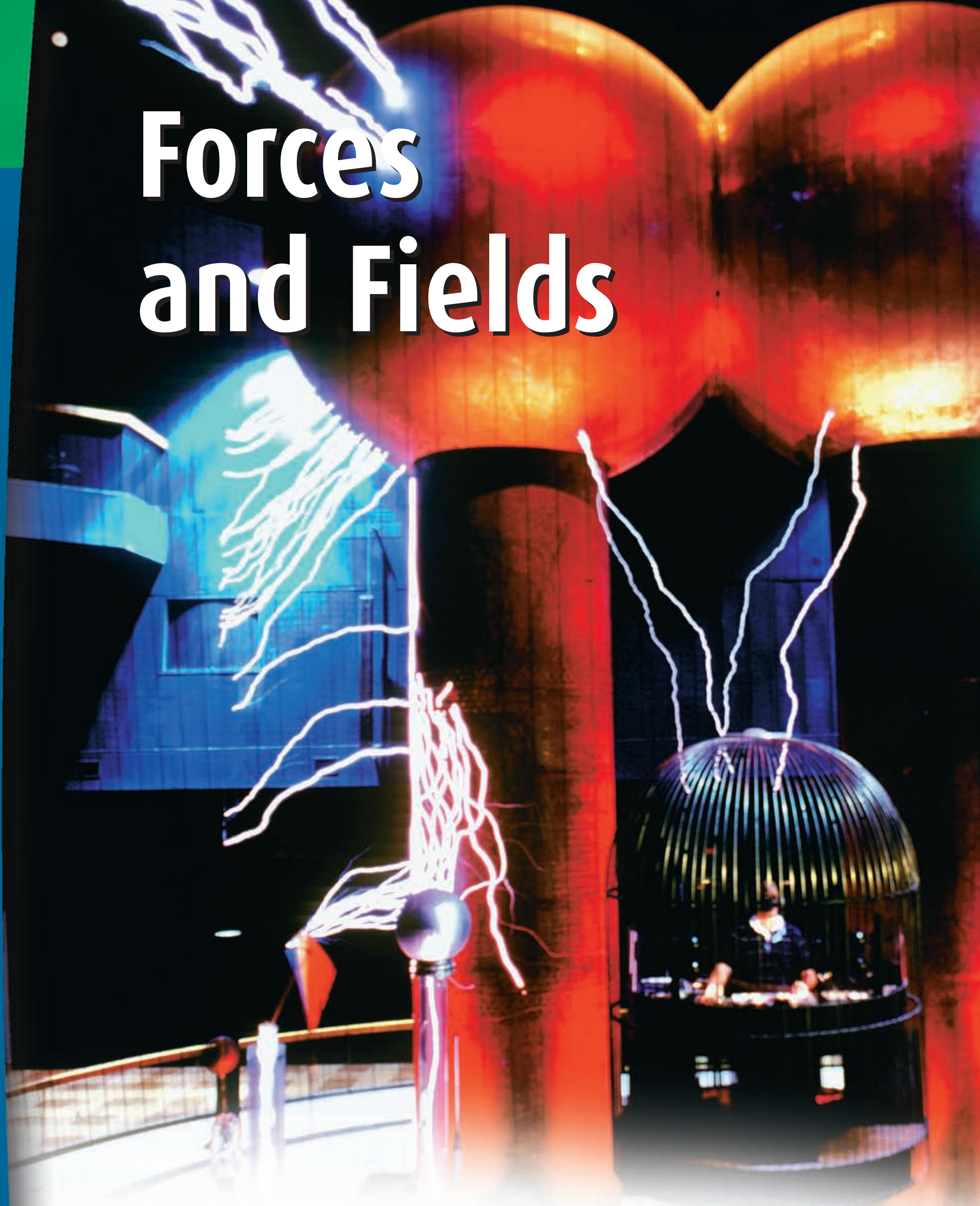
UNIT

VI

Forces and Fields



On huge metal domes, giant electrostatic charge generators can create voltages of 5 000 000 V, compared with 110 V in most of your household circuits. How are electrostatic charges produced? What is voltage? What happens when electric charges interact?

e WEB

The person in this photo is standing inside a Faraday cage. To find out how the Faraday cage protects her from the huge electrical discharges, follow the links at www.pearsoned.ca/school/physicssource.

Unit at a Glance

CHAPTER 10 Physics laws can explain the behaviour of electric charges.

10.1 Electrical Interactions

10.2 Coulomb's Law

CHAPTER 11 Electric field theory describes electrical phenomena.

11.1 Forces and Fields

11.2 Electric Field Lines and Electric Potential

11.3 Electrical Interactions and the Law of Conservation of Energy

CHAPTER 12 Properties of electric and magnetic fields apply in nature and technology.

12.1 Magnetic Forces and Fields

12.2 Moving Charges and Magnetic Fields

12.3 Current-carrying Conductors and Magnetic Fields

12.4 Magnetic Fields, Moving Charges, and New and Old Technologies

Unit Themes and Emphases

- Energy and Matter
- Nature of Science
- Scientific Inquiry

Focussing Questions

While studying this unit, you will investigate how the science of electricity, magnetism, and electromagnetism evolved and its corresponding effect on technology. As you work through this unit, consider these questions.

- How is the value of the elementary charge determined?
- What is the relationship between electricity and magnetism?
- How does magnetism assist in the understanding of fundamental particles?

Unit Project

Building a Model of a Direct Current Generator

- By the time you complete this unit, you will have the knowledge and skills to build a model of a direct current generator. For this task, you will research wind power and design and build a model of an electric generator that uses wind energy.

CHAPTER

10

Physics laws can explain the behaviour of electric charges.

▲ **Figure 10.1** A thunderbird on a totem pole in Vancouver

Key Concepts

In this chapter, you will learn about:

- electric charge
- conservation of charge
- Coulomb's law

Learning Outcomes

When you have completed this chapter, you will be able to:

Knowledge

- explain electrical interactions using the law of conservation of charge
- explain electrical interactions in terms of the repulsion and attraction of charges
- compare conduction and induction
- explain the distribution of charge on the surfaces of conductors and insulators
- use Coulomb's law to calculate the electric force on a point charge due to a second point charge
- explain the principles of Coulomb's torsion balance experiment
- determine the magnitude and direction of the electric force on a point charge due to one or more stationary point charges in a plane
- compare, qualitatively and quantitatively, the inverse square relationship as it is expressed by Coulomb's law and by Newton's universal law of gravitation

Science, Technology, and Society

- explain that concepts, models, and theories are often used in predicting, interpreting, and explaining observations
- explain that scientific knowledge may lead to new technologies and new technologies may lead to scientific discoveries

A bolt of lightning flashing across dark cloudy skies, followed a few moments later by the deafening sound of thunder, is still one of the most awe-inspiring physical events unleashed by nature. What is the cause of lightning? Why is it so dangerous?

So powerful is this display that many early civilizations reasoned these events must be the actions of gods. To the Romans, lightning was the sign that Jove, the king of the gods, was angry at his enemies. In some First Nations traditions, lightning flashed from the eyes of the enormous thunderbird, while thunder boomed from the flapping of its huge wings (Figure 10.1).

In this chapter, you will learn how relating lightning to simpler phenomena, such as the sparking observed as you stroke a cat, initially revealed the electrical nature of matter. Further studies of the nature of electric charges and the electrical interactions between them will enable you to understand laws that describe their behaviour. Finally, you will investigate the force acting on electric charges by studying the variables that determine this force and the law that describes how to calculate such forces.

10-1 QuickLab

Charging Objects Using a Van de Graaff Generator

Problem

What can demonstrations on the Van de Graaff generator reveal about the behaviour and interactions of electric charges?

Materials and Equipment

Van de Graaff generator and grounding rod
small piece of animal fur (approximately 15 cm x 15 cm)
5 aluminium pie plates
small foam-plastic cup with confetti
soap bubble dispenser and soap

CAUTION! Follow your teacher's instructions to avoid getting an electric shock.

Procedure

1. Copy Table 10.1 into your notebook. Make the table the full width of your page so you have room to write in your observations and explanations.

Table 10.1 Observations and Explanations from Using a Van de Graaff Generator

Demonstration	Observation	Explanation
Animal Fur		
Aluminium Pie Plates		
Foam-plastic Cup and Confetti		
Stream of Soap Bubbles		

2. Watch or perform each of the demonstrations in steps 3 to 9.
3. Place a piece of animal fur, with the fur side up, on the top of the charging sphere of the Van de Graaff generator.
4. Turn on the generator and let it run.
5. Record your observations in Table 10.1, making sure that your description is precise.
6. Ground the sphere with the grounding rod, and turn off the generator.
7. Repeat steps 3 to 6, replacing the animal fur with the aluminium pie plates (stacked upside down), and then the foam-plastic cup with confetti.
8. Turn on the Van de Graaff generator and let it run.
9. Dip the soap bubble dispenser into the soap and blow a stream of bubbles toward the charging sphere of the Van de Graaff generator.
10. Record your detailed observations in Table 10.1.
11. Ground the sphere with the grounding rod, and turn off the generator.

Question

1. Using your knowledge of electricity, provide a possible explanation of the events that occurred during each demonstration.

Think About It

1. How does the sphere of the Van de Graaff generator become charged?
2. Describe a situation during the demonstrations where the forces of interaction between the sphere of the generator and the various objects were:
   (a) attractive
   (b) repulsive
3. Why does touching the sphere with a grounding rod affect the charge on the sphere?

Discuss your answers in a small group and record them for later reference. As you complete each section of this chapter, review your answers to these questions. Note any changes to your ideas.

10.1 Electrical Interactions

info BIT
The plastic in contact lenses contains etafilcon, which is a molecule that attracts molecules in human tears. This electrostatic attraction holds a contact lens on the eye.

Your world runs on electricity. The music you listen to, the movies you watch, the video games you play—all require electricity to run. Today, electricity is so familiar that you probably don't even think about it when you turn on a light, pop a piece of bread into the toaster, or switch off the TV.

Try to imagine a time before electricity was even named. People had noticed interesting effects in certain situations that seemed almost magical. The Greek philosopher Thales (624–546 BCE) recorded that when he rubbed amber (a hard fossilized form of tree resin), it could attract small pieces of straw or thread. This effect was called "electricity," after the Greek word for amber, "elektron."

The ancient Greeks observed two important properties of electricity:

- Charged objects could either attract or repel each other. These two types of interactions suggested that there must be two different types of charge.
- Repulsion occurred when two similarly charged objects were placed near each other, and attraction occurred when two oppositely charged objects were placed near each other.

These observations can be summarized as the law of charges:

Like charges repel and unlike charges attract.

MINDS ON **Electrical Attraction**

Rub an ebonite rod with fur and hold the rod close to a fine stream of water from a faucet. Then rub a glass rod with silk and hold this rod close to a fine stream of water.

Observe what happens in each case. Using your knowledge of charging objects, explain why the ebonite rod or the glass rod affects the water.

info BIT
Gilbert was also a medical doctor and held the prestigious position of personal physician of Queen Elizabeth I of England.

There was little progress in understanding the nature of electricity until the 1600s, when the English scientist William Gilbert (1544–1603) performed extensive investigations. In *De Magnete,* his book on magnetism, Gilbert compared the effects of electricity and magnetism. He concluded that:

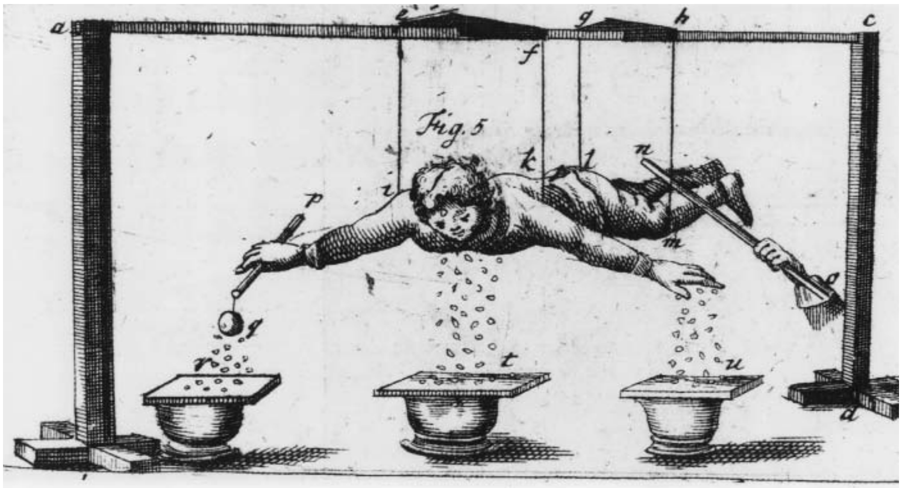
1. Objects only exhibit electrical effects when recently rubbed; magnetic objects do not need to be rubbed.
2. Electrified objects can attract small pieces of many types of objects; magnetic objects can attract only a few types of objects.
3. Electrified objects attract objects toward one central region; magnetic objects appear to have two poles.

Although Gilbert was able to describe certain effects of electricity, he still did not know the origins of electric charges.

In the 1700s, the American scientist and inventor Benjamin Franklin (1706–1790) attempted to prove that lightning in the sky was the same electricity as the spark observed when you reach for a metal door handle after shuffling across a carpet. He performed his famous kite experiment to explore whether lightning was a form of electricity (Figure 10.2). Luckily, he did not get killed, and he succeeded in drawing electricity from the clouds. He observed that lightning behaves the same way that electricity produced in the laboratory does. Through further investigations, he identified and named the two different types of electric charges as positive and negative charges.

It soon became apparent that electricity is in all substances. This idea caught the imagination of many different people. Scientists studied electricity's intriguing effects (Figure 10.3), and entrepreneurs exploited it. Magicians and carnivals featured the "mysterious" effects of electricity.

▲ **Figure 10.2** This figure is an artist's representation of Benjamin Franklin's famous kite experiment.



▲ **Figure 10.3** Boys were sometimes used in experiments such as this one in the early 1700s. The boy was suspended over the floor and electrostatically charged. His positive electric charge would attract pieces of paper.

info **BIT**

Some historians think that Franklin may not have actually performed his kite experiment. They suspect that Franklin sent a description of this dangerous experiment to the Royal Society in London, England as a joke, because this British academy had largely ignored his earlier work. In 1753, the Royal Society awarded Franklin the prestigious Copley Medal for his electrical research.

Studies to determine the nature of electricity continued. These studies were the beginning of the science of **electrostatics**, which is the study of electric charges at rest. It involves electric charges, the forces acting on them, and their behaviour in substances.

electrostatics: the study of electric charges at rest

The Modern Theory of Electrostatics

Today's theory of electrostatics and the nature of electric charges is based on the models of the atom that Ernest Rutherford (1871–1937) and Niels Bohr (1885–1962) proposed in the early 1900s. In their theories, an atom is composed of two types of charges: positively charged protons in a nucleus surrounded by negatively charged electrons. In nature, atoms have equal numbers of electrons and protons so that each atom is electrically neutral.

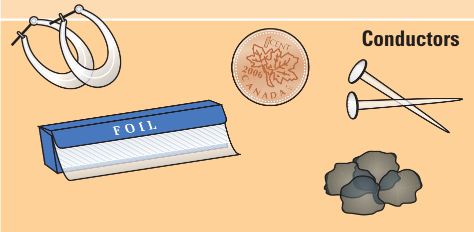
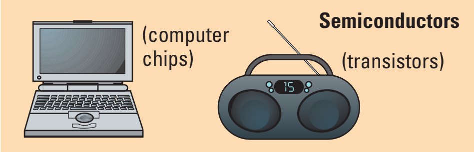
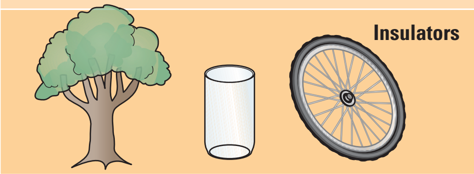
Just as some materials are good thermal conductors or insulators, there are also good conductors and insulators of electric charges. Electrical conductivity depends on how tightly the electrons are bound to the nucleus of the atom. Some materials have electrons that are tightly bound to the nucleus and are not free to travel within the substance. These materials are called **insulators**. Materials that have electrons in the outermost regions of the atom that are free to travel are called **conductors**.

insulator: material in which the electrons are tightly bound to the nucleus and are not free to move within the substance

conductor: material in which electrons in the outermost regions of the atom are free to move

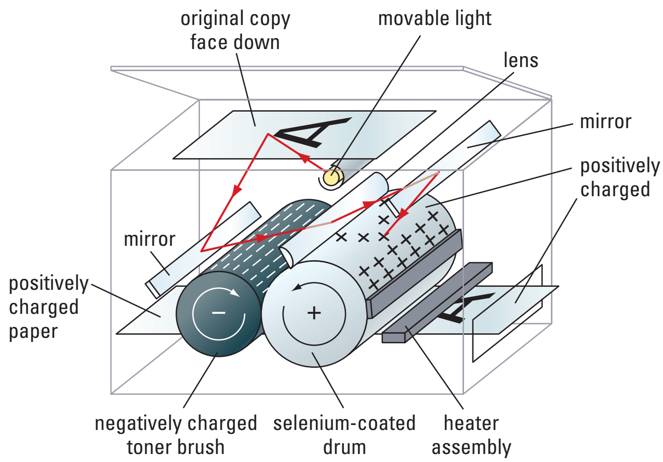
Figure 10.4 shows some examples of good conductors and insulators. Note that metals are usually good conductors. It is also interesting to note that a good conductor, such as silver, can have a conductivity 10^{23} times greater than that of a good insulator, such as rubber.

▶ **Figure 10.4** Relative electrical conductivity of some materials

Relative magnitude of conductivity	Material	
10^{8}, 10^{7}	silver, copper, aluminium, iron, mercury, carbon	 Conductors
10^{3}	germanium, silicon	 Semiconductors (computer chips) (transistors)
10^{-9}, 10^{-10}, 10^{-12}, 10^{-15}	wood, glass, rubber	 Insulators

Semiconductors

Materials that lie in the middle, between good conductors and good insulators, are called **semiconductors**. Because of their nature, they are good conductors in certain situations, and good insulators in other situations. Selenium, for example, is an insulator in the dark, but in the presence of light, it becomes a good conductor. Because of this property, selenium is very useful in the operation of photocopiers (Figure 10.5).



▲ **Figure 10.5** Photocopiers use the semiconductor selenium in the copying process.

The selenium-coated drum in the photocopier is initially given a positive charge and kept in the dark to retain the charge. When a flash of light shines on a document to be copied, an image of the document is transferred to the drum. Where the document is light-coloured, the selenium is illuminated, causing it to be conductive. Electrons flow into the conductive portions of the selenium coating, leaving them uncharged. The page remains light-coloured or white. Where the document is dark-coloured, the selenium remains non-conductive, and the positive charge remains. Negatively charged "toner" powder is sprinkled on the drum and attaches to the positively charged portions of the drum. When a sheet of paper is passed over the drum, the toner transfers to the paper and an image of the document is created. This toner image is then fused on the paper with heat, and the copying process is complete.

Silicon and germanium are also semiconductors. They become conductors when atoms such as gallium or arsenic are added to them. This process is called "doping" with impurities. The field of solid-state electronics, which includes components such as transistors, diodes, and silicon chips, is based on this type of semiconductor.

Superconductors

Recall from earlier science studies that resistance is a measure of how difficult it is for electrons to flow through a material. Materials with a low electrical resistance are better conductors because very little energy is lost to heat in the conduction of electricity.

Early attempts at conducting electricity efficiently used conducting materials with low electrical resistance, such as silver, copper, and gold. Researchers soon discovered that the electrical resistance of any material tends to decrease as its temperature decreases. Could the temperature of a material be lowered to the point that it loses all its resistive nature, creating the ideal conductor? This property of materials would have an enormous range of applications. Once a current is established in such a conductor, it should persist indefinitely with no energy loss.

In the early 20th century, a class of materials called **superconductors** was developed. These conductors have no measurable resistance at very low temperatures. The Dutch physicist Heike Kammerlingh Onnes (1853–1926) discovered this effect in 1911 when he observed that solid mercury lost its electrical resistance when cooled to a temperature of −269 °C. Although this discovery was significant, the usefulness of superconductors was limited because of the extremely low temperatures necessary for their operation.

It was not until 1986 that materials were developed that were superconductors at much higher temperatures. These materials are ceramic alloys of rare earth elements, such as lanthanum and yttrium. As an example, one such alloy was made by grinding yttrium, barium, and copper oxide into a mixture and heating the mixture to form the alloy $YBa_2Cu_3O_7$. This substance became a superconductor at −216 °C. In 1987, another alloy was developed that displayed superconductivity at −175 °C. More recent discoveries have reported copper oxide alloys that are superconductors at temperatures as high as −123 °C. The ultimate goal is to develop superconductors that operate at room temperature, thus creating a whole new era of useful applications in technology.

e **WEB**

Find out what research is being done on superconductors today. How soon will you be seeing superconductors in use around the house? Write a brief summary of what you discover. To learn more about superconductors, follow the links at www.pearsoned.ca/school/physicssource.

10-2 Inquiry Lab

Charging Objects

Required Skills
- Initiating and Planning
- Performing and Recording
- Analyzing and Interpreting
- Communication and Teamwork

Question

How can objects become electrically charged?

Materials and Equipment

2 white plastic polyethylene strips (or ebonite rods)
fur (approximately 15 cm x 15 cm)
2 clear plastic acetate strips (or glass rods)
silk (approximately 15 cm x 15 cm)
electroscope
silk thread
2 retort stands with clamps

Procedure

Part A: Charging by Friction

1. Copy Table 10.2 into your notebook.

Table 10.2 Observations for Charging by Friction

	White Polyethylene Strip Rubbed with Fur	Clear Acetate Strip Rubbed with Silk
Hanging White Polyethylene Strip		
Hanging Clear Acetate Strip		

2. Hang a white polyethylene strip from one retort stand and a clear acetate strip from another retort stand.
3. While holding the hanging white polyethylene strip in the middle, rub both ends of it with the fur. While holding the hanging clear acetate strip in the middle, rub both ends of it with the silk.
4. Rub the other white polyethylene strip with the fur.
5. Carefully bring this second polyethylene strip close to one end of the hanging white polyethylene strip. Do not allow the two plastic strips to touch each other.
6. Carefully bring the second polyethylene strip close to one end of the hanging clear acetate strip. Do not allow the two plastic strips to touch each other.
7. Observe what happens in each situation and record your observations in Table 10.2.
8. Rub a clear acetate strip with the silk.
9. Carefully bring this strip close to the hanging clear acetate strip. Do not allow the two plastic strips to touch each other. Observe what happens and record your observations in Table 10.2.
10. Carefully bring this clear acetate strip close to one end of the hanging white polyethylene strip. Do not allow the two plastic strips to touch each other. Observe what happens and record your observations in Table 10.2.

Part B: Charging by Conduction

11. Copy Table 10.3 into your notebook.

Table 10.3 Observations for Charging by Conduction

	Electroscope Charged with the White Polyethylene Strip Rubbed with Fur	Electroscope Charged with the Clear Acetate Strip Rubbed with Silk
Hanging White Polyethylene Strip		
Hanging Clear Acetate Strip		

12. Rub the unattached white polyethylene strip with the fur. Touch this white strip to the knob of the electroscope.
13. Carefully bring the electroscope close to one end of the hanging white polyethylene strip. Observe what happens to the leaves in the electroscope. Record your observations in Table 10.3.
14. Now bring the electroscope near one end of the hanging clear acetate strip. Observe what happens to the leaves in the electroscope. Record your observations in Table 10.3.
15. Ground the electroscope by touching the knob of the electroscope with your finger.
16. Rub a clear acetate strip with the silk and touch the strip to the knob of the grounded electroscope.
17. Repeat steps 13 and 14.

Part C: Charging by Induction

18 Copy Table 10.4 into your notebook.

▼ **Table 10.4** Observations for Charging by Induction

	Grounded Electroscope
Hanging White Polyethylene Strip	
Hanging Clear Acetate Strip	

19 Bring an uncharged electroscope near one end of the hanging white polyethylene strip. Observe what happens to the leaves of the electroscope, and record your observations in Table 10.4.

20 Bring an uncharged electroscope near one end of the hanging clear acetate strip. Observe what happens to the leaves of the electroscope, and record your observations in Table 10.4.

Analysis

1. What effect did you observe when two similarly charged white polyethylene strips were held near each other or when two similarly charged clear acetate strips were held near each other?
2. What effect did you observe when a charged white polyethylene strip was held near an oppositely charged hanging clear acetate strip or when a charged clear acetate strip was held near an oppositely charged hanging white polyethylene strip?
3. Based on your observations, what charge did the electroscope acquire when it was touched by the charged white polyethylene strip? when it was touched by the charged acetate strip?
4. What evidence shows a movement of charge in the electroscope when it is held near a charged object?
5. From your observations in Table 10.2, what general rule can you formulate about attraction and repulsion of charged objects?
6. From your observations in Table 10.3, what general rule can you formulate about the charge received by an object when it is touched by another charged object?
7. From your observations in Table 10.4, what general rule can you formulate about the charge received by an object when it is held near another charged object?
8. Does the electroscope acquire a net electrical charge during the process of charging by induction? Justify your answer.
9. What evidence is there from this investigation to prove that there are two types of electrical charges?
10. From the investigation, is there any evidence to prove which type of charge was developed on the white polyethylene strip and on the clear acetate strip?

*e*LAB

For a probeware activity, go to www.pearsoned.ca/school/physicssource.

Methods of Charging Objects

According to the modern theory of electrostatics, objects can become charged through a transfer of electrons. Electron transfer can occur in three ways: by friction, by conduction, and by induction.

Law of Conservation of Charge

During any charging procedure, it is important to keep in mind that new charges are not being created. The charges existing in materials are merely being rearranged between the materials, as the **law of conservation of charge** states:

The net charge of an isolated system is conserved.

Net charge is the sum of all electric charge in the system. For example, if a system contains +3 C of charge and −5 C of charge, the system's net

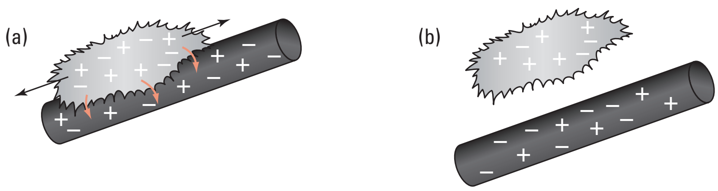
coulomb (C): SI unit for charge, equivalent to the charge on 6.25×10^{18} electrons or protons charge is −2 C. Suppose you have a system that initially consists of two electrically neutral objects, and there is a transfer of electrons from one object to the other. One object will lose electrons and become positively charged while the other object will gain these electrons and become equally negatively charged. However, the net charge of the system is still zero. Charges have not been created, they have only been rearranged.

Charging Objects by Friction

The most common method of charging objects is by rubbing or friction. You have probably had the unpleasant experience of receiving a shock when you touched a door handle after walking across a carpeted floor. Similarly, gently stroking a cat can result in the generation of small sparks, which are very uncomfortable for the cat.

Charging by this method involves separating electrons from the atoms in one object through rubbing or friction, and then transferring and depositing these electrons to the atoms of another object. The object whose atoms lose electrons then possesses positively charged ions. The object whose atoms gain electrons possesses negatively charged ions.

As shown in Figure 10.6, rubbing the ebonite rod with fur transferred some of the electrons in the fur to the rod. The fur becomes positively charged, and the rod becomes negatively charged.



▲ **Figure 10.6** (a) A neutral ebonite rod and a neutral piece of fur have equal amounts of negative and positive charge. When the fur is rubbed against the rod, a transfer of electrons occurs. (b) After rubbing, the ebonite has gained electrons and has a net negative charge. The fur has lost electrons and has a net positive charge.

▲ **Figure 10.7** The electrostatic or triboelectric series

Whether an object gains or loses electrons when rubbed by another object depends on how tightly the material holds onto its electrons. Figure 10.7 shows the electrostatic series, in which substances are listed according to how tightly they hold their electrons. Substances at the top have a strong hold on their electrons and do not lose electrons easily. Substances near the bottom have a weak hold on their electrons and lose them easily.

Concept Check

1. Using information from Figure 10.7, explain why ebonite acquires a greater charge when rubbed with fur rather than silk.
2. What type of charge does ebonite acquire when rubbed with fur?

Charging objects by friction can also occur during collisions. The collisions of water vapour molecules in rain clouds, for example, cause the separation and transfer of electrons. The result is that vapour molecules become positively or negatively charged, eventually resulting in lightning. You will learn more about lightning later in this chapter. This process of charging objects was also observed by the *Voyageur* spacecraft on its mission to Saturn. Colliding particles in the rings of Saturn create electrical discharges within the rings, similar to lightning on Earth.

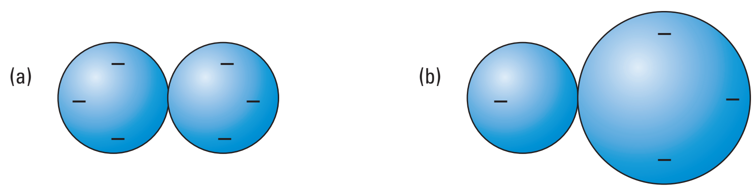
Charging Objects by Conduction

Objects can become charged by the transfer of electrons from a charged object to an uncharged object by simply touching the objects together (Figure 10.8). This process is called charging by **conduction**.

conduction: process of charging an object through the direct transfer of electrons when a charged object touches a neutral object

▲ **Figure 10.8** (a) During charging by conduction, electrons from a negatively charged metal conducting sphere transfer to a neutral metal conducting sphere, upon contact. (b) The neutral sphere gains electrons and is said to have been charged by conduction.

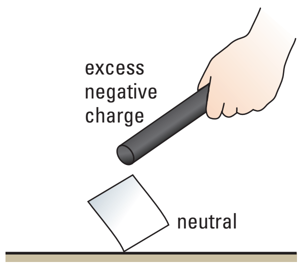
The quantity of charge that transfers from one object to another depends on the size and shape of the two objects. If both objects are roughly the same size and shape, the charge transferred will be such that both objects are approximately equally charged (Figure 10.9(a)). If one sphere is larger than the other, then the larger sphere will receive more of the charge (Figure 10.9(b)). When the spheres are separated, the excess charges move to become equidistant from each other because of the forces of repulsion between like charges. Charging by conduction is similar to charging by friction because there is contact between two objects and some electrons transfer from one object to the other.



▲ **Figure 10.9** Electrostatic repulsion of like charges forces excess charges within objects to redistribute so that the distances between charges are equal. (a) If two objects are the same size, the charges redistribute equally. (b) If the two objects are different sizes, the object with a larger surface area has more charges.

Once the charge has transferred to another object, it will either be distributed over the surface of the object, if the object is a conductor, or remain on the surface at the point of contact, if the object is an insulator.

Charging Objects by Induction



▲ **Figure 10.10** A piece of paper appears to be attracted to a charged ebonite rod, even before they touch.

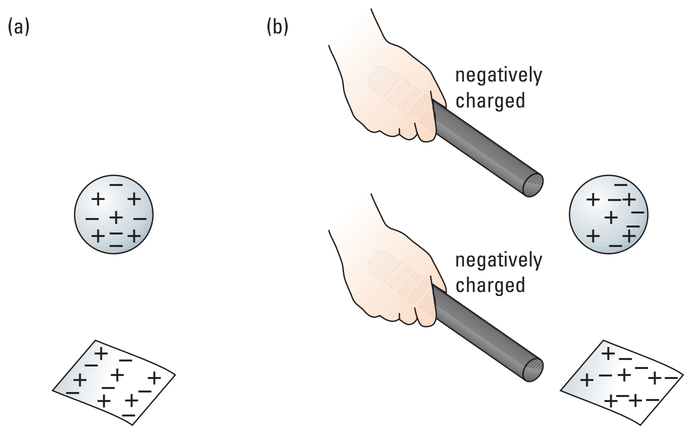
If you bring a negatively charged ebonite rod slowly toward a small piece of uncharged paper, the rod will attract the piece of paper, as shown in Figure 10.10. In fact, the piece of paper would begin to jiggle and move toward the rod even before the rod touches it. This reaction is a result of the forces acting on electrostatic charges. You know that electrostatic attraction can occur only between oppositely charged objects, but how can a charged object attract a neutral or uncharged object? And why is there never a force of repulsion between a charged object and a neutral object?

The answers to these questions are revealed in the third method of charging objects, which involves two processes: induction and charging by induction.

Induction

induction: movement of charge caused by an external charged object

Induction is a process in which charges in a neutral object shift or migrate because of the presence of an external charged object. This temporary charge separation polarizes the neutral object. One side of the object becomes positively charged and the other side is equally negatively charged. Although the object now behaves as if it is charged, it is still electrically neutral. The charging object and the neutral object do not touch each other, so there is no actual transfer of charge.



▲ **Figure 10.11** (a) A neutral metal sphere and a neutral piece of paper (b) The influence of the large negative charge of a rod causes *charge migration* within the conducting sphere, which polarizes the sphere. The influence of the rod causes *charge shift* within the atoms of the insulating paper. The atoms in the paper become polarized. Because of induction, the sides of the sphere and the atoms in the paper that are positively charged are closer to the negatively charged rod than their negatively charged sides are. The net result is attraction.

The process of induction varies slightly, depending on whether the charging object is approaching a substance that is an insulator or a conductor. Figure 10.11(a) depicts a neutral metal sphere (conductor) and a neutral piece of paper (insulator). Figure 10.11(b) shows a negatively charged rod approaching each neutral object. The electrons in the two neutral objects are repelled by the negative charge of an ebonite rod.

charge migration: movement of electrons in a neutral object where one side of the object becomes positive and the other side becomes negative

The metal sphere is a conductor, so the electrons can move easily through it to its other side. This process of **charge migration** causes the sphere to become polarized, where one side of the sphere is positive and the other side is negative.

Since the paper is an insulator, its electrons cannot move easily through it, so they just shift slightly relative to the nuclei. This process of **charge shift** causes the atoms to become polarized, where one side of an atom becomes positive and the other side becomes negative.

charge shift: movement of electrons in an atom where one side of an atom becomes positive and the other side becomes negative

In both cases, the distance from the negatively charged rod to the positive end of the neutral object is less than the distance to the negative end of the object. Therefore, the attraction of the opposite charges is greater than repulsion of like charges, and the net force is attractive.

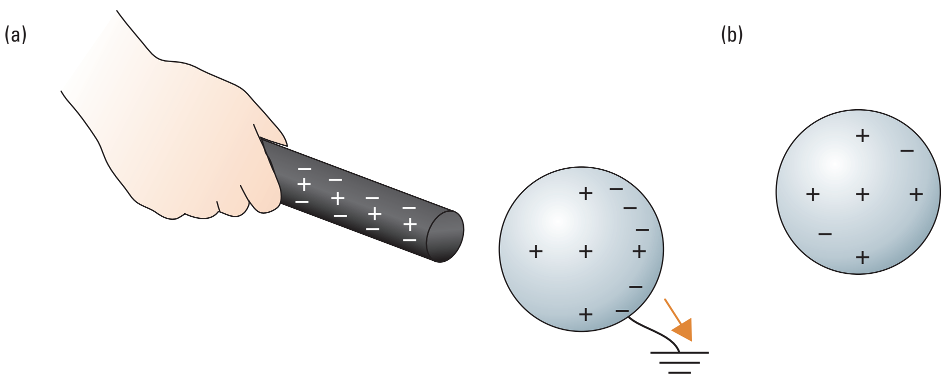
Charge separation by induction, which results in polarization of objects, explains electrostatic situations such as the initial attraction of a neutral piece of paper to a negatively charged rod without contact, as you saw in Figure 10.10.

Charging by Induction

In the situation shown in Figure 10.11, the electrons in the metal sphere and the paper return to their original positions when the negatively charged rod is removed. The objects lose their polarity and remain electrically neutral. For conductors, like the metal sphere, it is possible to maintain a residual charge by adding a grounding step. **Grounding** involves touching or connecting a wire from the object to the ground, as shown in Figure 10.12(a). The grounding path is then removed while the source charge is still present. The grounding step allows the conductor to maintain a charge (Figure 10.12(b)). The complete process of **charging by induction** includes grounding.

grounding: the process of transferring charge to and from Earth

charging by induction: the process of polarizing an object by induction while grounding it



▲ **Figure 10.12** (a) While the charged rod is held near the metal sphere, the sphere remains polarized by induction. Grounding the sphere removes excess charge. In this situation, the sphere appears to have excess electrons on one side, which are removed. The positive charges cannot move because they represent the fixed nuclei of atoms. (b) After the ground and charged rod are removed, the sphere retains a net positive charge because of the loss of electrons. It has been charged by induction.

PHYSICS INSIGHT

The symbol for ground is

A grounded conductor that is polarized by the presence of a charged object will always have a net charge that is opposite to that of the charged object if the ground is removed before the charged object is removed. The conductor has been charged by induction.

Concept Check

When you rub a balloon on your hair, you are charging it by friction. Explain why the balloon will then stick to a wall for a long time.

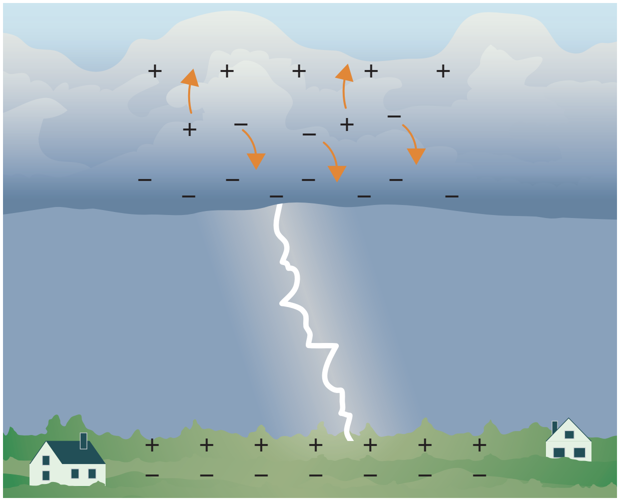
How Lightning Gets Its Charge

Many theories attempt to explain the formation of lightning. One theory relates the cause to the processes of evaporation and condensation of water in the clouds and different methods of charging objects. Under the right conditions, a churning cloud formation causes water vapour molecules to collide, resulting in a transfer of electrons between these molecules. The transfer of an electron from one water molecule to another leaves the molecules oppositely charged.

plasma: highly ionized gas containing nearly equal numbers of free electrons and positive ions

Cooling causes water vapour molecules to condense into water droplets. The atoms in these droplets hold onto electrons more readily than atoms in water vapour, and thus the droplets become negatively charged. Being heavier, these negatively charged water droplets accumulate at the bottom of the cloud, causing the bottom of the cloud to become negatively charged (Figure 10.13). The top of the cloud, containing the rising water vapour, becomes positively charged. The increasing polarization of the cloud ionizes the surrounding air, forming a conductive **plasma**. Excess electrons on the bottom of the cloud begin a zigzag journey through this plasma toward the ground at speeds of up to 120 km/s, creating a *step leader*. This is not the actual lightning strike.

The presence of the large negative charge at the bottom of the cloud causes the separation of charges at that location on Earth's surface. Earth's surface at that spot becomes positively charged, and the area below the surface becomes negatively charged. Charge separation has polarized Earth's surface. Air molecules near Earth's surface become ionized and begin to drift upward. This rising positive charge is called a *streamer*. When the rising positive streamer meets the step leader from the clouds, at an altitude of about 100 m, a complete pathway is formed and the lightning begins. A transfer of negative charge in the form of a lightning strike from the cloud travels to Earth's surface at speeds of up to 100 000 km/s (Figure 10.14).



▲ **Figure 10.13** Lightning forms when the bottom of the cloud becomes negatively charged and Earth's surface becomes positively charged.

▲ **Figure 10.14** A streamer moving up from Earth's surface meets a step leader coming down from the clouds and lightning lights up the sky.

10.1 Check and Reflect

Knowledge

1. What is the science of electrostatics?
2. Describe a simple experiment that enabled early scientists to determine that there were two different types of charges.
3. In the 1600s, William Gilbert compared the effects of electricity and magnetism.
   (a) Describe two similarities between these effects.
   (b) Describe two differences between these effects.
4. In the classification of substances by electrical conductivity, a substance may be a conductor, insulator, semiconductor, or superconductor.
   (a) What property of matter determines the electrical conductivity of a substance?
   (b) List the classifications given above in order of increasing electrical conductivity.
   (c) Give an example of a substance in each classification.
   (d) Describe the conditions when the semiconductor selenium becomes a conductor or an insulator.

Applications

5. (a) An ebonite rod is rubbed with fur. How can the electrostatic series chart in Figure 10.7 on page 518 help you determine which object will become negatively charged?
   (b) Why is it better to rub an ebonite rod with fur rather than silk?
6. Describe how you could charge a glass sphere positively using the following methods:
   (a) friction
   (b) conduction
   (c) induction
7. Describe how you would charge the sphere in Figure 10.12 negatively by induction.
8. A negatively charged ebonite rod is brought near a neutral pith ball that is hanging by an insulating thread from a support. Describe what happens
   (a) before they touch
   (b) after they touch
9. Compare the distribution of charge
   (a) on hanging aluminium and glass rods if both are touched at one end by a negatively charged ebonite rod
   (b) after a small negatively charged metal sphere momentarily touches a larger neutral metal sphere
10. A negatively charged ebonite rod is held near the knob of a neutral electroscope.
    (a) Explain what happens to the leaves of the electroscope.
    (b) Explain what happens to the leaves of the electroscope if the other side of the knob is now grounded while the rod is still in place.
    (c) Explain why removing the ground first and then the rod will leave a net charge on the electroscope.

Extensions

11. You are given an ebonite rod, fur, an electroscope, and a sphere of unknown charge. Describe an experimental procedure that you could use to determine the charge on the sphere.
12. If a glass rod becomes positively charged when rubbed with silk, use the law of conservation of charge to explain why the silk must be negatively charged.

eTEST

To check your understanding of electrical interactions, follow the eTest links at www.pearsoned.ca/school/physicssource.

info **BIT**

Charles de Coulomb was given credit for investigations into the electrostatic forces acting on charged objects, but the actual discovery of the relationship between electrostatic forces and charged objects was made earlier by Henry Cavendish (1731–1810), an English scientist. However, he was so shy that he didn't publish his results and thus was not credited with the discovery.

PHYSICS INSIGHT

Vertical bars around a vector symbol are an alternative method for representing the magnitude of a vector. This notation is used for the magnitude of force and field vectors from this chapter on. This notation avoids confusing the symbol for energy, E, with the magnitude of the electric field strength vector, $\vec{E}$, which is introduced in the next chapter.

10.2 Coulomb's Law

In Chapter 4, you studied Newton's law of universal gravitation and learned that any two objects in the universe exert a gravitational force on each other ($\vec{F}_g$). The magnitude of this force of gravitational attraction is directly proportional to the product of the two masses (m_1 and m_2):

$$|\vec{F}_g| \propto m_1 m_2$$

and inversely proportional to the square of the distance between their centres (r):

$$|\vec{F}_g| \propto \frac{1}{r^2}$$

These relationships can be summarized in the following equation:

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

where G is the universal gravitational constant in newton-metres squared per kilogram squared.

Charles de Coulomb suspected that the gravitational force that one mass exerts on another is similar to the electrostatic force that one charge exerts on another. To verify his hypothesis, he constructed an apparatus called a torsion balance to measure the forces of electrostatics. Although it could not be used to determine the quantity of charge on an object, Coulomb devised an ingenious method to vary the quantity of charge in a systematic manner.

10-3 Inquiry Lab

Required Skills

- Initiating and Planning
- Performing and Recording
- Analyzing and Interpreting
- Communication and Teamwork

Investigating the Variables in Coulomb's Law

Question

Two charged objects exert electrostatic forces of magnitude F_e on each other. How does F_e depend on the charges carried by the objects and on the separation between the objects?

Hypothesis

State a hypothesis relating the electrostatic force and each of the variables. Remember to write an "if/then" statement.

Variables

Read the procedure for each part of the inquiry and identify the manipulated variable, the responding variable, and the controlled variables in each one.

Materials and Equipment

Van de Graaff generator or ebonite rod and fur
3 small Styrofoam™ or pith spheres, about 1 cm in diameter, coated with aluminium or graphite paint
sewing needle
about 65 cm of thread
3 drinking straws
2 retort stands and 2 clamps
balance
2 rulers
tape
small mirror (about 10 cm long and 5 cm wide)
marking pen

Procedure

1. Determine the mass of one sphere (sphere 1) and record this mass in kilograms in your notebook.

2. Using the sewing needle, draw the thread through the centre of this sphere and attach both ends of the thread, with tape, to both ends of a drinking straw so that the sphere is suspended in the centre with the thread forming a V pattern. Clamp this straw, horizontally, to a retort stand, as shown in Figure 10.15.

3. Carefully insert the second drinking straw into the second sphere (sphere 2). Then fasten this drinking straw, horizontally, to the clamp on the other retort stand.

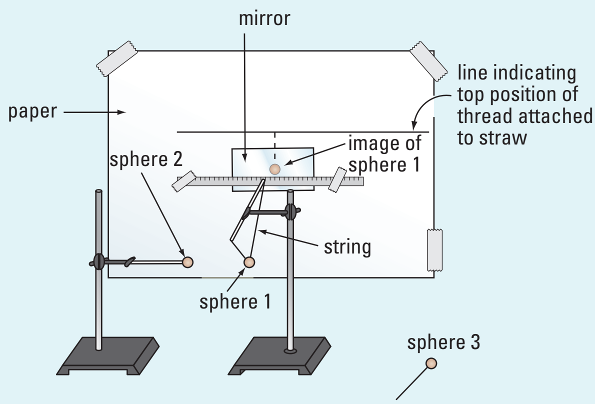
4. Adjust the clamps so that both spheres are at the same height.

5. Carefully insert the third drinking straw into the third sphere (sphere 3). (This sphere will be the grounding sphere that will be used to change the charges on spheres 1 and 2.)

6. Tape sheets of white paper to the wall. Place the retort stand with sphere 1 close to the wall, about 5 cm away, so that the centre of the sphere aligns with the centre of the paper. Using a ruler, draw a horizontal line on the paper indicating the top position of the string attached to the straw.

7. Tape the mirror on the paper so that the image of sphere 1 aligns with the centre of the mirror. Tape a ruler over the mirror just below the image of sphere 1. Using the marking pen, mark the position of the centre of the image of sphere 1 on the mirror while sighting in such a way that the sphere lines up with its image.

8. Do part A of the activity, which begins below, followed by part B.



▲ **Figure 10.15**

Part A: The relationship between the quantity of charge on each object and the electrostatic force

In this part of the lab, the distance between the spheres is held constant while the charges on the spheres are varied.

9. Copy Table 10.5 into your notebook, leaving out the numbers in parentheses in the first three columns. Use these numbers only if you are unable to measure the distances accurately. They are hypothetical values that you can use to complete the rest of the activity.

▼ **Table 10.5** Data and Calculations for Part A

Magnitude of Weight of Sphere 1 $\|\vec{F}_g\|$ (10^{-3} N) $\|\vec{F}_g\| = mg$	Vertical Height of Sphere 1 Δd_y (m)	Horizontal Distance to Centre of Sphere 1 from the Centre Mark Δd_x (m)	Product of Charges of Spheres 1 and 2 (q^2)	Magnitude of Force of Electrostatic Repulsion Acting on Spheres 1 and 2 $\|\vec{F}_e\|$ (N)
(1.28)	(0.300)	(0.0500)	$\frac{1}{2}q\frac{1}{2}q = \frac{1}{4}$	
(1.28)	(0.300)	(0.0250)	$\frac{1}{4}q\frac{1}{2}q = \frac{1}{8}$	
(1.28)	(0.300)	(0.0130)	$\frac{1}{4}q\frac{1}{4}q = \frac{1}{16}$	
(1.28)	(0.300)	(0.0062)	$\frac{1}{8}q\frac{1}{4}q = \frac{1}{32}$	
(1.28)	(0.300)	(0.0030)	$\frac{1}{8}q\frac{1}{8}q = \frac{1}{64}$	

10. Rub the ebonite rod with the fur or charge the Van de Graaff generator.

11. Carefully touch sphere 2 to the charged rod or generator to charge the sphere by conduction. Since it is nearly impossible to measure the quantity of charge transferred to sphere 2, assume that the quantity of charge on the sphere is q.

12. Slide the stand holding charged sphere 2 toward sphere 1 on the other stand and momentarily touch the two spheres together. The charge on each object can be assumed to be $\frac{1}{2}q$ because, on contact, the charge is equally divided between two similar spheres. Therefore, the charge product is $\frac{1}{2}q\frac{1}{2}q = \frac{1}{4}q^2$.

13. Slide sphere 2, parallel to the wall, to the left until the centre of its image is 1.0 cm away from the centre mark on the mirror.

14. Mark the new position of the centre of the image of sphere 1 on the mirror. Label it position 1.

15. To obtain more data, vary the charge on each sphere using sphere 3. Gently touch sphere 3 to sphere 1. Since the charge on each sphere should be shared equally, the new charge on sphere 1 is $\frac{1}{4}q$. The charge product on spheres 1 and 2 is now $\frac{1}{4}q\frac{1}{2}q = \frac{1}{8}q^2$. Label the new position of sphere 1 as position 2.

16. Remove sphere 3 to a safe distance and ground it by gently touching it with your hand.

17. Repeat steps 14 to 16, keeping sphere 2 in position and alternately touching spheres 1 and 2 with sphere 3 to obtain three more readings. Label these positions 3, 4, and 5.

18. With a ruler, accurately measure the vertical distance from the centre of the image of sphere 1 to the top horizontal line. Record this vertical distance (Δd_y) in metres in the appropriate column of Table 10.5.

19. Measure the distance between the original centre mark on the mirror and the centre of the image of sphere 1 in its new position for each trial. Record this distance (Δd_x) in metres in the appropriate column of Table 10.5.

Part B: The relationship between the distance between two charges and the electrostatic force

In this part of the lab, the charges on the spheres are fixed while the distances are varied.

20. Copy Table 10.6 into your notebook, leaving out the numbers in parentheses in the first three columns. Use these numbers only if you are unable to measure the distances accurately. They are hypothetical values that you can use to complete the rest of the activity.

▼ Table 10.6 Data and Calculations for Part B

Magnitude of Weight of Sphere 1 $\lvert\vec{F}_g\rvert$ (10^{-3} N) $\lvert\vec{F}_g\rvert = mg$	Vertical Height of Sphere 1 Δd_y (m)	Horizontal Distance to Centre of Sphere 1 from the Centre Mark Δd_x (m)	Distance Between the Centres of Spheres 1 and 2 r (m)	Magnitude of Force of Electrostatic Repulsion Acting on Spheres 1 and 2 $\lvert\vec{F}_e\rvert$ (N)
(1.28)	(0.300)	(0.0500)	(0.0600)	
(1.28)	(0.300)	(0.0467)	(0.0617)	
(1.28)	(0.300)	(0.0438)	(0.0638)	
(1.28)	(0.300)	(0.0409)	(0.0659)	
(1.28)	(0.300)	(0.0383)	(0.0683)	

21 Rub the ebonite rod with the fur or charge the Van de Graaff generator.

22 Carefully touch sphere 2 to the rod or the generator to give it a charge.

23 Slide the stand holding charged sphere 2 toward sphere 1 on the other stand and momentarily touch the two spheres together.

24 Slide sphere 2 to a position so that the centre of its image is 0.5 cm to the left of the original centre mark on the mirror.

25 Mark the new position of the image of sphere 1 on the mirror and label it position 1.

26 Repeat steps 24 and 25, sliding sphere 2 parallel to the wall so that its image positions are at 1.0 cm, 1.5 cm, 2.0 cm, and 2.5 cm away, to obtain four more readings. Label these positions 2, 3, 4, and 5.

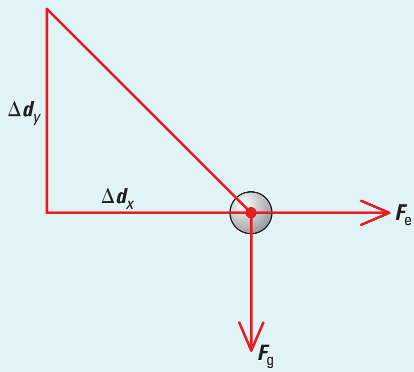
27 With a ruler, accurately measure the vertical distance from the centre of the image of sphere 1 to the horizontal line representing the top position of the string. Record this vertical distance (Δd_y) in metres in the appropriate column of Table 10.6.

28 Measure the distance from the original centre mark on the mirror to the centre of the image of sphere 1 in its new position for each trial. Record this distance (Δd_x) in metres in the appropriate column of Table 10.6.

29 Measure the distance between the centres of the two spheres. For each trial, record this distance (r) in metres in the appropriate column of Table 10.6.

Analysis

1. Although the force of electrostatic repulsion $|\vec{F}_e|$ acting on two similarly charged spheres cannot be measured directly, it can be calculated as shown in Figure 10.16. Complete the calculations as indicated in Table 10.5 for Part A.



▲ **Figure 10.16(a)** Use the concept of similar triangles:
$$\frac{\Delta d_y}{\Delta d_x} = \frac{|\vec{F}_g|}{|\vec{F}_e|} \qquad |\vec{F}_e| = \frac{|\vec{F}_g|\Delta d_x}{\Delta d_y}$$

2. Construct a graph of the force of electrostatic repulsion on the y-axis as a function of the charge product on the x-axis.

3. What does the shape of the graph indicate about the relationship between the force of electrostatic repulsion and the charge product?

4. Complete the calculations as indicated in Table 10.6 for Part B.

5. Construct a graph of the force of electrostatic repulsion on the y-axis as a function of the distance between the charges on the x-axis.

6. What does the shape of the graph indicate about the relationship between the force of electrostatic repulsion and the distance between the two charges?

7. From the investigation, identify the two variables that affect the force of electrostatic repulsion acting on two charges.

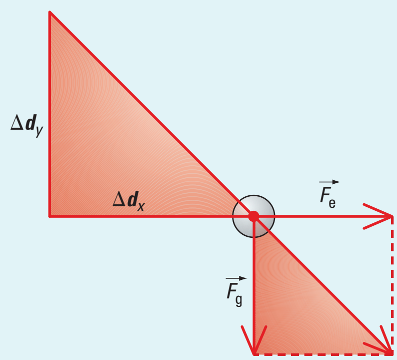
8. Using a variation statement, describe the relationship between these two variables and the force of electrostatic repulsion.

9. Does your investigation confirm your hypotheses about the relationship between the variables and the electrostatic force? Why or why not?

10. How does the relationship between the variables affecting the electrostatic force in this investigation compare with that of the variables affecting the force of gravitational attraction in Newton's law of gravitation?

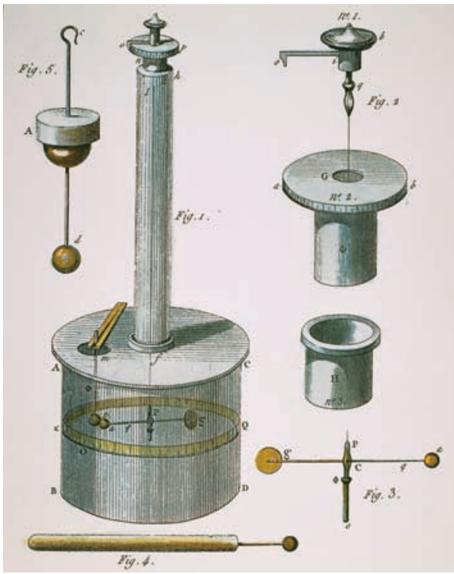
11. (a) What sources of error could have led to inaccuracy in the investigation?

(b) What modifications to the investigation would you recommend?



▲ **Figure 10.16(b)** The shaded triangles are similar.

The Force of Electrostatic Repulsion or Attraction



▲ **Figure 10.17**
Coulomb's apparatus

Coulomb correctly hypothesized that the two factors influencing the magnitude of the electrostatic force that one charge exerts on another were the magnitudes of the charges on each object and their separation distance. To experimentally derive the relationships between the two factors and the electrostatic force, Coulomb used a procedure similar to that used in the 10-3 Inquiry Lab but with a different apparatus—the torsion balance shown in Figure 10.17.

To determine the force of electrostatic attraction or repulsion acting on two charged objects, a charged ball on a rod is brought near a charged object at one end of the arm of the torsion balance. Repulsion or attraction causes the ball on the arm to move, rotating the arm. As the arm rotates, a sensitive spring either tightens or loosens, causing the needle to move a proportional angle. This movement of the needle can be measured on a scale. The amount of movement is related to a measure of the force of electrical attraction or repulsion.

e MATH

In 10-3 Inquiry Lab, Investigating the Variables in Coulomb's Law, you learned how separation and the magnitude of electric charges affect the electrostatic force. To graph the electrostatic force as a function of separation, and to analyze this relationship in more depth, visit www.pearsoned.ca/school/physicssource.

e SIM

Explore the inverse square relationship through a simulation using a sphere of uniform charge density. Follow the eSim links at www.pearsoned.ca/school/physicssource.

Determining Relative Charge

Realizing that there was not yet any way of measuring charge, Coulomb devised a method of accurately determining the relative magnitude of a charge. He knew that if a charged object with a charge of q touches a similar uncharged object, then the charge would be shared equally so that each object would have a charge of $\frac{1}{2}q$. Using this assumption, he was able to do his experiment.

Investigating the relationship between the electrostatic force and the distance between the centres of the spheres, he first charged a sphere with a charge q and touched it momentarily to the sphere on the torsion balance. Each sphere would then have a similar and equal charge of $\frac{1}{2}q$ and $\frac{1}{2}q$. Then, holding the first sphere a measured distance from the sphere in the torsion balance, he was able to measure the electrostatic force acting on the two spheres by the movement of the needle on the calibrated scale. Changing the distance between the spheres and measuring the force each time, he demonstrated there was an inverse square relationship between the electrostatic force and the separation distance. This relationship can be expressed as

$$|\vec{F}_{\mathrm{e}}| \propto \frac{1}{r^2}$$

Investigating further the relationship between the magnitude of the force and the magnitudes of the charges, he was able to accurately vary the charges on each sphere. By charging one sphere with a charge q and touching it to the sphere on the balance, he knew that the charge would be shared equally. The two spheres would have charges of $\frac{1}{2}q$ and $\frac{1}{2}q$ each, and the charge product would be $(\frac{1}{2}q)(\frac{1}{2}q)$. By touching each charged sphere alternately with a third neutral and similar sphere, he could vary the charge products as $(\frac{1}{4}q)(\frac{1}{2}q)$, then $(\frac{1}{4}q)(\frac{1}{4}q)$, and so on.

By varying the charges on both objects and measuring the electrostatic force acting on them, he demonstrated that the magnitude of the electrostatic force is proportional to the product of the two charges:

$$|\vec{F}_e| \propto q_1 q_2$$

In 1785, using the results from his experimentation on charged objects, Charles de Coulomb summarized his conclusions about the electrostatic force. This force is also known as the Coulomb force. His summary of his conclusions is called **Coulomb's law**.

The magnitude of the force of electrostatic attraction or repulsion ($|\vec{F}_e|$) is:

- directly proportional to the product of the two charges q_1 and q_2:

$$|\vec{F}_e| \propto q_1 q_2$$

- inversely proportional to the square of the distance between their centres r:

$$|\vec{F}_e| \propto \frac{1}{r^2}$$

If these are the only variables that determine the electrostatic force, then

$$|\vec{F}_e| \propto \frac{q_1 q_2}{r^2}$$

The beautiful fact about Coulomb's law and Newton's law of gravitation is that they have exactly the same form even though they arise from different sets of operations and apply to completely different kinds of phenomena. The fact that they match so exactly is a fascinating aspect of nature.

Although Coulomb was able to identify and determine the relationships of the variables that affect the electrostatic force acting on two charges, he was unable to calculate the actual force. To do so, the variation statement must be converted to an equation by determining a proportionality constant (k), whose value depends on the units of the charge, the distance, and the force. At the time, however, it was impossible to measure the exact quantity of charge on an object.

PHYSICS INSIGHT

Newton's law of gravitation is called an inverse square law because the gravitational force acting on any two masses is *inversely* proportional to the *square* of the distance between their centres.

The Magnitude of Charges

The SI unit for electric charge is the **coulomb (C)**. A bolt of lightning might transfer 1 C of charge to the ground, while rubbing an ebonite rod with fur typically separates a few microcoulombs (μC). It is difficult to build up larger quantities of charge on small objects because of the tremendous repulsive forces between the like charges.

As you will see in section 15.2, experiments at the beginning of the 20th century showed that an electron has a charge of about -1.60×10^{-19} C. So, 1 C of negative charge corresponds to the charge on 6.25×10^{18} electrons, or 6.25 billion billion electrons. Similarly, the charge on a proton is about $+1.60 \times 10^{-19}$ C.

Given these values, physicists were able to calculate the constant of proportionality for Coulomb's law. With this constant, Coulomb's law becomes:

$$|\vec{F}_e| = k\frac{q_1 q_2}{r^2}$$

where $|\vec{F}_e|$ is the magnitude of the force of electrostatic attraction or repulsion in newtons; q_1 and q_2 are the magnitudes of the two charges in coulombs; r is the distance between the centres of the charges in metres; k is the proportionality constant called Coulomb's constant and is equal to $8.99 \times 10^9\ \text{N}\cdot\text{m}^2/\text{C}^2$. This electrostatic force is attractive if the two objects have opposite charges and repulsive if the two objects have like charges.

This equation is used to determine electrostatic forces in many different types of problems involving charges and the electrostatic forces acting on them. Examples 10.1 and 10.2 show how to calculate the electrostatic force of attraction or repulsion acting on two charges in a one-dimensional situation.

info BIT

The electrostatic force acting on two charges of 1 C each separated by 1 m is about 9×10^9 N. This electrostatic force is equal to the gravitational force that Earth exerts on a billion-kilogram object at sea level!

Example 10.1

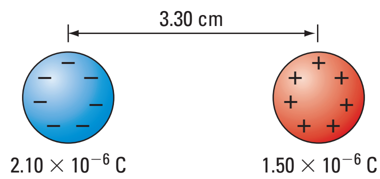
A small metal sphere with a negative charge of 2.10×10^{-6} C is brought near an identical sphere with a positive charge of 1.50×10^{-6} C so that the distance between the centres of the two spheres is 3.30 cm (Figure 10.18). Calculate the magnitude and type (attraction or repulsion) of the force of one charge acting on another.

Given

$q_1 = -2.10 \times 10^{-6}$ C

$q_2 = +1.50 \times 10^{-6}$ C

$r = 3.30 \times 10^{-2}$ m



▲ **Figure 10.18**

Required

magnitude and type of the electrostatic force acting on the two charges ($|\vec{F}_e|$)

Analysis and Solution

According to Newton's third law, the electrostatic forces acting on the two spheres are the same in magnitude but opposite in direction.

The magnitude of the electrostatic force is

$$\begin{aligned}|\vec{F}_e| &= k\frac{q_1 q_2}{r^2}\\ &= \frac{\left(8.99 \times 10^9 \frac{\text{N}\cdot\text{m}^2}{\cancel{\text{C}^2}}\right)(2.10 \times 10^{-6}\ \cancel{\text{C}})(1.50 \times 10^{-6}\ \cancel{\text{C}})}{(3.30 \times 10^{-2}\ \text{m})^2}\\ &= 26.0\ \text{N}\end{aligned}$$

The magnitude calculation does not use the positive and negative signs for the charges. However, you can use these signs to determine whether the electrostatic force is attractive or repulsive. In this example, the charges have opposite signs, so the force is attractive.

Practice Problem

1. In a hydrogen atom, an electron is 5.29×10^{-11} m from a proton. An electron has a charge of -1.60×10^{-19} C, and the proton's charge is $+1.60 \times 10^{-19}$ C. Calculate the electrostatic force of attraction acting on the two charges.

Answer

1. 8.22×10^{-8} N [attraction]

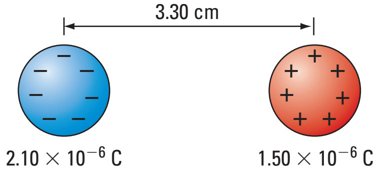
Paraphrase
The electrostatic force is one of attraction, with a magnitude of 26.0 N.

In the next example, the two spheres touch and the charge is distributed between them.

Example 10.2

The two spheres in Example 10.1 are momentarily brought together and then returned to their original separation distance. Determine the electrostatic force now exerted by one charge on the other.

Given
initial magnitude of the charges:
$q_1 = 2.10 \times 10^{-6}$ C
$q_2 = 1.50 \times 10^{-6}$ C
$r = 3.30 \times 10^{-2}$ m



▲ **Figure 10.19**

Required
magnitude and type of the electrostatic force acting on the two charges ($\vec{F}_e$)

Analysis and Solution
When a sphere with a negative charge of 2.10×10^{-6} C momentarily touches a sphere with a positive charge of 1.50×10^{-6} C, then -1.50×10^{-6} C of charge from the first sphere neutralizes the $+1.50 \times 10^{-6}$ C of charge on the second sphere. The remaining charge of -0.60×10^{-6} C from the first sphere then divides equally between the two identical spheres. Each sphere now has a charge of -3.0×10^{-7} C.

The magnitude of the electrostatic force is now

$$|\vec{F}_e| = k\frac{q_1 q_2}{r^2}$$

$$= \frac{\left(8.99 \times 10^9 \frac{\mathrm{N{\cdot}m^2}}{\cancel{\mathrm{C}^2}}\right)(3.0 \times 10^{-7}\ \cancel{\mathrm{C}})(3.0 \times 10^{-7}\ \cancel{\mathrm{C}})}{(3.30 \times 10^{-2}\ \mathrm{m})^2}$$

$$= 0.74\ \mathrm{N}$$

Since both spheres have a negative charge, the electrostatic force is repulsive.

Paraphrase
The electrostatic force is one of repulsion, with a magnitude of 0.74 N.

Practice Problem

1. A metal sphere with a negative charge of 3.00 μC is placed 12.0 cm from another similar metal sphere with a positive charge of 2.00 μC. The two spheres momentarily touch, then return to their original positions. Calculate the electrostatic force acting on the two metal spheres.

Answer

1. 1.56×10^{-1} N [repulsion]

Concept Check

Compare gravitational forces and electrostatic forces by identifying two similarities and two differences between the two types of forces.

Vector Analysis of Electrostatic Forces

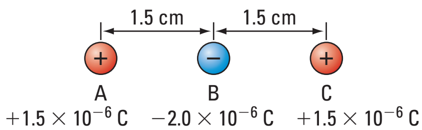
So far in this section, you have studied Coulomb's law and applied the equation to calculate the magnitude of the electrostatic force that one charged particle exerts on another. However, many situations involve more than two charges. The rest of this section illustrates how to use Coulomb's law to analyze the vector nature of electrostatic forces by determining the electrostatic forces of more than two charges in one-dimensional and two-dimensional situations.

Examples 10.3 and 10.4 illustrate how to apply Coulomb's law to three or more collinear charges. Recall from unit I that *collinear* entities lie along the same straight line.

Example 10.3

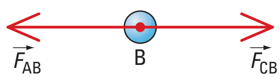
A small metal sphere (B) with a negative charge of 2.0×10^{-6} C is placed midway between two similar spheres (A and C) with positive charges of 1.5×10^{-6} C that are 3.0 cm apart (Figure 10.20). Use a vector diagram to find the net electrostatic force acting on sphere B.

Analysis and Solution



▲ **Figure 10.20**

Spheres A and C have equal charges and are the same distance from sphere B. As shown in Figure 10.21, the force vectors are equal in length and opposite in direction.



▲ **Figure 10.21**

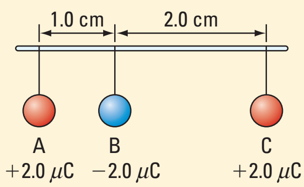
$|\vec{F}_{net}| = |\vec{F}_{CB}| - |\vec{F}_{AB}|$

$|\vec{F}_{AB}| = |\vec{F}_{CB}|$, so $\vec{F}_{net} = 0$.

Since the forces are equal in magnitude and opposite in direction, the net electrostatic force on charge B is 0.

Practice Problems

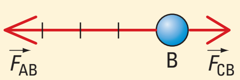
1. Three small, hollow, metallic spheres hang from insulated threads as shown in the figure below. Draw a free-body diagram showing the electrostatic forces acting on sphere B.



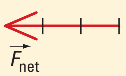
2. For the figure in problem 1 above, draw a vector for the net electrostatic force on sphere B.

Answers

1.



2.

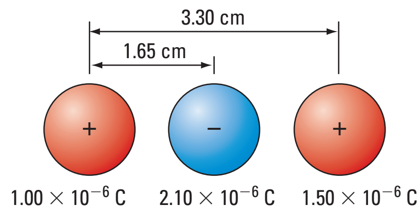


Example 10.4

A small metal sphere (B) with a negative charge of 2.10×10^{-6} C is placed midway between two similar spheres (A and C) 3.30 cm apart with positive charges of 1.00×10^{-6} C and 1.50×10^{-6} C, respectively, as shown in Figure 10.22. If the three charges are along the same line, calculate the net electrostatic force on the negative charge.

Given

$q_A = +1.00 \times 10^{-6}$ C
$q_B = -2.10 \times 10^{-6}$ C
$q_C = +1.50 \times 10^{-6}$ C
$r_{AC} = 3.30 \times 10^{-2}$ m
$r_{AB} = r_{BC} = \frac{1}{2} r_{AC}$



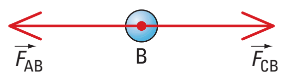
▲ **Figure 10.22**

Required

net electrostatic force on q_B ($\vec{F}_{net}$)

Analysis and Solution

The charge on sphere B is negative and the charge on sphere A is positive, so the electrostatic force of q_A on q_B, $\vec{F}_{AB}$, is an attractive force to the left. Similarly, the electrostatic force of q_C on q_B, $\vec{F}_{CB}$, is an attractive force to the right (Figure 10.23). Consider right to be positive.



▲ **Figure 10.23**

The sum of these two force vectors is the net force on q_B:

$\vec{F}_{net} = \vec{F}_{AB} + \vec{F}_{CB}$

Applying $|\vec{F}_e| = k\frac{q_1 q_2}{r^2}$ gives

$$\vec{F}_{net} = \frac{\left(8.99 \times 10^9 \frac{\text{N}\cdot\text{m}^2}{\cancel{\text{C}^2}}\right)(1.00 \times 10^{-6}\ \cancel{\text{C}})(2.10 \times 10^{-6}\ \cancel{\text{C}})}{\left(\frac{3.30 \times 10^{-2}\ \text{m}}{2}\right)^2} \text{ [left]}$$

$$+ \frac{\left(8.99 \times 10^9 \frac{\text{N}\cdot\text{m}^2}{\cancel{\text{C}^2}}\right)(1.50 \times 10^{-6}\ \cancel{\text{C}})(2.10 \times 10^{-6}\ \cancel{\text{C}})}{\left(\frac{3.30 \times 10^{-2}\ \text{m}}{2}\right)^2} \text{ [right]}$$

$= (-69.34$ N $+ 104.0$ N) [right]
$= 34.7$ N [right]

Paraphrase

The net electrostatic force on charge B is 34.7 N to the right.

Practice Problems

1. A metal sphere with a charge of -2.50×10^{-9} C is 1.50 cm to the left of a second metal sphere with a charge of $+1.50 \times 10^{-9}$ C. A third metal sphere of -1.00×10^{-9} C is situated 2.00 cm to the right of the second charged sphere. If all three charges form a line, determine the net electrostatic force on the second sphere.
2. In the situation described above, if the first and third spheres remain at their original positions, where should the second sphere be situated so that the net electrostatic force on it would be zero?

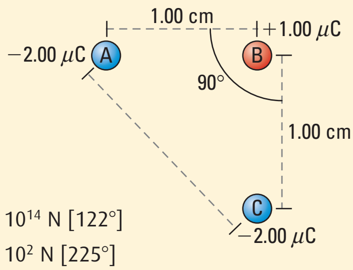
Answers

1. 1.16×10^{-4} N [to the left]
2. 2.14×10^{-2} m to the right of the -2.50×10^{-9} C charge

In Examples 10.3 and 10.4, the forces act along the same line, so the calculations involve only a single dimension. Examples 10.5 and 10.6 demonstrate how to calculate net electrostatic forces in two dimensions.

Practice Problems

1. A small metal sphere X with a negative charge of -2.50 C is 1.20 cm directly to the left of another similar sphere Y with a charge of $+3.00$ C. A third sphere Z with a charge of $+4.00$ C is 1.20 cm directly below sphere Y. The three spheres are at the vertices of a right triangle, with sphere Y at the right angle. Calculate the net electrostatic force on sphere Y, sketching diagrams as necessary.
2. Calculate the net electrostatic force on charge B shown in the figure below.



Answers

1. 8.83×10^{14} N [122°]
2. 2.54×10^{2} N [225°]

Example 10.5

A small metal sphere A with a negative charge of 2.10×10^{-6} C is 2.00×10^{-2} m to the left of another similar sphere B with a positive charge of 1.50×10^{-6} C. A third sphere C with a positive charge of 1.80×10^{-6} C is situated 3.00×10^{-2} m directly below sphere B (Figure 10.24). Calculate the net electrostatic force on sphere B.

Given

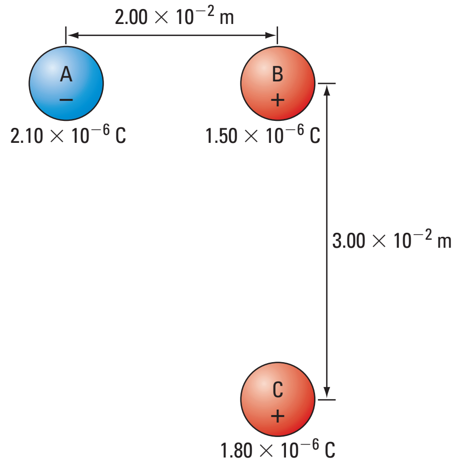
$q_A = -2.10 \times 10^{-6}$ C

$q_B = +1.50 \times 10^{-6}$ C

$q_C = +1.80 \times 10^{-6}$ C

$r_{AB} = 2.00 \times 10^{-2}$ m

$r_{BC} = 3.00 \times 10^{-2}$ m



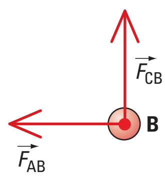
▲ **Figure 10.24**

Required

net electrostatic force on sphere B ($\vec{F}_{net}$)

Analysis and Solution

The electrostatic force of q_A on q_B, $\vec{F}_{AB}$, is a force of attraction directed from charge B toward charge A (left). The electrostatic force of q_C on q_B, $\vec{F}_{CB}$, is a force of repulsion directly upward (Figure 10.25).



▲ **Figure 10.25**

Applying $|\vec{F}_e| = k\dfrac{q_1q_2}{r^2}$ gives

$$|\vec{F}_{AB}| = k\frac{q_Aq_B}{r^2_{AB}}$$

$$= \frac{\left(8.99 \times 10^9 \frac{\text{N}\cdot\text{m}^2}{\cancel{\text{C}^2}}\right)(2.10 \times 10^{-6}\ \cancel{\text{C}})(1.50 \times 10^{-6}\ \cancel{\text{C}})}{(2.00 \times 10^{-2}\ \text{m})^2}$$

$$= 70.80\ \text{N}$$

Similarly,

$$|\vec{F}_{CB}| = k\frac{q_Bq_C}{r^2_{BC}}$$

$$= \frac{\left(8.99 \times 10^9 \frac{\text{N}\cdot\text{m}^2}{\cancel{\text{C}^2}}\right)(1.50 \times 10^{-6}\ \cancel{\text{C}})(1.80 \times 10^{-6}\ \cancel{\text{C}})}{(3.00 \times 10^{-2}\ \text{m})^2}$$

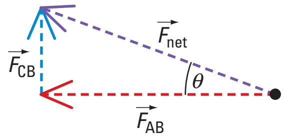
$$= 26.97\ \text{N}$$

Use trigonometry to find the net electrostatic force on charge B, as shown in Figure 10.26.
Use the Pythagorean theorem to find the magnitude of the net force:

$$|\vec{F}_{net}| = \sqrt{(70.80\text{ N})^2 + (26.97\text{ N})^2}$$
$$= 75.8\text{ N}$$

Determine the angle θ:

$$\tan\theta = \frac{26.97\ \cancel{\text{N}}}{70.80\ \cancel{\text{N}}}$$
$$\theta = 20.9°$$



▲ **Figure 10.26**

The direction of the net force is [20.9° N of W] or [159°].

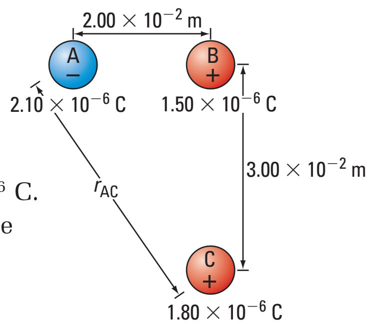
Paraphrase
The net electrostatic force on charge B is 75.8 N [20.9° N of W], or 75.8 N [159°].

PHYSICS INSIGHT

Recall that with the polar coordinates method, angles are measured counterclockwise from the positive *x*-axis of the coordinate system, which is given a value of 0°.

Example 10.6

A small metal sphere A with a charge of -2.10×10^{-6} C is 2.00×10^{-2} m to the left of a second sphere B with a charge of $+1.50 \times 10^{-6}$ C. A third sphere C with a charge of $+1.80 \times 10^{-6}$ C is situated 3.00×10^{-2} m directly below sphere B. Calculate the net electrostatic force on sphere C.



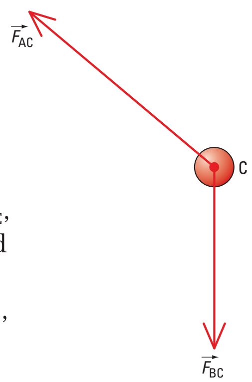
▲ **Figure 10.27**

Given

$q_A = -2.10 \times 10^{-6}$ C
$q_B = +1.50 \times 10^{-6}$ C
$q_C = +1.80 \times 10^{-6}$ C
$r_{AB} = 2.00 \times 10^{-2}$ m
$r_{BC} = 3.00 \times 10^{-2}$ m

Required
net electrostatic force on sphere C ($\vec{F}_{net}$)

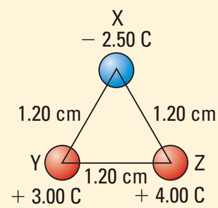
Analysis and Solution
The electrostatic force of q_A on q_C, $\vec{F}_{AC}$, is an attractive force directed from charge C toward charge A.
The electrostatic force of q_B on q_C, $\vec{F}_{BC}$, is a repulsive force directed downward (Figure 10.28).



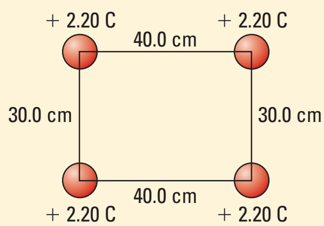
▲ **Figure 10.28**

Practice Problems

1. Three metal spheres are situated in positions forming an equilateral triangle with sides of 1.20 cm, as shown below. X has a charge of −2.50 C; Y has a charge of +3.00 C; and Z has a charge of +4.00 C. Calculate the net electrostatic force on the Y charge.



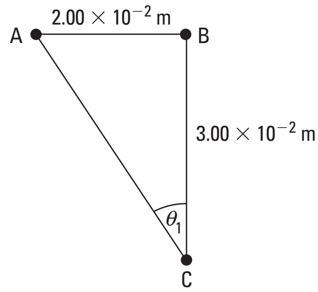
2. Four charged spheres, with equal charges of +2.20 C, are situated in positions forming a rectangle, as shown in the figure below. Determine the net electrostatic force on the charge in the top right corner of the rectangle.



Answers
1. 6.56×10^{14} N [142°]
2. 7.17×10^{11} N [55.0°]

Determine the distance between charges A and C by using the Pythagorean theorem (Figure 10.29):

$$\begin{aligned} r_{AC} &= \sqrt{(2.00 \times 10^{-2}\ \text{m})^2 + (3.00 \times 10^{-2}\ \text{m})^2} \\ &= 3.606 \times 10^{-2}\ \text{m} \\ &= 3.61 \times 10^{-2}\ \text{m} \end{aligned}$$



▲ **Figure 10.29**

Applying $|\vec{F}_e| = k\dfrac{q_1 q_2}{r^2}$ gives

$$\begin{aligned} |\vec{F}_{AC}| &= k\frac{q_A q_C}{r^2_{AC}} \\ &= \frac{\left(8.99 \times 10^9 \dfrac{\text{N}\cdot\text{m}^2}{\cancel{\text{C}^2}}\right)(2.10 \times 10^{-6}\ \cancel{\text{C}})(1.80 \times 10^{-6}\ \cancel{\text{C}})}{(3.61 \times 10^{-2}\ \text{m})^2} \\ &= 26.13\ \text{N} \end{aligned}$$

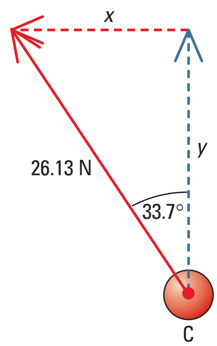
Similarly,

$$\begin{aligned} |\vec{F}_{BC}| &= k\frac{q_B q_C}{r^2_{BC}} \\ &= \frac{\left(8.99 \times 10^9 \dfrac{\text{N}\cdot\text{m}^2}{\cancel{\text{C}^2}}\right)(1.50 \times 10^{-6}\ \cancel{\text{C}})(1.80 \times 10^{-6}\ \cancel{\text{C}})}{(3.00 \times 10^{-2}\ \text{m})^2} \\ &= 26.97\ \text{N} \end{aligned}$$

Use the component method to find the sum of the two force vectors.

Use trigonometry to determine the angle θ_1 for the direction of $\vec{F}_{AC}$ (Figure 10.29):

$$\begin{aligned} \tan\theta_1 &= \frac{2.00 \times 10^{-2}\ \cancel{\text{m}}}{3.00 \times 10^{-2}\ \cancel{\text{m}}} \\ \theta_1 &= 33.69° \end{aligned}$$



▲ **Figure 10.30**

Then resolve $\vec{F}_{AC}$ into x and y components, as shown in Figure 10.30:

$$\begin{aligned} F_{AC_x} &= -(26.13\ \text{N})(\sin 33.69°) \\ &= -14.49\ \text{N} \\ F_{AC_y} &= (26.13\ \text{N})(\cos 33.69°) \\ &= 21.74\ \text{N} \end{aligned}$$

The electrostatic force of charge B on charge C has only a y component (see Figure 10.28).

So, the x component of $\vec{F}_{BC}$ is 0 N and the y component is −26.97 N.

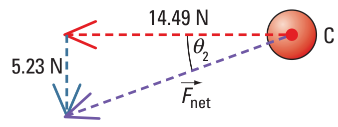
Now find the sum of the x and y components of $\vec{F}_{net}$.

$$\vec{F}_{net} = \vec{F}_{AC} + \vec{F}_{BC}$$

$$\begin{aligned} F_{net_x} &= F_{AC_x} + F_{BC_x} \\ &= -14.49\ \text{N} + 0\ \text{N} \\ &= -14.49\ \text{N} \end{aligned}$$

$$\begin{aligned} F_{net_y} &= F_{AC_y} + F_{BC_y} \\ &= 21.74\ \text{N} + (-26.97\ \text{N}) \\ &= -5.23\ \text{N} \end{aligned}$$

Use trigonometry to determine the magnitude and direction of the net electrostatic force on charge C, as shown in Figure 10.31.



▲ **Figure 10.31**

Determine the magnitude of the net force using the Pythagorean theorem:

$$|\vec{F}_{net}| = \sqrt{(14.49\ N)^2 + (5.23\ N)^2}$$
$$= 15.4\ N$$

To determine the angle θ_2, use the tangent function:

$$\tan\ \theta_2 = \frac{5.23\ \cancel{N}}{14.49\ \cancel{N}}$$
$$\theta_2 = 19.8°$$

The direction of the net force is [19.8° S of W] or [200°].

Paraphrase

The net electrostatic force on charge C is 15.4 N [19.8° S of W] or 15.4 N [200°].

THEN, NOW, AND FUTURE ESD Control Manager

Since the early 1970s, electrostatic discharge (ESD) has evolved from an interesting, but generally harmless, phenomenon to one of the most rapidly expanding fields of research in science today.

As electronic devices have become smaller and smaller, ESD has become a major cause of failure. Each year, billions of dollars' worth of electronic devices and systems are destroyed or degraded by electrical stress caused by ESD.

A dangerous property of ESD is its ability to cause fires in a flammable atmosphere. Property loss, injuries, and fatalities due to the accidental ignition of petrochemical vapours, dusts, and fuels by ESD are on the rise. ESD has been the proven ignition source in many fires. However, research into the fire-sparking nature of ESD is still in its infancy.

Today, electronics manufacturers have ESD awareness and control programs, ESD control program managers, and, in some cases, entire departments dedicated to preventing the damaging effects of ESD.

Ron Zezulka (Figure 10.32) is the chief technical officer of TB&S Consultants and has specialized in the science of ESD for over 30 years. He graduated from the Southern Alberta Institute of Technology with a diploma as a telecommunications technician and began his career as a failure analyst specializing in the science of ESD for Alberta Government Telephones.

Ron completed many courses to become a control program manager. Because of the newness of the industry, there are no specific qualifications for becoming a control program manager in the field of ESD.

▲ **Figure 10.32** Ron Zezulka

An ESD control program manager might have a technical diploma and related job experience, a Master's degree, or a Ph.D. in physics.

In 2001, Ron formed TB&S Consultants and has developed and delivered over 25 different training programs and management systems for the awareness and control of ESD in industry. He has written on the topic and lectured in industry, universities, and colleges on awareness and control of ESD.

Static electricity is now tied to almost every aspect of the physical sciences. As technology advances, so does our need for a greater understanding of ESD phenomena.

Questions

1. Describe two hazards associated with ESD.
2. How could ESD have damaging and harmful effects in your home?
3. How are ESD control program managers employed in industry?

10.2 Check and Reflect

Knowledge

1. Identify the two factors that influence the force of electrostatic attraction or repulsion acting on two charges. Write a mathematical expression to describe the relationship.

2. Describe how the inverse square law, first proposed by Newton for gravitational forces, was applied to electrostatic forces by Coulomb.

3. (a) What is the SI unit for electric charge?
   (b) Compare the charge on an electron to that produced by rubbing an ebonite rod with fur.

4. Coulomb could not measure the amount of charge on his spheres, but he could vary the amount of charge on each sphere. Describe the procedure he used to do so.

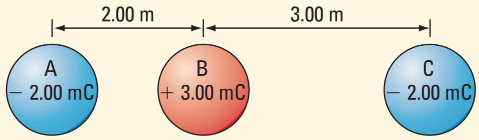
Applications

5. An electrostatic force of 10 N acts on two charged spheres, separated by a certain distance. What will be the new force in the following situations?
   (a) The charge on one sphere is doubled.
   (b) The charge on both spheres is doubled.

6. (a) Why is it difficult to attain a large charge of 100 C on a small object?
   (b) During the rubbing process, an object acquires a charge of -5.0×10^{-9} C. How many electrons did the object gain?

7. Two identical conducting spheres have charges of 5.00×10^{-5} C and 6.00×10^{-5} C and are in fixed positions, 2.00 m apart.
   (a) Calculate the electrostatic force acting on the two charges.
   (b) The spheres are touched together and returned to their original positions. Calculate the new electrostatic force acting on them.

8. Three charges are placed in a line, as shown in the diagram below.



   (a) What is the net electrostatic force on charge A?
   (b) What is the net electrostatic force on charge B?

Extensions

9. A helium nucleus has a positive charge with a magnitude twice that of the negative charge on an electron. Is the electrostatic force of attraction on an electron in a helium atom equal to the force acting on the nucleus? Justify your answer.

10. Electrical forces are so strong that the combined electrostatic forces of attraction acting on all the negative electrons and positive protons in your body could crush you to a thickness thinner than a piece of paper. Why don't you compress?

e TEST

To check your understanding of Coulomb's law, follow the eTest links at www.pearsoned.ca/school/physicssource.

Key Terms and Concepts

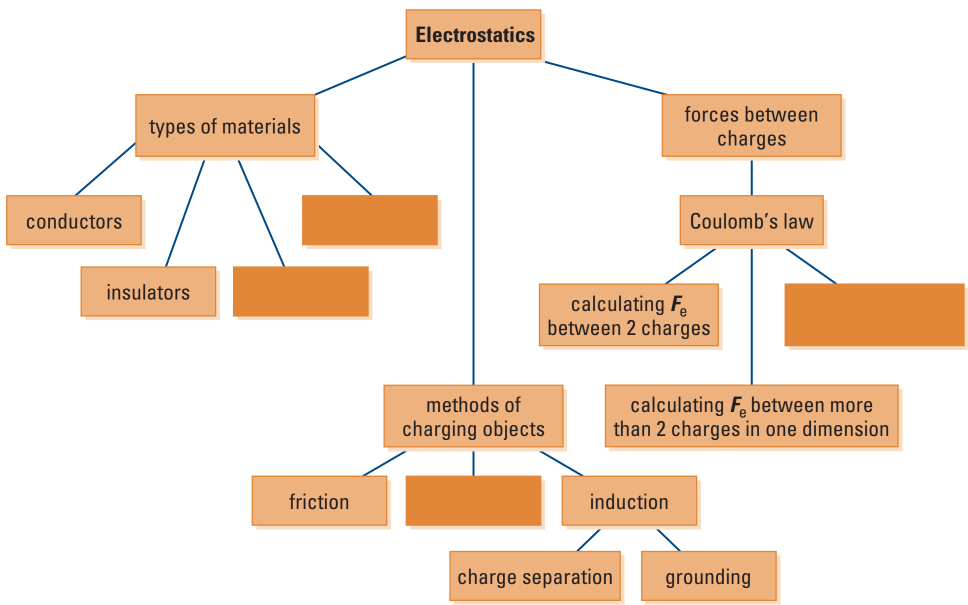
electrostatics
insulator
conductor
semiconductor
superconductor
law of conservation of charge
net charge
conduction
induction
charge migration
charge shift
grounding
charging by induction
plasma
Coulomb's law
coulomb (C)

Key Equation

$$|\vec{F}_e| = k\frac{q_1 q_2}{r^2}$$

Conceptual Overview

The concept map below summarizes many of the concepts and equations in this chapter. Copy and complete the map to have a full summary of the chapter.



Knowledge

1. (10.1) What is an electrostatic charge?
2. (10.1) On what property of materials does thermal and electrical conductivity depend?
3. (10.1) Under what conditions does selenium become a good conductor or a good insulator? What are materials with this property called?
4. (10.1) What are three methods of charging objects?
5. (10.1) During the process of charging objects by friction, what determines which object becomes negatively or positively charged?
6. (10.1) How are the processes of charging objects by conduction and friction alike? How are they different?
7. (10.1) State the law of charges.
8. (10.1) Who is credited with first naming the two types of charges as negative and positive charges?
9. (10.1) State the law of conservation of charge.
10. (10.1) Selenium and germanium are both semiconductors. Explain why selenium is used in photocopiers rather than germanium.
11. (10.2) Calculate the electrostatic force acting on two charged spheres of $-3.00\ \mu C$ and $-2.50\ \mu C$ if they are separated by a distance of 0.200 m.

Applications

12. What is the distance between two charges of -5.00 C each if the force of electrostatic repulsion acting on them is 5.00×10^3 N?
13. Charge A has a charge of $-2.50\ \mu C$ and is 1.50 m to the left of charge B, which has a charge of $+3.20\ \mu C$. Charge B is 1.70 m to the left of a third charge C, which has a charge of $-1.60\ \mu C$. If all three charges are collinear, what is the net electrostatic force on each of the following?
    (a) charge B
    (b) charge C
14. Why is dust attracted to the front of a cathode-ray tube computer monitor?
15. Why is it desirable to develop materials with low electrical resistance?
16. Explain why a charged ebonite rod can be discharged by passing a flame over its surface.
17. Explain why repulsion between two objects is the only evidence that both objects are charged.
18. Why do experiments on electrostatics not work well on humid days?
19. Why does a charged pith ball initially attract a neutral pith ball, then repel it after touching it?
20. Why can you not charge a copper rod while holding one end with one hand and rubbing the other end with a piece of fur?
21. A person standing on an insulated chair touches a charged sphere. Is the person able to discharge the sphere and effectively ground it? Explain.
22. Two charged spheres, separated by a certain distance, attract each other with an electrostatic force of 10 N. What will be the new force in each of the following situations?
    (a) The charge on both spheres is doubled and the separation distance is halved.
    (b) The charge on one sphere is doubled while the charge on the other sphere is tripled and the separation distance is tripled.
23. Calculate and compare the electrical and gravitational forces acting on an electron and a proton in the hydrogen atom when the distance between their centres is 5.29×10^{-11} m.
24. An equilateral triangle with sides of 0.200 m has three charges of $-2.50\ \mu C$ each, situated on the vertices of the triangle. Calculate the net electrostatic force on each charge. What assumption did you have to make to complete the calculation?

25. In a Coulomb-type experiment, students were investigating the relationship between the force of electrostatic repulsion acting on two charged spheres and their separation distance. The results of their investigation yielded the results shown in the table below.

Separation Distance (r) ($\times 10^{-2}$ m)	Magnitude of Force of Repulsion $\lvert\vec{F}\rvert$ (N)
1.00	360.0
2.00	89.9
3.00	40.0
4.00	27.5
5.00	14.4

(a) Draw a graph of the results shown in the table.

(b) From the shape of the graph, what is the relationship between the electrostatic force and the separation distance between two charges?

(c) Make a new table of values to obtain data to straighten the graph.

(d) Draw a graph of the data in your new table of values.

(e) Determine the slope of the graph.

(f) What value does the slope of this graph represent?

(g) If the charges of the two spheres are the same, what is the value of the charge on each sphere?

Extensions

26. Can a neutral object contain any charges? Explain.

27. Is it possible for a single negative or a single positive charge to exist in nature under normal conditions? Explain your answer.

28. Explain why it is impossible to charge a coin by rubbing it between your fingers.

29. Compare the production of lightning on Earth with the lightning between the rings of Saturn observed by the *Voyager* spacecraft on its mission to Saturn.

30. You are given two equally sized metal spheres on insulated stands, a piece of wire, a glass rod, and some silk. Devise and describe a method to do the following without touching the rod to the spheres:

(a) give the spheres equal and opposite charges

(b) give the spheres equal and like charges

31. Using the principles of electrostatics, explain the causes and effects of the following demonstrations:

(a) Two strips of clear adhesive tape are stuck together and then carefully separated. When the two strips are brought close to each other, attraction occurs.

(b) Two strips of clear adhesive tape are stuck onto a desktop and then carefully removed. When the two strips are held close to each other, repulsion occurs.

Consolidate Your Understanding

Create your own summary of the behaviour of electric charges and the laws that govern electrical interactions by answering the questions below. If you want to use a graphic organizer, refer to Student Reference 3: Using Graphic Organizers. Use the Key Terms and Concepts listed on page 539 and the Learning Outcomes on page 510.

1. Create a flowchart to describe how to calculate the electrostatic forces between two or more charged objects in one- or two-dimensional situations.

2. Write a paragraph explaining the three methods of charging objects. Share your report with a classmate.

Think About It

Review your answers to the Think About It questions on page 511. How would you answer each question now?

eTEST

To check your understanding of the behaviour of electric charges, follow the eTest links at www.pearsoned.ca/school/physicssource.