23.0 - Introduction

In this chapter, we begin the study of electricity and magnetism by discussing electric charge and the electrostatic force. Although you cannot see the individual charged particles, such as electrons and protons, that cause this force, you certainly see its effects. Phenomena ranging from the annoying static cling in freshly laundered clothing to the operation of laser printers are based on the electrostatic force. In the sections that follow, we will cover the fundamentals of electric charge: what it means to say that an object is charged and the nature of the forces created by charged objects.

We start with two simulations, shown to the right. The first allows you to experiment with positively and negatively charged particles and see the forces they exert on one another. The positively charged particles in this simulation have the same charge as protons, and the negatively charged particles have the same charge as electrons.

After you launch this simulation, drag particles from the control panel onto the screen above it. Once there, they will exert forces on each other. The amount and direction of each force will be shown on the screen. You can drag particles closer together or farther apart to see how the force they exert on one another relates to the distance between them (the heavier grid lines are exactly one meter apart). If you press GO, the particles, which all have equal mass, will be free to accelerate in response to the forces they exert on each other. *Electrostatics* is the study of electric charges at rest, so the simulation is also providing you with an extremely informal introduction to the topic of *electrodynamics*, the study of charges in motion.

As you use the simulation, take note of the direction of the forces between, say, two negative or positive particles or between a positive and a negative particle. You can also place two particles with the same charge next to each other, and see how the force on a third particle changes. How the electric force changes with both the distance between the charged particles — frequently just called “charges” — and the amount of charge is a fundamental focus of this chapter.

In the second simulation, you can play “proton golf”. The ball is positively charged, and you add protons to the putter to make it positively charged as well. The protons in the putter exert a force, called the electrostatic force, on the ball even when the two are not touching. You can control both the location of the putter, by dragging it, and how many protons it contains, by clicking the up- and down-arrows in the console. The moment you load protons into the putter they exert a force on the ball, but the ball is locked in place until you press PUTT. The grass of the green supplies a frictional force that will cause the ball to stop rolling.

Your mission, as always in golf, is to sink the ball in the hole — in four or less shots, if you can! The important thing (in addition to having fun) is to observe how the electrostatic force relates to the amount of charge and to distance. Be warned, though: Obstacles do exist! A clump of protons acts as a hill that causes the ball to roll away from it, while a clump of electrons is a sand trap that will attract the ball. Fore!

23.1 - Electric charge

*Electric charge*: A property of the particles that make up matter. It causes attraction and repulsion.

Electric charge is a property of matter that can cause attraction and repulsion. In this section, we focus on electrons and protons, and the role they play in causing an object to have an electric charge.

An electron is defined as having a **negative** charge and a proton is defined as having a **positive** charge. Charge is a scalar, not a vector. A negative charge is not less than zero, just the opposite of positive. In this book we will represent negative charges as black and positive charges as red.

The amount of charge of an electron or proton is written as \(e\) and is called the elementary charge. An electron has a negative charge of \(-e\) and a proton has a positive charge of \(+e\). This amount of charge is the smallest amount that has been isolated. (Subatomic particles called quarks have charges of \(+2/3e\) or \(-1/3e\) but they have not been isolated.)

The SI unit for charge is the *coulomb*. An electron or a proton has a charge of magnitude \(e = 1.602 \times 10^{-19}\) coulombs. This means

This woman's hair is electrically charged. As you will see, the strands of her hair repel each other because each one of them carries a negative charge.
approximately 6,250,000,000,000,000,000,000 electrons or protons are required for a coulomb of charge to be present. This is a vast number! However, numbers like this are often present in nature: A bolt of lightning typically contains about 25 C of charge. To provide you with another idea of the magnitude of a coulomb, approximately 0.8 C of charge flows through a 100 watt light bulb every second.

Some scientists, chemists in particular, use another unit, the esu or electrostatic unit. One esu equals 3.335 64×10⁻¹⁰ C.

A small amount of matter contains a large number of electrons and protons. For instance, a one-kilogram sample of copper contains about 2.75×10²⁶ protons. When an object has the same number of electrons and protons, it has no net charge and is said to be electrically neutral.

The addition or removal of electrons from an object causes it to become charged. A negatively charged object has more electrons than protons and a positively charged object has more protons than electrons. If the kilogram of copper has a charge of +0.1 C, which is a relatively large amount of charge, this means that about 0.000 002 % of its electrons have been removed.

**Electric charge**

- Property of particles that make up matter
- Electrons negative, protons positive
- They have opposite amounts of charge

**Electron:**

\[ q = -1.60 \times 10^{-19} \text{ C} \]

**Proton:**

\[ q = +1.60 \times 10^{-19} \text{ C} \]

\( q \) is symbol for charge

Units: coulombs (C)

**Example 1**

\[ q = -1.60 \times 10^{-19} \text{ C} \]

**How much charge do these five electrons have?**

\[ q_{\text{total}} = (5) \text{ (charge of 1 electron)} \]

\[ q_{\text{total}} = -1.60 \times 10^{-19} \text{ C} \]

\[ q_{\text{total}} = 5 \times (-1.60 \times 10^{-19}) \]

\[ q_{\text{total}} = \text{negative} \ 8.00 \times 10^{-19} \text{ C} \]

---

**23.2 - Creating charged objects**

How does an object become electrically charged? The answer is that the addition or removal of electrons creates negatively and positively charged objects. Except under extreme conditions, protons stay in place and electrons move.

A piece of silk and a glass rod can be used to demonstrate one manner in which objects can become charged. We will assume these two objects start out electrically neutral. In other words, the silk has equal numbers of protons and electrons, as does the glass.

You can transfer electrons from the glass to the silk by rubbing the two materials together. This close contact results in a net flow of electrons from the glass to the silk and causes the silk to become negatively charged. It now contains more electrons than protons. In turn, the glass
becomes positively charged, since it now has fewer electrons than protons.

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You may wonder why rubbing silk and glass together causes them to become charged. The electrons move because the silk molecules have a greater affinity for electrons than do the glass molecules. Rubbing the two materials together facilitates the transfer of electrons by providing a greater level of contact between their molecules.

The charging process can be reversed. When free to move, electrons will flow from a negatively charged object to a positively charged one, reducing or ending a charge imbalance. Lightning provides a dramatic example of such movement, a grand display of excess electrons moving to a region that is less negatively charged. With lightning, the electrons may be moving to a positively charged region of a cloud, or to an electrically neutral region such as the surface of the Earth. Charges take advantage of any opportunity to reduce an imbalance.

A charged comb induces electric charges in the paper dots which cause them to stick together. This phenomenon is called static cling.

Creating charged objects
Neutral objects become charged by movement of electrons
Excess electrons: negatively charged
Excess protons: positively charged

Creating charged objects

\[ q = \pm Ne \]

- \( q \) = charge
- \( N \) = number of excess charges
- protons positive, electrons negative
- \( e \) = elementary charge

What is the net charge on the
Conservation of charge: The net charge of an isolated system of objects remains constant.

Electric charge is conserved. The net charge of an isolated system may be positive, negative or neutral. Charge can move between objects in the system, but the net charge of the system remains unchanged.

To illustrate this principle, we again use the example of a silk cloth and a glass rod to demonstrate how two different objects can become charged while, at the same time, overall charge is conserved. Let’s assume that the cloth and the rod are both neutral to begin with. They each become charged when rubbed together, but their combined charge is unchanged: It remains zero, or neutral. It is true that electrons have moved between the rod and the cloth, but to the extent that one object is negative, the other is positive. The cloth and the rod constitute an isolated system because all the charge moves solely between them and no charge leaves them. If charge flowed to a person holding these objects, that person would become part of the system as well, and charge would still be conserved.

Early on, scientists such as Benjamin Franklin (yes, that Ben Franklin) suggested this conservation principle based on experimental data and intuition, but he and his colleagues were unable to show why it was so. The discovery of electrons showed why the conjecture was true: It was the movement of electrons that created the charged objects that Franklin observed. Under ordinary circumstances, these particles are neither created nor destroyed, and Franklin observed the results of electrons flowing from one object to another.

An object is charged when it has an imbalance of electrons and protons. Charge is said to be quantized: It is always observed as an integer multiple of $e$, the magnitude of the charge of an electron or a proton.

In extreme circumstances, charged particles can be destroyed. For example, when a positron (an exotic particle that is the mirror image of an electron, identical in mass but opposite in charge) collides with an electron, the two will annihilate each other and produce gamma rays, a kind of high-energy radiation. Does this scenario violate the conservation of charge? No, because gamma rays have no net charge. Before the collision, the system of one electron and one positron has no net charge. After the collision, the system consists of neutral gamma radiation, so charge is conserved.
23.4 - Sample problem: charge conservation in nuclear decay

The nucleus of an atom of oxygen contains 8 protons, while the nucleus of an atom of neon contains 10 protons. Via a process called beta decay, a neutron can decompose into one proton plus one electron, and oxygen-21 transmutes into neon-21.

Applying conservation of charge, how many electrons must be emitted by the oxygen nucleus as the atom transmutes into neon-21?

Variables

| charge of oxygen-21 nucleus | +8e |
| charge of neon-21 nucleus | +10e |
| charge of one electron | −e |

What is the strategy?

1. Calculate the change in the positive charge of the nucleus when it transmutes into neon.
2. The number of electrons emitted must balance this change in charge.

Physics principles and equations

The conservation of charge holds for all isolated systems. A process like beta decay will not change the total charge of an isolated system.

Solution

To transmute an atom of oxygen into neon, two additional protons are required in the nucleus. The change in charge is +10e − (+8e), which is +2e. Since charge is conserved, the total charge does not change, and the process of beta decay must also result in the creation of a charge of −2e, which is the charge of two electrons. The nucleus emits the two electrons, and the total charge of the system containing the atom and its emissions does not change.

Oxygen-21 is what is called an unstable isotope (form) of oxygen. The beta decay process described in this problem occurs in two steps: first oxygen-21 transmutes to the unstable fluorine-21 and then fluorine-21 transmutes to the stable substance neon-21.

23.5 - Conductors, insulators, and grounds

*Conductor:* An object or material in which charge can flow relatively freely.

*Insulator:* An object or material in which charge does not flow freely.

*Ground:* Charge flows from a charged object to a ground, leaving the object neutral.

You can easily find conductors and insulators (also called nonconductors) in your home or classroom. If you examine an electrical cord, you will find that it consists of a conducting core of copper wire surrounded by an insulator such as vinyl plastic.

Charge can be moved relatively easily through a conductor such as copper using a device like a battery. A battery will cause electrons to flow through a copper wire like the one shown in Concept 1. In contrast, it is difficult to cause electrons to flow in insulators like rubber or many plastics. This difference explains the design of electrical cords: Often, they are made of copper wire wrapped with a flexible vinyl insulator so that electrons flowing through the wire remain within the cord.

Insulators do not allow charges to flow when they are subjected to only moderate amounts of force. When great amounts of force are applied, charge can flow through an insulator. There are also materials called semiconductors that enable charge to flow in some circumstances, but not others. Given their role in devices like transistors, they are an important topic, but lie outside the scope of this section.
A ground is a neutral object that can accept or supply an essentially unlimited number of charges. The Earth functions as an electric ground. If you touch a conducting, charged object to the ground, the object will also become electrically neutral—in other words, grounded. Excess electrons will flow out of a negatively charged object to the ground, and electrons will flow into a positively charged object from the ground. Charges move to a ground because charges of the same sign move as far away from each other as possible due to their mutual repulsion. The ground distributes the excess charge far enough away that it ceases to affect the object.

Protecting houses from lightning presents engineers with the need to use conductors and grounds. A building is not usually a conductor, but lightning can transform a house into a reluctant conductor, with disastrous, highly flammable results. A lightning rod is a conductor that protects houses and other structures by providing an easier, alternate route to the ground. A conducting wire connects the rod to the Earth. The shape of the rod also increases the likelihood that it will be the preferred target for lightning.

### Conductors and insulators

- **Conductor:** charge moves freely
- **Insulator:** charge does not readily flow

### Ground

Makes conductors electrically neutral

---

### 23.6 - Interactive problem: charged rods

These interactive simulations are versions of a classic game. In the original version of this game, you are given glasses, some filled with water and others empty. You are shown or told a final configuration of glasses and water. Your challenge is to start with the initial configuration, and by pouring water from one glass to another in a sequence of steps, end with the specified final configuration. For instance, a simple challenge would be to start with an empty glass, a half-full glass, and a quarter-full glass, and end up with a three-quarters-full glass. By pouring the half-full glass into the quarter-full glass, you achieve that goal.

In the simulations to the right, the same overall idea applies to electric charge. You are supplied with a configuration of charges on rods. Some of the rods have no charge, some have positive charge, and some are negatively charged. All the rods are the same size and are made of identical conducting material. In this game, charge flows between rods instead of water flowing between glasses. Charge flows until equilibrium is reached. For example, if you touch a rod with +4.000 microcoulombs of charge to a rod with no charge, both rods end up with +2.000 microcoulombs of charge.

To play the game, click on any rod and drag it to another rod. When you release the mouse button, charge will transfer between the rods.

In the topmost game to the right, you are given a rod with a charge of positive 10,000 µC, a rod with a charge of −3,000 µC, and several neutral rods. Your goal is to produce a rod with a charge of +1,000 µC. This can be done in two moves. The second game requires a greater number of moves and more planning. You can see the initial configuration to the right. The challenge again is to create a rod with +1,000 µC of charge. However skilled you are at these two games, the main point is to observe how charge is conserved.

Keep in mind that you do not have to be good at the games to practice the physics you are learning in this chapter. Give it a try! Whether you get the minimum number of moves or not, the simulations offer a chance to employ the principle of conservation of charge.

If you have any questions about the conservation of charge or about grounds, review the preceding sections on these topics.
**Electrostatic force:**
Attraction or repulsion due to electric charge.

Electrostatics is the study of electric forces between charges at rest. If you have ever visited a science museum, you may have seen people press their hands against an electrically charged device surmounted by a shiny metallic sphere, and then watched in amazement as their hair stands on end. This device, called a Van de Graaff generator, amusingly illustrates how electric charge creates a repulsive force. In the photograph above you see the spectacular display that can be created by such forces in a large Van de Graaff generator, as its huge electrostatic accumulation discharges through the atmosphere. The Boston Museum of Science states that it is home to the largest Van de Graaff generator in the world.

Clothes dryers provide a more mundane example of electrostatic forces at work. When your socks stick to your pants and then crackle as you pull them apart, you are witnessing the static cling caused by electrostatic forces. In this case, electrostatic force is causing oppositely charged pieces of clothing to attract each other. As the clothing is pulled apart, electric charges arc between the clothing items in an attempt to reach a more balanced state. (Imagine: When you fold your laundry, you can both please your parents and review your physics studies. What a deal! ) The electric charge responsible for that annoying cling in a sock is typically in the range of a few microcoulombs.

When objects have opposite charges, like laundry items or a glass rod and a silk cloth, they attract. When objects like the two balloons you see to the right have the same charge, either positive or negative, they repel each other. The old cliché – opposites attract and likes repel – proves true in physics. When dealing with issues of attraction and repulsion, it really is important to know your sign.

Two charged objects exert equal but opposite forces on each other. In other words, if they attract, they pull toward each other with the same force. If they repel, they push against each other with equal force.

The forces act along a straight line between the centers of the two charges. For instance, if they attract, each force points directly toward the other charge, as illustrated in Concept 2. If they repel, each force points directly away from the other charge.
23.8 - Inducing an electric charge

*Inducing an electric charge*: Creating a charged object or region of an object without direct contact.

Objects can become electrically charged when they are put into contact with each other, for example, by rubbing glass and silk together, or by touching a charged rod to a neutral one. In this process, electrons flow from one object to the other.

Objects can also become charged without touching. Like gravity, electrostatic forces act at a distance, so charges cause other charges to move without direct contact. When a charged object, like the nonconducting sphere shown in Concept 1, is placed near a neutral object in which electrons are free to move, such as the joined pair of conducting metal rods to its right, the charged object causes electrons to move in the neutral object. Charges in the rods, initially evenly distributed throughout the pair, end up in the asymmetrical configuration you see in Concept 1. The rod pair as a whole is still electrically neutral.

To explain how charged objects can be created without direct contact, we use the sphere and the pair of neutral rods just discussed. First, the negatively charged sphere approaches the rods. As the sphere repels electrons in the rods, the closer end of the rod combination becomes positively charged. As a result of the movement of electrons, the far end of the rod combination becomes negatively charged. Two regions of charge have been induced without contact by a charged object.

Next, the rods are separated. The closer one will remain positive and the farther one will remain negative, even after the charged sphere has moved away. This example shows how two objects can become charged without coming into direct contact with a third charged object.

23.9 - Coulomb’s law: calculating electrostatic forces

*Coulomb's law*: The electrostatic force a charged particle exerts on another is proportional to the product of the charges and inversely proportional to the square of the distance between them.

Named for Charles Augustin de Coulomb, the eighteenth century French physicist who formulated it, this law quantifies the amount of force between charged particles. His law is shown in Equation 1 to the right.

The force is measured in newtons. The constant $k$ in the equation has been experimentally determined. It equals $8.987\times 10^9 \text{ N} \cdot \text{m}^2/\text{C}^2$.

The charges are shown with absolute value signs around them, so that two positive values are multiplied together to calculate the amount of the force. To determine the direction, the rule "opposites attract, likes repel" is used. Two opposite charges attract, so both forces pull the charges together. Two like charges repel, so both forces push the charges away from each other. Recalling Newton's third law helps to insure the correct result: The forces are always equal but opposite to each other.

Coulomb’s law means that larger quantities of charge create more force and that the force weakens with the square of the distance.

Electrostatic forces can be added; they obey the principle of superposition. For example, if there are three charges, the force exerted by two of the charges on the third equals the vector sum of the forces exerted by each charge. This is similar to other forces you have studied; if two people are pushing a car, the net force equals the vector sum of the individual forces exerted by each person.

In Coulomb’s law, $r$ is the distance between two point charges, two infinitesimal sites of charge. If charges are symmetrically distributed on each of two spheres, a principle called the shell theorem can be used to show that all the charge on each sphere acts as
though it were located at the sphere’s center. In this case, the distance \( r \) is the distance between the centers of the spheres.

If you have studied gravity, you may notice that Coulomb’s law is similar to the equation for calculating gravitational force. Both are inverse square laws: The forces are inversely proportional to the distance squared. With Coulomb’s law, the force is proportional to the product of the charges; with gravity, the force is proportional to the product of the masses. Both are field forces, acting at a distance. Similarities like these cause physicists to search for one unified explanation of gravitational and electrostatic forces. Do remember, however, there is a crucial difference between the two forces: Masses always attract, while electric charges can both attract and repel.

Sometimes Coulomb’s law is expressed in another fashion, using the permittivity constant \( \varepsilon_0 \). This traditional way of expressing the law can be particularly helpful in your later studies. The equation expressed with the permittivity constant is also shown to the right, as Equation 2. The permittivity constant is related to Coulomb’s constant by the equation \( \varepsilon_0 = \frac{1}{4\pi k} \), and it equals \( 8.854 \times 10^{-12} \text{ C}^2/\text{N}\cdot\text{m}^2 \).

**Coulomb’s law, permittivity constant**

\[
F = \frac{1}{4\pi \varepsilon_0} \frac{|q_1| |q_2|}{r^2}
\]

\( \varepsilon_0 = \) permittivity constant

Constant \( \varepsilon_0 = 8.85 \times 10^{-12} \text{ C}^2/\text{N}\cdot\text{m}^2 \)

---

**example 1**

\[ + 5.00 \times 10^{-6} \text{ C} \quad + 1.00 \times 10^{-6} \text{ C} \]

\[ \begin{array}{c}
\downarrow \\
0.0500 \text{ m}
\end{array} \]

What is the magnitude and direction of the force the right charge exerts on the left charge?

\[
F = k \frac{|q_1| |q_2|}{r^2}
\]

\[
F = k \frac{(5.00 \times 10^{-6} \text{ C})(1.00 \times 10^{-6} \text{ C})}{(0.0500 \text{ m})^2}
\]

\( F = 18.0 \text{ N} \) (to the left)
The two balls above are floating in deep space, with the only significant gravitational forces acting upon them being the ones they exert upon one another. If they were electrically neutral, they would drift slowly together due to these forces and, after about an hour, come to rest against each other.

You are asked to determine how many electrons should be added to each sphere so that the electrostatic force exactly counteracts the gravitational force. You add the same number of electrons to each sphere, and disregard the change in mass of the spheres due to the added electrons. It is negligible.

**Variables**

<table>
<thead>
<tr>
<th></th>
<th>sphere 1</th>
<th>sphere 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>mass of sphere</td>
<td>$m_1 = 1.00 \text{ kg}$</td>
<td>$m_2 = 1.00 \text{ kg}$</td>
</tr>
<tr>
<td>charge of sphere</td>
<td>$q_1$</td>
<td>$q_2$</td>
</tr>
<tr>
<td>gravitational constant</td>
<td>$G = 6.67 \times 10^{-11} \text{ N} \cdot \text{m}^2/\text{kg}^2$</td>
<td></td>
</tr>
<tr>
<td>distance between spheres</td>
<td>$r = 1.00 \text{ m}$</td>
<td></td>
</tr>
<tr>
<td>gravitational force on sphere</td>
<td>$F_g$</td>
<td></td>
</tr>
<tr>
<td>electric force on sphere</td>
<td>$F_e$</td>
<td></td>
</tr>
<tr>
<td>Coulomb’s constant</td>
<td>$k = 8.99 \times 10^9 \text{ N} \cdot \text{m}^2/\text{C}^2$</td>
<td></td>
</tr>
<tr>
<td>number of excess electrons</td>
<td>$N$</td>
<td></td>
</tr>
<tr>
<td>elementary charge</td>
<td>$e = 1.60 \times 10^{-19} \text{ C}$</td>
<td></td>
</tr>
</tbody>
</table>

**What is the strategy?**

1. Calculate the gravitational attraction between the lead spheres.
2. Set the gravitational force equal to the repulsive electrostatic force between them and solve for the charge. The amount of charge on each sphere is the same.
3. Convert the charge from coulombs to the equivalent number of excess electrons.

**Physics principles and equations**

We will use Newton’s law of gravitation

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

Together with Coulomb’s law

$$F_e = \frac{k |q_1 q_2|}{r^2}$$

The charge due to $N$ excess electrons is

$$q = -Ne$$
Step-by-step solution

In the first steps, we calculate the charge \( q \) needed on the spheres to balance their gravitational attraction.

<table>
<thead>
<tr>
<th>Step</th>
<th>Reason</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>( F_g = G \frac{m_1 m_2}{r^2} ) Newton’s law of gravitation</td>
</tr>
<tr>
<td>2.</td>
<td>( F_g = G \frac{(1.00 \text{ kg})(1.00 \text{ kg})}{(1.00 \text{ m})^2} ) ( F_g = 6.67 \times 10^{-11} \text{ N} ) evaluate</td>
</tr>
<tr>
<td>3.</td>
<td>( F_g = F_e = k \frac{</td>
</tr>
<tr>
<td>4.</td>
<td>( q = \pm \sqrt{\frac{F_g r^2}{k}} ) solve for ( q )</td>
</tr>
<tr>
<td>5.</td>
<td>( q = - \sqrt{\frac{(6.67 \times 10^{-11} \text{ N})(1 \text{ m})^2}{8.99 \times 10^9 \text{ N} \cdot \text{m}^2/\text{C}^2}} ) note electron charge negative and evaluate ( q = -8.61 \times 10^{-11} \text{ C} )</td>
</tr>
</tbody>
</table>

In the following steps we find the number of excess electrons.

<table>
<thead>
<tr>
<th>Step</th>
<th>Reason</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.</td>
<td>( q = -Ne ) equation for charge</td>
</tr>
<tr>
<td>7.</td>
<td>( N = \frac{q}{e} ) solve for ( N )</td>
</tr>
<tr>
<td>8.</td>
<td>( N = \frac{-8.61 \times 10^{-11} \text{ C}}{1.60 \times 10^{-19} \text{ C}} ) ( N = 5.38 \times 10^8 \text{ electrons} ) evaluate</td>
</tr>
</tbody>
</table>

Step 5 shows that a miniscule amount of charge – about a ten-thousandth of the charge you transfer to a balloon when you rub it on your shirt – is enough to balance the gravitational attraction between two one-kilogram masses separated by one meter. If you were concerned about whether adding the excess electrons would alter the mass of each sphere enough to require recalculating their gravitational attraction, you can compute that they add an insignificant mass, about \( 5 \times 10^{-22} \text{ kg} \), to each sphere.

As an additional exercise, you can use Avogadro’s number, and the atomic weight and atomic number of lead, to find the total number of electrons in an uncharged kilogram of lead. This calculation is not shown, but the total number is \( 2.39 \times 10^{26} \text{ electrons} \). This means that the excess electrons constitute about \( 10^{-16} \text{ percent} \) of the electrons in the sphere.

23.11 - Interactive checkpoint: electric vs. gravitational force

Compute the ratio of the electric to the gravitational force between the proton and electron in a hydrogen atom. Use the average distance between the two, which is called the Bohr radius and equals \( 5.29 \times 10^{-11} \text{ m} \).

Answer:

\[ \frac{F_E}{F_G} = \]
23.12 - Superposition of electrostatic forces

Electrostatic forces obey the principle of superposition. The forces caused by multiple charges can be added as vectors. For instance, consider the charges shown in Concept 1. To calculate the net force exerted by the other charges on the charge labeled $q_1$, the forces exerted by $q_2$ and $q_3$ on $q_1$ are individually calculated and then those two forces are added as vectors. In the next section, we solve a sample problem involving charges that requires the use of this principle.

You must be careful about the directions of electrostatic forces, especially when combining forces that may point in opposite directions. The location and signs of the charges determine the direction of the forces.

For example, consider another set of charges, $q_4$, $q_5$, and $q_6$, with all the charges on a line, and $q_6$ the rightmost charge. Let’s say charges $q_4$ and $q_5$ have opposite signs. Since both are on the same side of $q_6$, the forces they exert upon it will act in opposite directions. There will be cancellation and the net force will be less than the sum of the magnitudes of the individual forces. There is no “rocket science” here. Just be careful to consider the direction of forces before combining them.

Electrostatic forces: vectors

Electrostatic forces are vector quantities

Net force = vector sum

Forces $F_1$, $F_2$, ..., $F_n$

$F_{net} = \sum_{m=1}^{n} F_m = F_1 + F_2 + ... + F_n$

23.13 - Sample problem: net force on a charge

Find the magnitude and direction of the net force exerted by the charged spheres $q_1$ and $q_3$ on sphere $q_2$.

Diagram

The net force on $q_2$ is the vector sum of $F_{12}$ and $F_{32}$.
Variables

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Coulomb’s constant</td>
<td>$k = 8.99 \times 10^9 \text{ N} \cdot \text{m}^2/\text{C}^2$</td>
</tr>
<tr>
<td>magnitude of charge</td>
<td>$q$</td>
</tr>
<tr>
<td>distance between charges</td>
<td>$r$</td>
</tr>
</tbody>
</table>

$x$ component $y$ component

<table>
<thead>
<tr>
<th>force of $q_1$ on $q_2$</th>
<th>$F_{12,x}$</th>
<th>$F_{12,y}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>force of $q_3$ on $q_2$</td>
<td>$F_{32,x}$</td>
<td>$F_{32,y}$</td>
</tr>
<tr>
<td>net force on $q_2$</td>
<td>$F_{\text{net},x}$</td>
<td>$F_{\text{net},y}$</td>
</tr>
</tbody>
</table>

In the table it is indicated that the $x$ component of $\mathbf{F}_{12}$ is zero, since this vector points straight up. Similarly $\mathbf{F}_{32}$ points to the right, so its $y$ component is zero. For the sake of brevity, we have not listed the individual values of all the charges and distances shown in the diagram above.

What is the strategy?

1. Find the $x$ and $y$ components of the force $\mathbf{F}_{12}$ exerted by sphere 1 on sphere 2.
2. Find the $x$ and $y$ components of the force $\mathbf{F}_{32}$ exerted by sphere 3 on sphere 2.
3. Add the vectors found above, component-by-component. Convert the resulting vector to polar notation to find its magnitude and direction.

Equations

We will use Coulomb’s law

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

In so doing, we may assume that all the charge of a charged sphere is concentrated in a single point at its center.

The magnitude and direction of the vector $\mathbf{A} = (a, b)$ are

$$A = \sqrt{a^2 + b^2}$$

$$\theta = \arctan\left(\frac{b}{a}\right)$$

Step-by-step solution

We use Coulomb’s law to find the components of $\mathbf{F}_{12}$:

<table>
<thead>
<tr>
<th>Step</th>
<th>Reason</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>$\mathbf{F} = k \frac{</td>
</tr>
<tr>
<td>2.</td>
<td>$F_{12} = k \frac{</td>
</tr>
<tr>
<td>3.</td>
<td>$\mathbf{F}<em>{12} = (F</em>{12,x}, F_{12,y}) = (0.00 \text{ N}, 8.63 \text{ N})$ components of $\mathbf{F}_{12}$</td>
</tr>
</tbody>
</table>

We use Coulomb’s law to find the components of $\mathbf{F}_{32}$:

<table>
<thead>
<tr>
<th>Step</th>
<th>Reason</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.</td>
<td>$\mathbf{F} = k \frac{</td>
</tr>
<tr>
<td>5.</td>
<td>$F_{32} = k \frac{</td>
</tr>
<tr>
<td>6.</td>
<td>$\mathbf{F}<em>{32} = (F</em>{32,x}, F_{32,y}) = (7.25 \text{ N}, 0.00 \text{ N})$ components of $\mathbf{F}_{32}$</td>
</tr>
</tbody>
</table>
Finally, we add \( \mathbf{F}_{12} \) and \( \mathbf{F}_{32} \) as vectors, component by component, and find the magnitude and direction of \( \mathbf{F}_{\text{net}} \).

<table>
<thead>
<tr>
<th>Step</th>
<th>Reason</th>
</tr>
</thead>
<tbody>
<tr>
<td>7. ( \mathbf{F}<em>{\text{net}} = (F</em>{\text{net}x}, F_{\text{net}y}) = (7.25 \text{ N}, 8.63 \text{ N}) )</td>
<td>vector addition</td>
</tr>
<tr>
<td>8. [ F_{\text{net}} = \sqrt{F_{\text{net}x}^2 + F_{\text{net}y}^2} ] ( F_{\text{net}} = \sqrt{(7.25)^2 + (8.63)^2} ) ( F_{\text{net}} = 11.3 \text{ N} )</td>
<td>magnitude of vector</td>
</tr>
<tr>
<td>9. [ \theta = \arctan \left( \frac{F_{\text{net}y}}{F_{\text{net}x}} \right) ] ( \theta = \arctan \left( \frac{8.63}{7.25} \right) ) ( \theta = 50.0^\circ )</td>
<td>direction of vector</td>
</tr>
</tbody>
</table>

### 23.14 - Interactive checkpoint: charges on a line

Three charges are arranged on a line as shown. Compute the net force exerted on the middle charge (charge 2) by the other two charges.

Answer:

\[ \Sigma F = \text{[Blank]} \text{ N} \]

### 23.15 - Physics at work: laser printers

When you print a document created on your computer, you may use a laser printer. Laser printers use the electrostatic force as a crucial part of the process of transferring an image from the computer to a sheet of paper. The process is known as xerography or electrophotography.

A key component of the laser printer is a rotating metal cylinder or drum. This drum is coated with a light-sensitive material called an organic photoconductor, a carbon-based compound whose electric properties change when it is exposed to light. In the dark it is an insulator, and electric charges cannot move through it. When it is exposed to light, it becomes a conductor and charges can flow freely. The organic photoconductor layer is on the outside surface of the drum. Inside it is a hollow metal cylinder connected to a ground, which allows any charge trapped in a portion of the photoconductor to drain away if that portion becomes conductive.

The printing process begins with a charging step, shown on the right, where the drum is given a uniform negative charge by bringing it into contact with a charged roller. Since the drum is shielded from light in the interior of the printer, the photoconductive layer acts as an insulator, trapping negative charges on its surface.

In the imaging step, shown next on the right, a laser controlled by signals from the computer directs light at the surface of the drum in a pattern corresponding to the image to be printed. Areas of the drum exposed to the laser light become conductive, allowing charge to escape from the drum surface to the ground. In this way the laser draws an electrostatic image of the document on the surface of the drum. Areas of the drum struck by the laser will be electrically neutral while the unexposed areas will retain their
negative charge.

It is interesting to note that the laser itself is stationary. Its beam is projected onto the drum by a series of movable lenses and mirrors controlled by the printer’s microprocessor, using data from your computer.

The next step is the development step. As the drum continues to rotate, it is brought close to a container or roller furnished with a toner, consisting of fine particles of ink that have a negative charge. The printer uses small pulses of electricity to eject the toner onto the drum surface. The negatively charged toner particles are repelled from the negatively charged unlit regions of the drum but cling to the neutral areas that were struck by the laser. The drum surface now holds toner particles in the pattern of the image to be printed.

Then the image is transferred to paper. A sheet of paper is given a positive charge and pressed against the drum. The negatively charged toner on the drum is attracted to the positively charged paper. The toner is permanently fused to the paper by a heated roller that melts the ink particles into the paper fiber. A final step, not shown on the right, prepares the drum for the next image by flashing it with light, causing the complete discharge of all charged areas on the drum.

23.16 - Interactive summary problem: proton golf

Above and to the right, you see the 24th century version of golf. Protons in the putter cause the proton golf ball to move away. Coulomb’s law is well known, well loved and well used.

To sink the putt in the first game, your putter must supply an initial force of \(1.96 \times 10^{-25}\) newtons. This will cause the ball to be rolling slowly as it reaches the hole, overcoming the force of friction due to the grass. If you apply too much force, the ball will fly over the hole. The ball is free to move when you press PUTT. In this game, you cannot move the putter, and you get only one stroke, but you can play again by pressing RESET.

The ball is initially 0.200 meters away from the putter and has a charge of \(+e\). What should the charge be in the putter? You set the amount of charge by specifying the number of protons.

After you calculate your answer, click on Interactive 1 to launch the simulation. You use the up and down arrows to set the number of protons in the putter. Select your value, press PUTT and the golf ball will roll toward the hole. If you need to review how to calculate the repulsive force between two positive charges, see the section on Coulomb’s law.

The second game is like the game of golf you played at the beginning of this chapter. You can change both the charge and the position of the proton golf ball.
putter. You will almost certainly need several strokes to sink the ball. The challenge of the game is to do so in as few strokes as you can. Again, the grass supplies a force of friction that must be overcome. You may feel that you are now more familiar with charges and the way they behave. Grab your prodigious proton putter and give it another try!

23.17 - Interactive group problem: minesweeper

On the right, you see an ocean overlaid with a grid. Hidden beneath the water are one or two mines loaded with electric charge. How many are hidden depends on which of the games you choose to play. Your mission is to deploy detectors to determine the location of the mines. The detectors will tell you the direction and amount of force being exerted on them, providing crucial information as to the location of the hidden mines.

To play the game, click on any of the graphics to the right. Each graphic includes text that describes the type of game (some are for one player, some are for two, and some have one hidden mine, while others have two).

Once you have launched a simulation, you can place the detector, which is a test charge, anywhere you like on the grid by dragging it from the control panel. Then click DEPLOY. If your detector is on exactly the same square as a mine charge, the charge will be revealed. The counter at the bottom of the game keeps track of the number of undetected mines.

If you do not place the detector on the same square as a mine charge, you will see a vector. The vector tells you the direction and magnitude of the force that the mine charge exerts on your test charge. Most of the vectors you see will be drawn with lengths proportional to their actual magnitudes, but not the shortest ones. Those we draw a little longer so that you can see what direction they are pointing in.

In all the games, the test charge in the detector has a magnitude of $+0.005 \, 00$ coulombs. In the one-mine, one-player game, the mine charge is $-0.010 \, 0 \, C$. Each square of the map grid is $50.0$ meters on a side, and the mine charges and detectors are both placed at the centers of squares. When there is just one hidden mine of known charge, then with one test charge — and some calculation — you should be able to determine the location of the mine charge. Using a couple of detectors may make it easier!

The two-mine game is harder. The force vector on any test charge is the vector sum of the forces from both hidden mines. There are two mines each with a charge of $-0.010 \, 0 \, C$ concealed, so it takes a little more experimenting and pondering to determine where they are.
There are also a couple two-player versions of the game. In both, you hide a charged mine or mines on your opponent’s board (opposite from where you drag out your mines), and your opponent does the same on yours. (Look away when your opponent hides hers.)

You both get to choose from a set of varied charges. In one version of the game, only one charged mine is hidden. In the other, two charged mines are hidden. You drag detectors to locations on your own board, trying to find the mine(s) hidden there. Whoever discovers all the mines first, wins. All the games rely on the material in the sections on electrostatic force and Coulomb’s law.
23.18 - Gotchas

A neutral object that gains electrons is negatively charged. Yes, a neutral object that gains electrons becomes negative; a neutral object that loses electrons becomes positive.

An object has a net charge of negative 10 coulombs. How many electrons does it contain? Do not bother trying to calculate a value. You could calculate how many excess electrons the object contains — how many more electrons than protons — with the given information. But unless someone tells you how many electrons the object contained when it was neutral, you cannot answer the question. The point here is: Charge refers to the number of excess electrons. A neutral object has electrons, too, but they are balanced by an equal number of protons.

You use the number of excess protons and electrons in Coulomb’s law. No, the charges \( q_1 \) and \( q_2 \) in Coulomb’s law are measured in (what else?) coulombs. If you are given the number of excess electrons or protons in a problem, you must determine the electric charge in coulombs.

I calculated a negative force from Coulomb’s law. Then you erred. The amount (magnitude) of the force is calculated by multiplying the absolute values of the charges, so it will always be positive. The direction of the force will vary by sign: attraction when the signs are opposite, repulsion when they are the same.

23.19 - Summary

Electric charge is a property of matter. It occurs in positive and negative forms. One unit of charge is \( e \). A proton has a charge of \( +e \) and an electron has a charge of \( -e \). Charge, represented by \( q \), is measured in coulombs (C). The elementary charge \( e \) equals \( 1.602 \times 10^{-19} \) C.

An ordinary object is charged when it has an imbalance of protons and electrons.

Charge is always conserved. Though charges may be transferred from object to object, charge cannot be created or destroyed, and the net charge of an isolated system will remain the same.

Electrons flow more freely in some objects than in others. Conductors allow electrons to move relatively easily, while insulators do not. A ground can drain away any excess charge from a conducting object. The most common ground is literally the ground: Earth.

Charged particles exert an electrostatic force on each other. Unlike gravity, which is always attractive, the electrostatic force can be either attractive or repulsive. Opposite charges attract each other; like charges repel.

Coulomb’s Law describes the amount of the electrostatic force between two point charges. It is proportional to the product of the charges’ magnitudes and inversely proportional to the square of the distance between them.

\[
F = \frac{k|q_1 q_2|}{r^2}
\]
C.1 Two scientists are locked in a bitter dispute about the charge on a particularly famous particle of dust. Maria claims it has a charge of $2.40 \times 10^{-19}$ C. Richard disagrees; he thinks its charge is $3.20 \times 10^{-19}$ C. Which scientist should you believe? Explain.

○ Maria ○ Richard

C.2 You are given an apple and an orange. The apple has a net charge of $+3 \times 10^{-17}$ C. The orange has a net charge of $-3 \times 10^{-17}$ C. With only this information, can you determine which one has more total electrons? Explain.

○ Yes ○ No

C.3 In a process known as beta decay, a neutron in an unstable atomic nucleus becomes a proton, in the process ejecting an electron and an antineutrino. (a) Use conservation of charge to determine the charge of an antineutrino. (b) Sixty billion neutrinos (mostly from the Sun) pass through every square centimeter on Earth every second. They are hardly noticeable due to their negligible mass and weak interaction with matter. When a neutrino and an antineutrino collide, however, they annihilate each other and produce two (electrically neutral) gamma rays traveling in opposite directions. What is the charge of a neutrino?

(a) C
(b) C

C.4 The Sun generates most of its light through a series of nuclear reactions called the proton-proton chain. The overall process of these nuclear reactions can be summarized as $4 \ H \rightarrow \ \ ^{4}\ He + 2\nu + 2\gamma + 2?$. Where $\nu$ is a small neutral particle called a neutrino, and $\gamma$ is a photon (a particle of light), which is also neutral. The pre-subscripts on the element symbols H (hydrogen) and He (helium) indicate the number of protons in the nucleus of each element. What is the charge of the unknown entity “?”?

○ $+2e$ ○ $+e$ ○ $0$ ○ $-e$ ○ $-2e$

C.5 Under typical conditions in a safe home, classify the following materials as conductors or insulators: (a) rubber, (b) iron, (c) copper, and (d) wood.

(a) Rubber is a(n) i. conductor ○ ii. insulator ○
(b) Iron is a(n) i. conductor ○ ii. insulator ○
(c) Copper is a(n) i. conductor ○ ii. insulator ○
(d) Wood is a(n) i. conductor ○ ii. insulator ○

C.6 Vanessa has been walking around all day, and electrons that rubbed off from the carpet have caused her to acquire a net negative charge. Explain why her hair might stand on end.

C.7 A positively charged eraser is placed near the "0 cm" end of a 10 cm metal ruler. As a result of the induced charge effect, which end of the ruler becomes positively charged: the "0 cm" end, or the "10 cm" end?

○ the "0 cm" end ○ the "10 cm" end

C.8 You are locked in a rubber room and given a pair of rubber gloves along with a positively charged bar of gold (marked with a "+") and two electrically neutral bars of gold. You will be released if you can produce a negatively charged bar of gold, and you get to keep the gold. Explain how you might accomplish this.

C.9 Two unequally charged pellets are held apart at a fixed distance. The charge on one of the pellets is halved, and the charge on the other is doubled. How this will affect the electric force one pellet exerts on the other? Explain.

i. The force will quadruple.
ii. The force will double.
iii. The force does not change.
iv. The force will be halved.
v. The force will be quartered.
C.10 A can of root beer and a can of cola are given different amounts of charge. Consider the cans to be point charges. By what factor must their separation be changed so that the electric force on the root beer can is the same (a) if the charge on each of the cans is doubled, and (b) if only the charge on the root beer is doubled?

(a) Multiply original separation by  
   i. 0.500  
   ii. 1.000  
   iii. 1.414  
   iv. 2.000  
   v. 4.000

(b) Multiply original radius by  
   i. 0.500  
   ii. 1.000  
   iii. 1.414  
   iv. 2.000  
   v. 4.000

C.11 Consider an isolated system of three stationary nonzero charges. No other forces are present. (a) Is it possible that any of the charges is experiencing zero net force? (b) If your answer to part "a" is yes, give an example. If no, explain why not.

(a) ☐ Yes ☐ No
(b)

C.12 A professor pets her cat, which is initially neutral, as is she (even in an election year). Immediately afterwards, the professor reaches for a doorknob and feels a shock as electrons travel from the knob into her hand. Is the cat positively charged, negatively charged or electrically neutral?

i. Positively charged  
ii. Negatively charged  
iii. Electrically neutral

C.13 Two objects are seen to electrostatically repel each other. From this information, can you tell (a) whether they are positively or negatively charged or (b) whether the product of their charges is negative or positive?

(a) ☐ Yes ☐ No
(b) ☐ Yes ☐ No

C.14 A llama has a charge of 1.0 \(\mu\)C, while a distant planet has a charge of 2.0 coulombs. How does the magnitude of the electric force that the llama exerts on the planet relate to the magnitude of the electric force that the planet exerts on the llama? Is it the same, greater or less?

i. Less  
ii. The same  
iii. Greater

Section Problems

Section 0 - Introduction

0.1 Using the simulation in the first interactive problem in this section, answer the following questions. What is the direction of the force between (a) two particles whose charges are the same sign and (b) two particles of opposite sign? (c) What happens to the magnitude of the force when the distance between two particles is increased?

(a) i. Towards each other  
ii. Away from each other
(b) i. Towards each other  
ii. Away from each other
(c) i. Increases  
ii. Stays the same  
iii. Decreases

Section 1 - Electric charge

1.1 The nucleus of a helium atom contains two protons, two neutrons, and no electrons. Neutrons have no net charge. What is the charge of the nucleus?

\[\text{C}\]

1.2 An electron has a mass of \(9.11 \times 10^{-31}\) kg. What is the charge of 1.00 grams of pure electrons?

\[\text{C}\]
1.3 An initially neutral ball bearing is hooked up to a machine that transfers electrons onto it. Afterwards, the ball bearing is analyzed and its charge is \(-2.81 \times 10^{-9}\) C. Find the mass increase due to the electron transfer. An electron has a mass of \(9.11 \times 10^{-31}\) kg.

\[
\text{Mass increase} = \frac{q}{e} \times m_e
\]

\[
\text{Mass increase} = \frac{-2.81 \times 10^{-9}}{1.602 \times 10^{-19}} \times 9.11 \times 10^{-31} = 1.7 \times 10^{-20} \text{ kg}
\]

\section*{Section 2 - Creating charged objects}

2.1 Chlorine is used in the making of computers and blood bags, and is found in household bleach as well as in the skin of the Ecuadorian tree frog. (a) A chlorine molecule (Cl\(_2\)) has 34 protons and 34 electrons. What is its charge? (b) A chlorine ion (Cl\(^-\)) has 17 protons and 18 electrons. What is its charge?

(a) \(0\) C
(b) \(-1\) C

2.2 The game of checkers has two players, black and red. Each player has 12 pieces. Suppose each red piece has a charge of \(+2.10 \times 10^{-15}\) coulomb and each black piece has a charge of \(-5.00 \times 10^{-16}\) C. Find the net charge of the following systems: (a) a black piece and a red piece, (b) two black pieces and a red piece, (c) all the pieces.

(a) \(-1.20 \times 10^{-15}\) C
(b) \(-6.00 \times 10^{-15}\) C
(c) \(-1.80 \times 10^{-15}\) C

2.3 An iron arrowhead has an initial charge of \(3.35 \times 10^{-6}\) C. How many electrons are required to give it a charge of \(-2.82 \mu\text{C}\)?

\[
\text{Number of electrons} = \frac{q}{e} = \frac{-2.82 \times 10^{-6}}{1.602 \times 10^{-19}} = 1.76 \times 10^{13}\]

\section*{Section 3 - Conservation of charge}

3.1 In an experiment, a particle called a pion (\(\pi\)) is observed to decay into two other particles, a muon and a neutrino. The muon then decays into an electron and two more neutrinos. Neutrinos are electrically neutral. (a) What is the charge of a muon? (b) Pions come in three types: \(\pi^+\) has a charge of \(+1.60 \times 10^{-19}\), \(\pi^-\) has a charge of \(-1.60 \times 10^{-19}\), and \(\pi^0\) is electrically neutral. What kind of pion could decay as described in this experiment?

(a) \(0\) C
(b) \(\pi^+\)

3.2 In a complex circuit, three colored wires (red, green, and blue) are joined together inside a mysterious black box. An ammeter, a device that measures the rate of charge flow (current), shows you that charge enters the box at 3 coulombs per second through the red wire and leaves the box at 2 coulombs per second through the green wire. There is no buildup of charge inside the box. After 10 seconds has elapsed, how much charge has flowed out of the box through the blue wire?

\[
\text{Charge out of blue wire} = \text{Charge in} - \text{Charge out} = 3 \times 10 - 2 \times 10 = 1 \text{ coulomb}
\]

\section*{Section 5 - Conductors, insulators, and grounds}

5.1 A nine-volt battery has two terminals that are 1.0 cm apart. The space between them is filled by air. How much charge flows between the two terminals in 1.0 minutes?

\[
\text{Charge} = \text{Current} \times \text{Time} = \frac{E}{R} \times \text{Time} = \frac{9}{1000} \times 1 = 9 \times 10^{-6} \text{ coulombs}
\]

\section*{Section 6 - Interactive problem: charged rods}

6.1 Using the simulation in the first interactive problem in this section, produce a rod with a charge of \(+1.000 \mu\text{C}\) in two turns. Explain the steps you took to achieve this.
6.2 Using the simulation in the second interactive problem in this section, produce a rod with a charge of +1.000 \( \mu \text{C} \) in five turns. Explain the steps you took to achieve this.

**Section 7 - Electrostatic force**

7.1 Three indistinguishable balloons are given charges of \(-1.1 \mu \text{C}, -2.5 \mu \text{C}, \) and \(+2.0 \mu \text{C}\) respectively. You are given two of them at random, and you observe that they repel each other. Find the total charge of the balloons you have been handed.

\[ \text{C} \]

7.2 Danny has a pile of four metallic marbles. Each marble has a charge of either \(-0.2 \mu \text{C} \) or \(+0.4 \mu \text{C} \). He observes that red attracts blue, blue attracts green, and green attracts black. Red and black are brought in contact with each other so that they have the same charge. Afterwards, Danny observes that red now repels blue. For each color of marble, use the radio buttons below to tell the initial charge of the marble.

Red: \(+0.4 \mu \text{C}, -0.2 \mu \text{C}\)
Blue: \(+0.4 \mu \text{C}, -0.2 \mu \text{C}\)
Green: \(+0.4 \mu \text{C}, -0.2 \mu \text{C}\)
Black: \(+0.4 \mu \text{C}, -0.2 \mu \text{C}\)

**Section 8 - Inducing an electric charge**

8.1 A pack of 100-dollar bills is charged so that each bill has a charge of \(-0.0100 \mu \text{C}\). The pack is suspended by an insulating thread inside of a neutral safe made out of a conducting metal. No charge can flow between the bills and the safe, or the safe and its surroundings. (a) Explain how the induced charge effect will change the distribution of charges on the safe. (b) A burglar knows that there is no net electrical charge on the safe. If the charge on the outer surface has magnitude \(-4.00 \mu \text{C}\), what is the charge on the inner surface of the safe? (c) How much money is in the safe?

(a) 
(b) \( \mu \text{C} \)
(c) \( \text{dollars} \)

**Section 9 - Coulomb's law: calculating electrostatic forces**

9.1 Two grapes are given equal charges and held apart at a distance of 1.3 m. They experience a repulsive force of 2.2 N. Find the magnitude of the charge on each grape.

\[ \text{C} \]

9.2 Two 2.0 kg plastic garbage cans are sitting 2.6 meters apart on a sticky classroom floor (coefficient of static friction \( \mu_s = 0.40 \)). They are not moving. If the first one has a charge of 10 \( \mu \text{C} \), find (a) the most negative possible charge and (b) the most positive possible charge for the other garbage can. Assume that the charges can be represented as point charges located at the cans' centers.

(a) \( \mu \text{C} \)
(b) \( \mu \text{C} \)

9.3 Two positively charged skaters, Stacy and Bob, are traveling straight towards each other on frictionless ice. Consider them to be point charges. When they are 5.0 m apart, Stacy feels an attractive electric force of 2.2 N towards Bob. (a) What is the magnitude of the attractive force that Bob feels from Stacy? (b) The magnitude of Stacy's charge is twice as much as Bob's. What is the magnitude of Bob's charge? (c) Bob has twice the mass that Stacy does. At the instant that they are 5.0 m apart, from Bob's reference frame, Stacy appears to be moving towards him with an acceleration of \(7.3 \times 10^{-2} \text{ m/s}^2\). Find Stacy's mass.

(a) \( \text{N} \)
(b) \( \mu \text{C} \)
(c) \( \text{kg} \)

**Section 10 - Sample problem: electric vs. gravitational force**

10.1 The single electron and the single proton in a hydrogen atom in its lowest energy state are separated by a tiny distance called the Bohr radius, \(5.29 \times 10^{-11} \text{ m}\). Both particles carry a charge of magnitude \(e = 1.60 \times 10^{-19} \text{ C}\). (a) Is the force between them attractive or repulsive? (b) What is the magnitude of the force?

(a) i. Attractive
   ii. Repulsive
(b) \( \text{N} \)
10.2 Two steel juggling balls each carry a charge of 2.75 $\mu$C. There is a repulsive force between them of 1.45 N. What is the distance between the centers of the two balls?

\[ \text{m} \]

10.3 Two balls of radius 2.00 mm have a separation between their centers of 5.33 cm. The same electric charge is placed on both balls so that there is a repulsive force between them of 2.75 N. Assume that the charge is uniformly distributed over each ball. What is the magnitude of the charge?

\[ \text{C} \]

Section 12 - Superposition of electrostatic forces

12.1 Goldilocks is visiting the Three Bears' house and she notices three bowls of porridge arranged on the table. Papa Bear's porridge has a positive charge of +2.0 $\mu$C and is too hot. Mama Bear's porridge has a charge of $\pm 2.0 \mu$C and is too cold. Baby Bear's porridge is just right and has a charge of +1.0 $\mu$C. If the bowls are in an equilateral triangle (with sides 0.50 m) what is the magnitude of the net force on Baby Bear's bowl?

\[ \text{N} \]

12.2 A doorframe is twice as tall as it is wide. There is a positive charge on the top left corner and an equal but negative charge in the top right corner. What is the direction of the electric force due to these charges on a negatively charged dust mite in the bottom left corner of the doorframe?

\[ \text{°} \]

12.3 Particles $P_1$ and $P_2$ are located in three dimensional space at the points (2.00, -3.50, 1.75) mm and (-3.50, 2.25, -2.00) mm. These particles carry charges of +3.00 $\mu$C and +4.50 $\mu$C respectively. What is the magnitude of the net force they exert on another particle $P_3$, with charge $-3.50 \mu$C, located at the origin?

\[ \text{N} \]

12.4 A positively charged ant is crawling through a plastic drinking straw with non-zero charges on both ends. One end is located at $x = 0$ and the other is located at $x = 10$ cm. The ant experiences zero net electric force at $x = 3.0$ cm. (a) Can you say whether the ends are positively or negatively charged? (b) Which end has a charge with greater magnitude? (c) Find the ratio of the charge at the 0 cm end to the charge at the 10 cm end. Express your answer as a decimal number.

(a)  \( \bigcirc \) Yes  \( \bigcirc \) No
(b)  \( \bigcirc \) The 0 cm end  \( \bigcirc \) The 10 cm end
(c)  \[ \bigcirc \]
12.5 Two positively charged objects and two negatively charged objects are kept in the corners (NE, NW, SW, and SE) of a square dorm room. The charge on each object has the same magnitude, $Q$, and no more than one charge can be kept in a corner. Describe the configuration of charges if the net force on a positive test charge in the center of the room (a) is zero and the charge in the NE corner is $+Q$, (b) points north, and (c) points west.

(a) NW corner
   i. $+Q$
   ii. $-Q$

(b) NE corner
   i. $+Q$
   ii. $-Q$

(c) SW corner
   i. $+Q$
   ii. $-Q$

12.6 A bicycle wheel with radius 35 cm has 73 charges (1.0 $\mu$C each) spaced at regular intervals along its edge. A flea with charge $-0.010 \mu$C lands in the center of the wheel. (a) What is the net electric force on the flea? (b) One of the charges is removed. Find the magnitude of the new net electric force on the flea.

(a) $\gamma$ N
(b) $\delta$ N

12.7 A mad scientist is designing a trap for intruders that will lift them up into the air and hold them helpless. The device consists of an equilateral triangle, 10.0 meters to a side, embedded in his floor. When he flips a switch, the corners of the triangle will be charged equally by a generator and any negatively charged object above the center of the triangle will be lifted upwards by the electric force. A computer-controlled system of giant fans keeps the intruder from straying horizontally from the center of the triangle. While he is testing the system, his cat walks into the trap. She has a net charge of $-1.00$ nanocoulombs due to electrons that rubbed off from the carpet. The cat, which has a mass of 5.00 kg, begins to hover 3.00 meters up in the air. Find the charge on each corner of the triangle.

$\gamma$ C

12.8 Four particles with charges of $+1.00 \mu$C, $-2.00 \mu$C, $+3.00 \mu$C, and $-4.00 \mu$C are located at the points (0, 0), (2.00, 0) cm, (2.00, 4.00) cm, and (0, 4.00) cm, respectively. What are the magnitude and direction of the total force they exert on a particle of charge $+5.00 \mu$C located at (1.00, 2.00) cm?

$\gamma$ N, directed in the i. positive $x$ direction
   ii. negative $x$
   iii. positive $y$
   iv. negative $y$

12.9 Three particles $P_1$, $P_2$, and $P_3$ are located at the points $(-2.00, -1.00)$ m, (0, 2.00) m, and (3.00, $-1.00$) m, respectively. $P_1$ has a charge of 5.35 $\mu$C, $P_2$ has a charge of 6.03 $\mu$C, and $P_3$ has a charge of $-2.75$ $\mu$C. What are the magnitude and direction of the net force these three particles exert on a fourth particle of charge 2.50 $\mu$C, located at the origin?

$\gamma$ N, directed $\gamma$ C
   i. above the $x$-axis.
   ii. below

12.10 Three particles $P_1$, $P_2$, and $P_3$ are located at the points $(-2.00, -1.00)$, (0, 2.00), and (3.00, $-1.00$), respectively. $P_1$ has a charge of 5.00 $\mu$C, but the charges of $P_2$ and $P_3$ are unknown. However, the three particles exert no net force on a charged particle that is placed at the origin. You are asked to find the unknown charges. (a) Use the fact that the net horizontal force on the particle at the origin is zero to find the unknown charge on $P_3$. (b) Then use the fact that the net vertical force on the particle at the origin is zero to find the unknown charge on $P_2$.

(a) Charge on $P_3$ is $\gamma$ $\mu$C
(b) Charge on $P_2$ is $\gamma$ $\mu$C
12.11 A six-sided die has a positive charge in the center of each face, and a negative charge embedded in the center. The charge on each face is proportional to the value on the face. The top side of the die is 6; the bottom is 1; the east is 4; the west is 3; the north face is 5; the south is 2. Find the direction of the electric force on the charge in the center. Express your answer as a vector of length one by stating its components in the up, east, and north directions.

The unit vector has components _______ in the up, _______ in the east, and _______ in the north directions.

Section 16 - Interactive summary problem: proton golf

16.1 Using the information given in the first interactive problem in this section, how many protons should be loaded onto the putter to sink the ball in the hole (without banking it off the wall)? Test your answer using the simulation.

_______ protons

Additional Problems

A.1 Hydrogen is a flammable, nontoxic, colorless, odorless, and tasteless gas. The U.S. produces 100 billion cubic feet per year of hydrogen for industry and for the space program. A hydrogen atom consists of an electron \( (9.11 \times 10^{-31} \text{ kg}) \) and a proton \( (1.67 \times 10^{-27} \text{ kg}) \). (a) What is the net charge of a hydrogen atom? (b) Find the ratio of the electric to the gravitational force between the electron and the proton \( (e 1.60 \times 10^{-19} \text{ C}) \). (c) Suppose we adjusted the mass of the proton so that the ratio is 1. What would be the new mass of the proton? (d) Instead, suppose we adjusted the elementary charge, \( e \), so that the ratio is 1. What would be the new elementary charge?

(a) _______ C
(b) _______ kg
(c) _______ C
(d) _______ C

A.2 A thin plastic pipe \( (0.60 \text{ kg/m}) \) pivots at the origin, and extends along the x axis from \( x = 0 \) to \( x = 3.0 \text{ m} \). There is a very light particle with \( 2.6 \mu \text{C} \) of charge plugging the pipe at \( x = 3.0 \text{ m} \). Another charged particle \(( -3.0 \mu \text{C} ) \) is at \( x = 3.0 \text{ m}, y = 1.0 \text{ m} \). Find (a) the magnitude of the initial torque on the pipe and (b) its initial angular acceleration. Assume that the xy plane is horizontal.

(a) _______ N \cdot \text{m}
(b) _______ \text{rad/s}^2

A.3 Two 0.600 kg oppositely charged basketballs are following a clockwise circular path on a frictionless, freshly waxed basketball court. The balls are on opposite sides of the circle at all times, and are 10.0 m apart. Their charges cause the balls to continue on the circular path at a speed of 1.20 m/s. (a) Determine the product of the charges on the basketballs. (b) Now assume the charge on the positively charged ball is twice the magnitude of the negatively charged one. Determine the charge on the negative ball. (c) Determine the charge on the positive ball. (d) The same basketballs are now 5.00 m apart, but they are still moving in a circular path. Determine their speed. (e) One of the basketballs now has a mass of only 0.550 kg. Is it still possible for the two balls to hold each other so that they travel along identical circular paths? Explain your answer.

(a) _______ C^2
(b) _______ C
(c) _______ C
(d) _______ m/s
(e) ☐ Yes ☐ No

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