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Chapter 15

Electrical Charges and Forces

Benjamin Franklin's famous kite experiment has been referred to many times, even though it is not known when, or if he even actually did the experiment at all. The major question of the day was "Is lightning an electrical phenomenon?"

Back in the mid 1700's, the longest spark that could be generated was about 1 inch long, so it was not obvious that powerful lightning bolts could be similar to the small sparks seen in laboratory experiments.

Popular legend explains that Franklin attached a metal key to the end of a kite string and flew the kite in a raging lightning storm. Because he knew the experiment would be dangerous, he most likely attached a second silk string to the key that insulated him from the electrical charges, and held onto that string. He did not do his experiments during the peak of the storm, but chose to fly the kite as the storm was beginning to form. He noticed, according to an account written several years later, that he did receive a shock when he touched his knuckle to the metal key. He determined that lightning exhibited the same properties as small static electricity sparks, and he was correct!

In this chapter, you will study how atoms are ultimately responsible for electrical charges. You learned in an earlier chapter that all atoms contain positive and negative charges, and now you will see that these charges are the very same ones that allow us to benefit from generating, conducting, and using electricity.

Key Questions

- ✓ What is the actual source of current in a household electrical system?
- ✓ After you rub a balloon on your hair, why can you then stick the balloon to a wall but not to a metal doorknob?
- ✓ How does a defibrillator work, and what does it have to do with electricity?

15.1 Electric Charge and Current

In chapters 13 and 14 we looked at how electricity is used and measured. Amps, volts, and ohms describe most of what you need to know to use electricity safely. However, we did really discuss what electricity *is* on the atomic level. What is current? What sort of thing can flow through solid metal? Why can a little electric motor do the work of two horses?

Positive and negative charge

The true cause of electric current

Virtually all the matter around you has electric charge because atoms are made of electrons and protons (and neutrons). Electrons have negative charge and protons have positive charge. The electrons and protons are usually stuck together in atoms and are unable to separate from each other. However, in electrical conductors (like copper) a few electrons are not stuck to their atoms, but are free to move around. These mobile electrons are the real cause of electric current!

Like charges repel and unlike charges attract

Whether two charges attract or repel depends on whether they have the same or opposite sign. A positive and a negative charge will attract each other. Two positive charges will repel each other. Two negative charges will also repel each other. The force between charges is shown in Figure 15.1.

Charge is measured in coulombs

The unit of charge is the **coulomb (C)**. The name was chosen in honor of Charles Augustin de Coulomb (1736-1806), the French physicist who performed the first accurate measurements of the force between charges. One coulomb is a *huge* amount of charge. A single proton has a charge of 1.602×10^{-19} coulomb (Figure 15.1). An electron has the exact same charge, only negative. The charge of an electron -1.602×10^{-19} coulomb.

Two types of charge

Electric charge, like mass, is a fundamental property of matter. An important difference between mass and charge is that there are two types of charge, which we call positive and negative. We know there are two kinds because electric charges can attract or repel each other. As far as we know, there is only one type of mass. All masses *attract* each other through gravity. We have never found masses that repel each other.

Vocabulary

coulomb, electrically neutral, charged, static electricity, Coulomb's law, electroscope, charging by contact, charging by friction, polarized, charging by induction

Objectives

- ✓ Distinguish between a positive and negative net charge.
- ✓ Explain the meaning of Coulomb's law.
- ✓ Describe different ways of charging an electroscope.

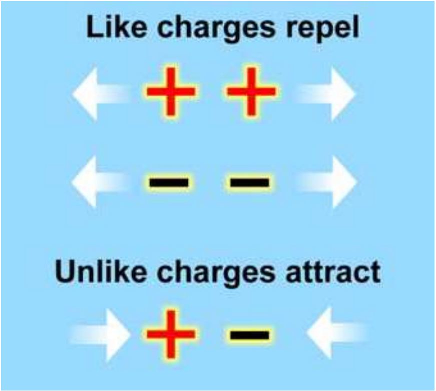


Figure 15.1: *The direction of the forces on charges depends on whether they have the same or opposite charges.*

Static electricity

Neutral objects

Matter contains trillions and trillions of charged electrons and protons because matter is made of atoms. Neutral atoms have the same number of electrons and protons. Therefore, the charge of an atom is *exactly zero*. Similarly, there is perfect cancellation between positive and negative in matter leaving a *net charge* of precisely zero. An object with a net charge of zero is described as being **electrically neutral**. Your pencil, your textbook, even your body are electrically neutral, at least most of the time.

Charged objects

An object is **charged** when its net charge is *not* zero. If you have ever felt a shock when you have touched a doorknob or removed clothes from a dryer, you have experienced a charged object. An object with more negative than positive charge has a net negative charge overall (Figure 15.2). If it has more positive than negative charge, the object has a positive net charge. The net charge is also sometimes called *excess* charge because a charged object has an excess of either positive or negative charges.

Static electricity and charge

A tiny imbalance in either positive or negative charge on an object is the cause of **static electricity**. If two neutral objects are rubbed together, the friction often pulls some electrons off one object and puts them temporarily on the other. This is what happens to clothes in the dryer and to your socks when you walk on a carpet. The static electricity you feel when taking clothes from a dryer or scuffing your socks on a carpet typically results from an excess charge of less than one-millionth of a *coulomb*, the unit of charge.

What causes shocks

You get a shock because excess of charge of one sign strongly attracts charge of the other sign and repels charge of the same sign. When you walk across a carpet on a dry day, your body picks up excess negative charge. If you touch a neutral door knob some of your excess negative charge moves to the door knob. Because the door knob is a conductor, the charge flows *quickly*. The moving charge makes a brief, intense electric current between you and the door knob. The shock you feel is the electric current as some of your excess negative charge transfers to the door knob (Figure 15.3).

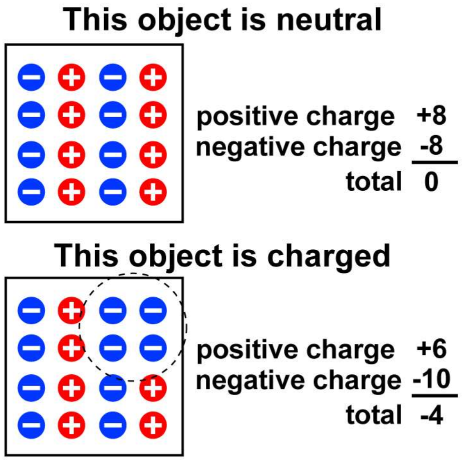


Figure 15.2: *An object is neutral if it has an equal number of positive and negative charges.*

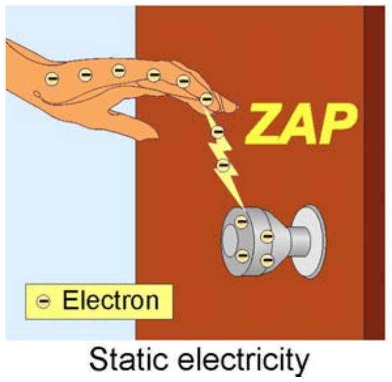


Figure 15.3: *The shock you get from touching a door knob on a dry day comes from moving charge.*

Coulomb's law

The force between charges is very strong

Electric forces are so strong it is hard to imagine. A millimeter cube of carbon the size of a pencil point contains about 77 coulombs of positive charge and the same amount of negative charge. If you could separate all the positive and negative charges by a distance of one meter, the attractive force between them would be 50 thousand billion newtons. This is the weight of three thousand, *million* cars. From the charge in a pencil point (Figure 15.4)! The huge forces between charges are the reason objects are electrically neutral.

More charge means more force

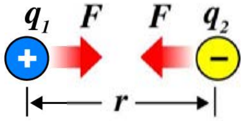
The force between two charges depends on the charge and the distance. The force is directly proportional to the charge of each object. The greater the charge, the stronger the force. Doubling the charge of one object doubles the force. Doubling the charge of both objects quadruples the force.

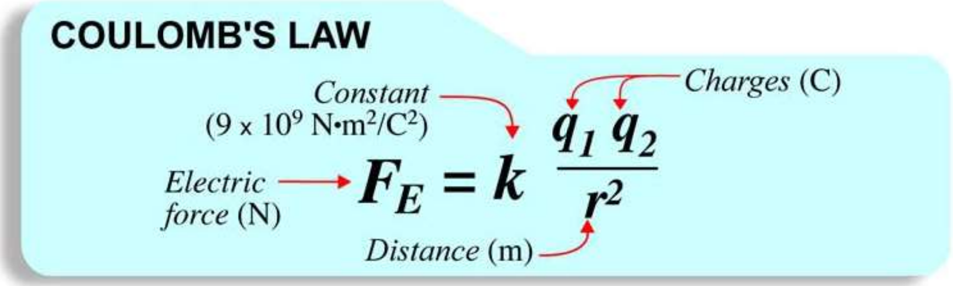
Less distance means more force

The force is inversely proportional to the square of the distance between the charges (Figure 15.5). Electric forces get stronger as charges move closer and weaker as they move farther apart. Doubling the distance makes the force 1/4 as strong ($1 \div 2^2$). The force is $^1/_9$ as strong ($1 \div 3^2$) at triple the distance.

Coulomb's law

Coulomb's law explains the relationship between the amount of each charge (q_1 and q_2), the distance between their centers (r), and the electrical force (F_E). The constant k relates the distance and charges to the force. Coulomb's law is very similar to Newton's law of gravitation (chapter 6).





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

Action-reaction pairs

The force between two charges acts along a line joining their centers. As required by Newton's third law of motion, the forces on each charge make an action-reaction pair. They are equal in strength and opposite in direction.

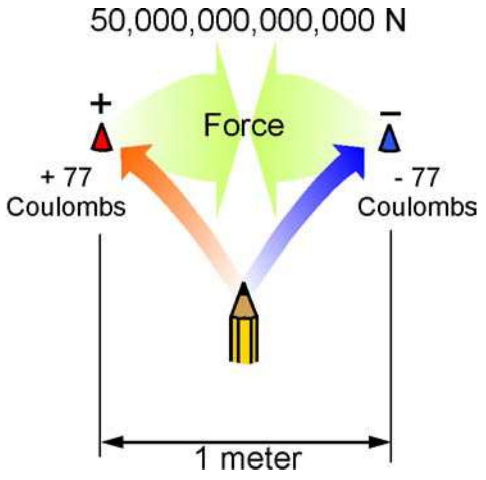


Figure 15.4: *If you could separate the positive and negative charge in a pencil point by one meter, the force between the charges would be 50 thousand, billion newtons!*

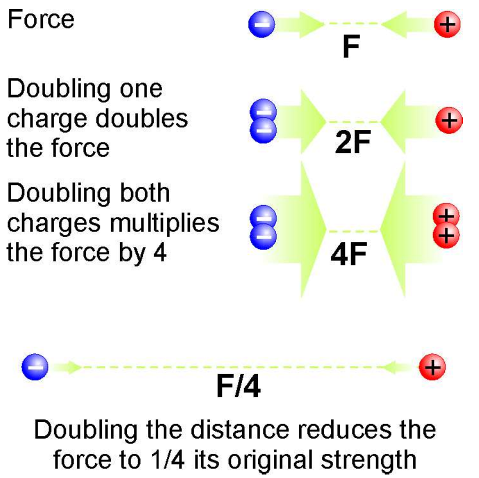


Figure 15.5: *How the electric force changes with charge and distance in Coulomb's law.*

Electrostatics

What is electrostatics? Electrostatics is the part of physics that deals with the forces created by unmoving charges. A conventional television uses electrostatics to create pictures. The tiny transistors inside a computer also work on electrostatics.

The picture tube and electron guns The working part of a television is the picture tube. At the back of the picture tube are three electron guns which make beams of electrons. The beams of electrons go back and forth across the front of the picture tube drawing the picture by lighting up colored dots called *phosphors*. An electron gun has three key parts: an emitter of electrons, a control grid, and an accelerator. The emitter is heated to a high temperature so electrons “boil off” its surface. The accelerator uses electric force to attract the electrons from the emitter.

Acceleration by electric fields in the electron gun The accelerator is kept at a high positive charge relative to the emitter. The electric force accelerates the negatively charged electrons from the emitter towards the accelerator. The beam is created by the electrons that pass through a small hole in the accelerator. Of course, some of the electrons also hit the accelerator plate itself and go back through the circuit. In a true electron gun, the shape of the accelerator steers most of the electrons through the hole and not into the plate (Figure 15.7).

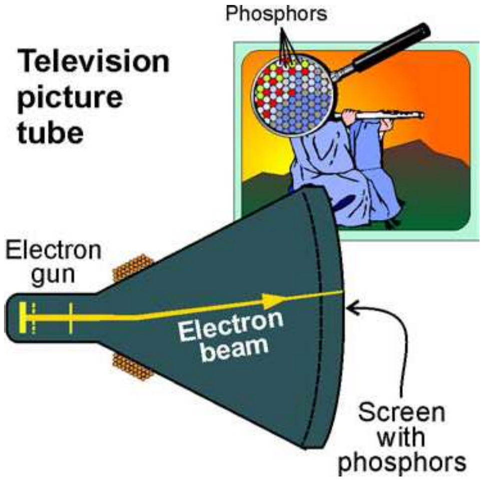


Figure 15.6: *The working parts of a conventional television.*

Using Coulomb's law

Two steel marbles are each given a net charge of one thousandth (0.001) of a coulomb. Calculate the size of the force on the marbles if they are held 2 meters apart.

1. Looking for: You are asked for the electric force in newtons.

2. Given: Two charges (0.001 C each) and the distance in meters.

3. Relationships: $F_E = k\dfrac{q_1 q_2}{r^2}$

4. Solution: $F_E = (9\times10^9\ \mathrm{N\cdot m^2/C^2})\dfrac{(0.001\ \mathrm{C})(0.001\ \mathrm{C})}{(2\ \mathrm{m})^2} = 2250\ \mathrm{N}$

Your turn...

a. Calculate the size of the force if the marbles are held 4 m apart. **Answer:** 563 N

b. Calculate the size of the force between 3 C and 4 C charges 500 m apart. **Answer:** 432,000 N

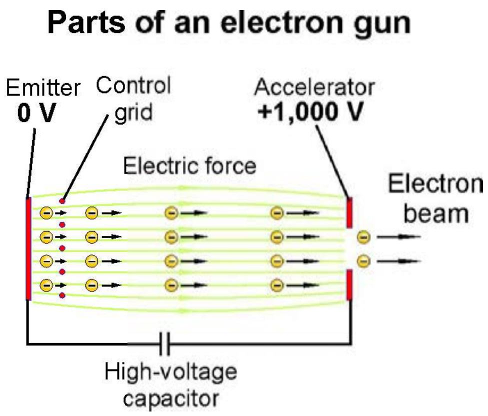


Figure 15.7: *An electron gun uses the attraction from a positively charged plate (accelerator) to create a beam of moving electrons.*

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The electroscope

Electrons and static electricity

Electric forces are so strong that a “charged” object is really almost completely neutral. A tiny excess of charge, smaller than 1 part in a million, is enough to cause the “static electricity” effects we observe. Since electrons are small, light, and on the outside of atoms, almost all electrical effects are caused by moving electrons. A negatively charged object has an excess of electrons. A positively charged object is missing some electrons.

Charge spreads out in a conductor

Electrons in a conductor are free to move around. If a conductor has an excess of electrons, they repel each other with strong forces. The repelling forces cause the electrons to move as far away from each other as they can get. That means excess electrons spread out evenly over the surface of any conductor and flow along the conductor wherever they can get farther away from each other.

Electroscopes

The force between charges can be observed with an **electroscope**. An electroscope is an instrument that contains two very thin leaves of metal that can swing from a central rod (Figure 15.8) which may have a ball on it. Electrons can flow freely between the leaves, ball, and rod.

Observing electric forces

Suppose a negatively charged rod is held above (but not touching) a neutral electroscope. Free electrons in the electroscope are repelled by the rod and move from the ball down into the leaves. The leaves now have an excess of electrons. This gives the leaves a net negative charge and they repel each other. If the rod is pulled away, the excess electrons return to the ball, making the leaves neutral again.

Testing for positive or negative

If the rod touches the metal ball, some electrons are transferred to the electroscope. This is called **charging by contact**. The electroscope now has excess electrons all over it, so both leaves are negative and they repel. A charged electroscope can be used to test other charged objects. If a negative rod is brought close to the electroscope, the excess electrons in the ball move down to the leaves and they spread farther apart. But if a positive rod is held near the electroscope, electrons are attracted to the rod. They move away from the leaves and into the ball. Because the leaves have lost some excess electrons, they do not repel as strongly and fall toward each other.

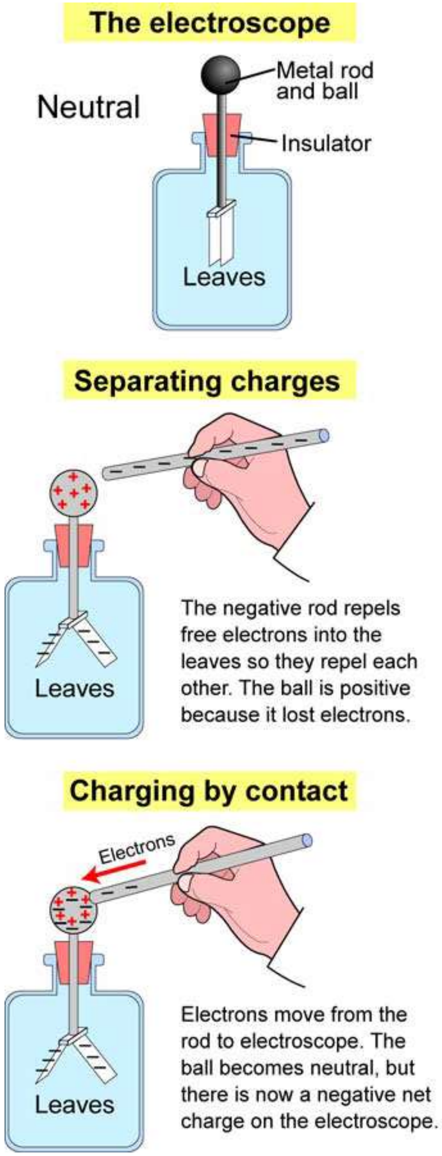

Figure 15.8: *You can use an electroscope to observe electric forces.*

Static electricity, charge polarization, and induction

Charging by friction

If you rub a balloon on your hair, you can make it stick to a wall but not to a metal doorknob. When the balloon and your hair are rubbed together, electrons are transferred from your hair to the balloon. This is called **charging by friction**. Because the balloon gains electrons, it has a negative net charge. Your hair loses electrons, so it has a net positive charge.

Polarization

When the balloon is brought near the wall, electrons inside atoms near the wall's surface are slightly repelled toward the far side of the atom. The wall's atoms become **polarized** — one end positive, the other negative (Figure 15.9). The balloon is both attracted to the positive side of each atom and repelled by the negative side. The attractive force is stronger because the positive side of each atom is closer to the balloon than the negative side.

Conductors

If the balloon is brought toward a doorknob or other conductor, it doesn't stick. Because electrons in the doorknob can move freely, they repel to the opposite side of the doorknob as the balloon approaches. The side of the doorknob near the balloon becomes positively charged. The balloon first attracts the doorknob. But when the two touch, some of the balloon's excess electrons move onto the doorknob because it is a conductor. When the doorknob gains electrons, it becomes negative like the balloon and they repel.

Charging by induction

Charging by induction is a method of using one object to charge another without changing the net charge on the first (Figure 15.10). Suppose you hold a negative balloon close to an electroscope. The balloon repels the electroscope's electrons, so they move down into the leaves. If you touch the ball (*grounding* the electroscope), electrons are repelled onto your finger. If you remove your finger, the electroscope is left with a net positive charge.

15.1 Section Review

1. Explain how there can be charge inside matter yet the matter is electrically neutral.
2. Write down Coulomb's law and explain what the symbols mean.
3. Explain the difference between an electrically charged and a neutral object.
4. Explain two ways to charge an electroscope.

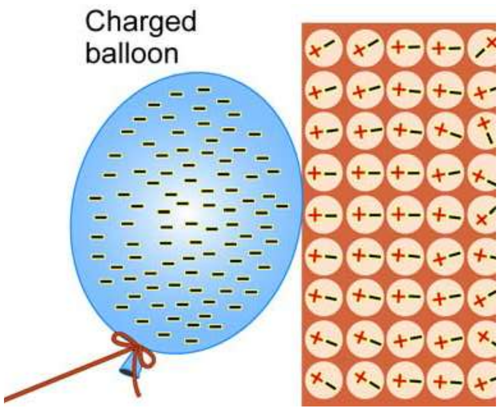

Figure 15.9: *A negative balloon sticks to a neutral wall.*

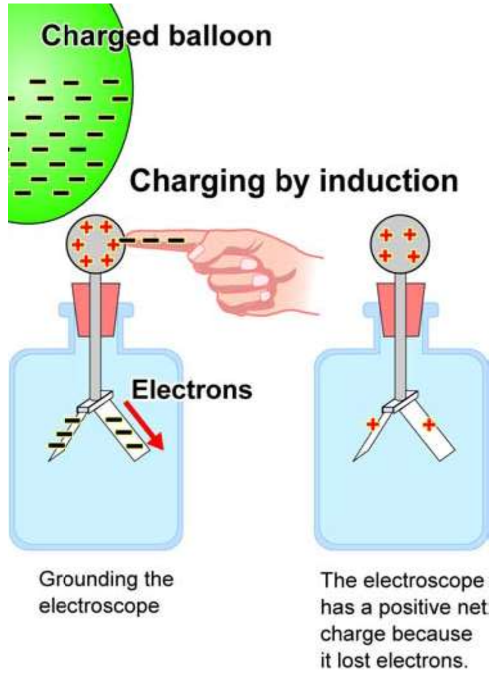

Figure 15.10: *When a balloon charges the electroscope through induction, the charge on the balloon is not disturbed.*

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15.2 Electric Current, Resistance, and Voltage

In Chapter 13 we said electric current was what flowed and could do work. We can now say current is the *movement* of electric charge. Electric charge is always there, but it may not be moving. Current flows when charges move. One ampere is a flow of one coulomb per second. Higher current means more charge flows per second. For example, a current of 10 amperes means that 10 coulombs of charge flow every second.

Vocabulary

superconductor

Objectives

- ✓ Describe the relationship between electrons and current.
- ✓ Explain, at the atomic level, the difference between insulators, semiconductors, conductors.
- ✓ Identify how voltage and charge are related.

Charge and current

Current is the flow of charge Electric current is the flow of charge. If the current in a wire is one ampere, one coulomb of charge passes by a point in the wire in one second. The unit ampere is a shorter way of saying “coulomb per second.”

> If the current in a wire is one ampere, one coulomb of charge passes by a point in the wire in one second.

Positive and negative Benjamin Franklin first used the terms “positive” and “negative” to describe charge. He believed electricity was a type of fluid. He thought positive objects had too much and negative objects had too little of the fluid. According to Franklin’s theory, a positive object’s extra fluid naturally flowed toward a negative object. The flow would stop when each had the right amount and became neutral.

The direction of current Because of Franklin’s work, the direction of electric current is defined as going *from positive to negative*. Long after Franklin’s work, scientists discovered that current in wires is the flow of *electrons*. The direction in which electrons move in a circuit is *from negative to positive*, opposite the way current was defined earlier (Figure 15.11).

Current is from positive to negative We still define current as going from positive to negative. For ordinary electric circuits it does not matter that negative electrons are really moving the other way. In a conductive liquid such as salt water, both positive and negative charges can move to create current. No matter what the sign of the moving charges, current is always defined as flowing from positive voltage to negative voltage.

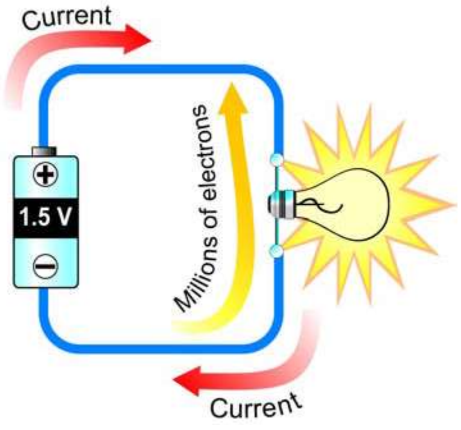
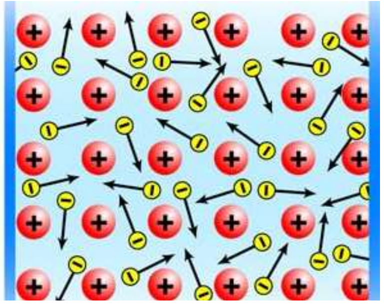


Figure 15.11: *Electrons move from negative to positive, but the conventional direction of current is from positive to negative.*

The source of current

Electron motion



When atoms of a metal (like copper) are together they all bond together by sharing electrons. In some ways a solid piece of copper acts like a single huge molecule. Some *valence electrons* can move freely anywhere within the copper. The copper atoms (⊕) with the remaining electrons are bonded together and stay fixed in place.

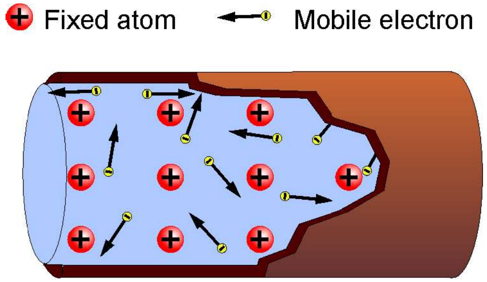
If a copper wire is not connected to a battery, the free electrons bounce around at high speeds. They have no average motion because as many are going one way as the other way. However, the free electrons move energy very effectively, so metals are good conductors of *heat* as well as electricity.

Drift velocity

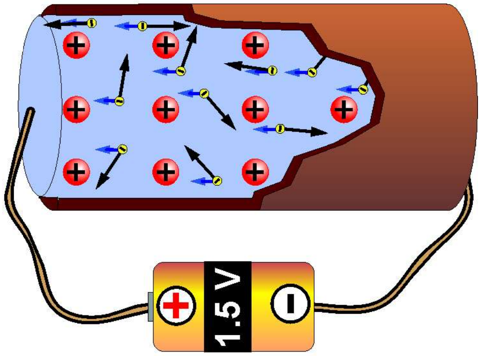
If a battery is connected across a copper wire, the free electrons are attracted to the positive terminal and repelled by the negative terminal. However, the electrons do not move directly from one end of the wire to the other because the copper atoms are in the way. Instead, the electrons bounce off the atoms while slowly making their way toward the positive end of the battery. The electric force created by the battery voltage creates a slow drift velocity in one direction on top of the electron's random bouncing (Figure 15.12). This slow *drift velocity* is what creates electrical current. The bouncing transfers some energy from the drift motion to the copper atoms. This explains how wires heat up when current is passed through them.

The source of current carrying electrons

With a 1.5 volt battery the drift velocity is slower than a turtle, a few millimeters per second. So why does the bulb light up instantly? The electrons carrying current in a wire *do not come from the battery.* Current flows because the voltage from a battery makes electrons move that are *already in the wire.* This is why a light bulb goes on as soon as you flip the switch. A copper wire contains many electrons bouncing randomly around. Without an applied voltage, as many electrons bounce one way as the other. There is no net flow of electrons and no electrical current. When a voltage is applied all the free electrons in the wire start drifting because of the electric force.



No voltage
electrons have only random motion
no average current



Applied voltage
electrons have random motion plus
small drift velocity
current flows

Figure 15.12: *When a voltage is applied across a wire, electrons slowly drift while randomly colliding with atoms in the wire.*

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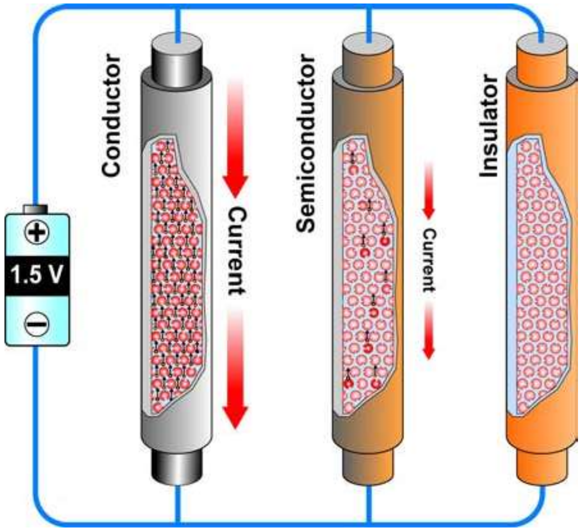
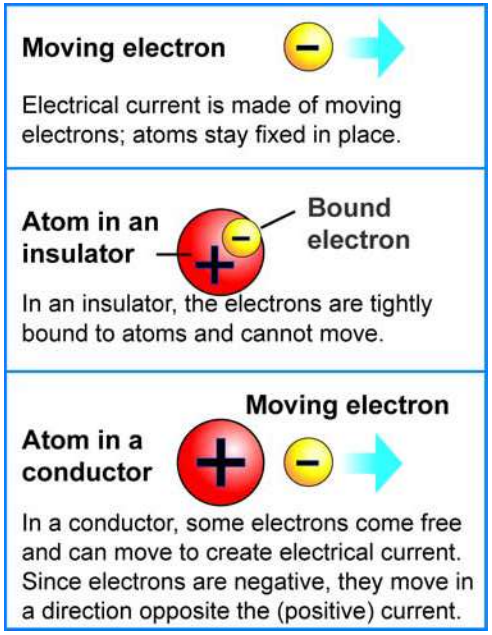
Conductors, insulators, and resistance

Insulators The electrons in insulators are not free to move — they are tightly bound inside atoms (Figure 15.13). Since the atoms are fixed in place, the electrons in insulators are also fixed in place. Insulators have very high resistance because there are no free electrons to carry any current.

Semiconductors A semiconductor has some free electrons, but not nearly as many as a conductor has. Semiconductors have a resistance in between conductors and insulators. The diagram below shows a model of the atoms and electrons in conductors, insulators, and semiconductors. The arrows on the electrons show the direction of their drift velocity (but not of their random bouncing).





Electrical current is made of moving electrons; atoms stay fixed in place.

In an insulator, the electrons are tightly bound to atoms and cannot move.

In a conductor, some electrons come free and can move to create electrical current. Since electrons are negative, they move in a direction opposite the (positive) current.

Figure 15.13: *In a conductor, some of an atom's electrons are free to move. In an insulator, all of the electrons are tightly bound to their atoms.*

Super-conductors Certain materials become **superconductors** when they are cooled to very low temperatures. For example, the metal alloy niobium-zirconium becomes a superconductor at -262°C. A superconductor carries electrical current with *zero resistance*. A current in a loop of superconducting wire will keep flowing forever, even without a battery! An electric motor made with superconducting wires would be far more efficient than one made with copper wires. Many researchers are searching for superconductors that work at normal temperatures.

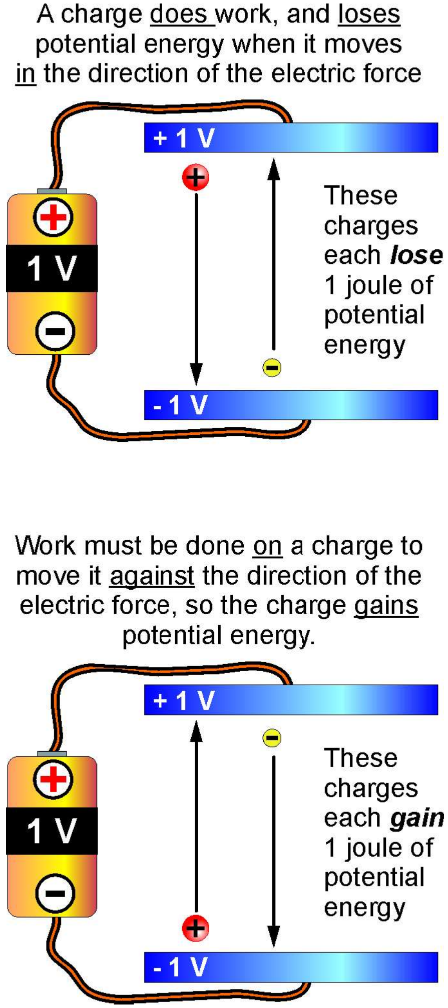
Voltage and charge

Current and voltage In chapter 13 you learned that current flows in response to differences in voltage. If one point in a circuit is at 3 volts and another is at zero volts, current will flow toward the point at zero volts and away from the point at 3 volts. We now know current is moving charge. How do we understand voltage in terms of charges?

A volt is a joule per coulomb Voltage measures electrical potential energy *per unit of charge*. One volt is one joule per coulomb. That means one coulomb of charge that moves through a difference of one volt gains or loses one joule of potential energy. The charge *loses* one joule if it goes from higher voltage to lower voltage. This is what happens in a device that uses energy, like a light bulb. The charge *gains* one joule if it moves from lower voltage to higher voltage. This is what happens inside a battery. A battery transforms chemical energy to electrical energy.

Joules or watts? This new definition of a volt is really the same as our old one. In terms of charge, one volt is a joule per coulomb. One amp is a coulomb per second, and a watt is a joule per second. If you work the units out you can prove to yourself that a joule per coulomb (charge) is exactly the same as a watt per amp (current).

$$\text{Volt} = \frac{\text{Watt}}{\text{Amp}} = \frac{\left(\frac{\text{Joule}}{\text{Second}}\right)}{\left(\frac{\text{Coulomb}}{\text{Second}}\right)} = \frac{\left(\frac{\text{Joule}}{\cancel{\text{Second}}}\right)}{\left(\frac{\text{Coulomb}}{\cancel{\text{Second}}}\right)} = \frac{\text{Joule}}{\text{Coulomb}}$$


A charge does work, and loses potential energy when it moves in the direction of the electric force

Work must be done on a charge to move it against the direction of the electric force, so the charge gains potential energy.

Figure 15.14: *A charge of 1 coulomb can either gain or lose 1 joule of energy by moving across a voltage difference of 1 volt.*

15.2 Section Review

1. Explain what it means to say an object has a positive net charge.
2. What flows when there is a current in a wire?
3. How can charges in a circuit move at high speeds while having a slow drift velocity?
4. Why is it easy to create a current in a conductor and not in an insulator?

15.3 Capacitors

The circuits you have studied so far contained only wires, batteries, switches, and resistors such as bulbs. In these circuits, the current stops immediately when the source of voltage is removed. This section discusses a device called a *capacitor* which stores charge. If the voltage is removed from a circuit containing a capacitor, the current keeps going for a while, until all the capacitor's stored charge has flowed out. Almost all electric appliances, including televisions, cameras, and computers, use capacitors in their circuits. Capacitors are also a useful tool for investigating the relationship between electric charge, voltage, and current.

Vocabulary

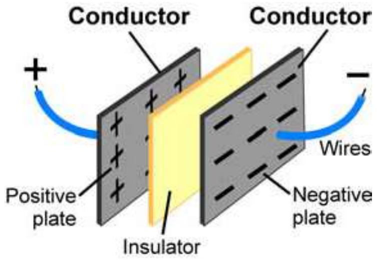
capacitor, capacitance, farad

Objectives

- ✓ Describe what happens in a capacitor as it charges.
- ✓ Recognize that current decreases over time as a capacitor charges or discharges.
- ✓ Explain the factors that determine how much charge a capacitor holds.

A capacitor is an energy storage device

A capacitor stores energy



A **capacitor** is a device that stores electrical energy by keeping positive and negative charges separated. The simplest type of capacitor is made of two parallel plates with an insulator between them. Both plates of the capacitor start out neutral. Energy is stored in the capacitor by transferring electrons from one plate to the other. The greater the number of electrons transferred, the greater the amount of stored energy. The plate that gains electrons gets a negative net charge, and the one that loses electrons gets an equal but opposite positive net charge.

Using a capacitor's stored energy

Once a capacitor's plates are charged, it has a voltage and can drive current in a circuit. A capacitor is connected just like a battery (Figure 15.15). The positive plate attracts free electrons, and the negative plate repels them. This creates a voltage and current flows out of the capacitor from positive to negative just as it would be with a battery. Eventually the positive plate has gained enough electrons for it to be neutral and the negative plate has lost all its excess electrons. The current stops and the voltage of the capacitor drops to zero. A camera flash uses a capacitor in this way. When you press the button to take a picture, you close the circuit between the flash and a charged capacitor. The current is large, so the capacitor's energy is converted very quickly into the light you see.

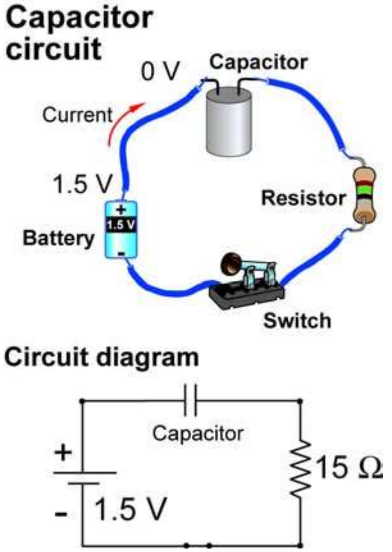


Figure 15.15: *A charged capacitor can create current in a circuit.*

Charging a capacitor

Equal and opposite charges

We say a capacitor is *charged* when one of its plates has a positive net charge and the other has a net negative charge. The amount of charge on each plate is the same but opposite in sign. Suppose one plate has a charge of +2 coulombs and the other has a charge of -2 coulombs. We say this capacitor's charge is 2 coulombs. However, the net charge on the *whole* capacitor is zero no matter how many electrons are transferred between the plates.

A battery can charge a capacitor

A capacitor can be charged by connecting it to a battery or any other source of voltage. In Figure 15.16, a capacitor, bulb, battery, and switch are connected in series. The capacitor's starts with zero charge and has zero voltage across its terminals. When the switch is closed, current flows and the capacitor builds up a charge separation on its plates. As the capacitor charges, a voltage develops across its terminals. The voltage keeps increasing until the capacitor has the same voltage as the battery. At this point, the capacitor has stored as much charge as it can for the voltage of the battery.

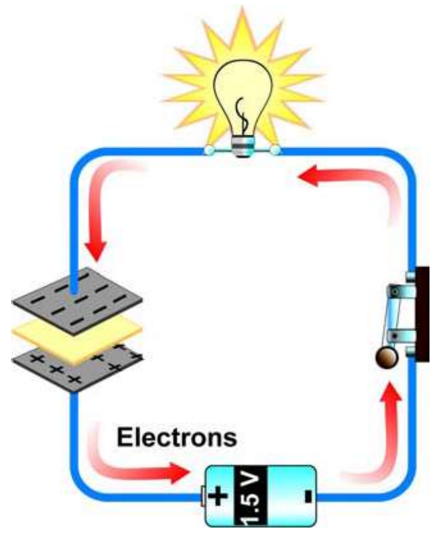


Figure 15.16: *A battery can be used to charge a capacitor.*

Current

The bulb is very bright at first, but gradually it becomes dim and eventually it goes out. The current starts out large and finally decreases to zero when the capacitor is fully charged (Figure 15.17). The amount of current and the time for the capacitor to charge is determined by the amount of resistance in the circuit. The greater the resistance, the smaller the current, and the longer the time needed to charge.

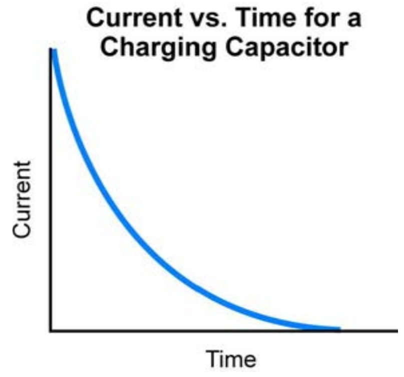


Figure 15.17: *The current starts out large but decreases as the capacitor charges*

Voltage

The voltage of the capacitor starts at zero when no charge is stored. As the charge increases, the voltage also increases. The energy stored in the capacitor also increases with its voltage.

Electrons enter one plate

Think about what happens on the capacitor's plates. One plate (which was neutral) gradually has electrons added to it. The excess electrons repel the new electrons trying to get on by increasing the capacitor's voltage. This is similar to what happens when people climb onto a bus. If the bus is empty, it is very easy for people to get on. As the bus fills up, it becomes more and more difficult for each additional person to get on. The current decreases because each new electron has to fight a higher repulsive voltage to get on. Eventually, the voltage reaches the battery voltage and current stops.

Table of Contents

Capacitance

Voltage and charge The amount of charge a capacitor will hold before the current stops depends on the voltage of the battery (or other source) that charges it. Voltage is what pushes the electrons onto the negative plate and pulls them from the positive plate. The higher the voltage, the greater the amount of charge on the capacitor when the current stops.

Measuring capacitance The amount of charge a capacitor will hold also depends on its **capacitance**. Capacitance is the measure of a capacitor's ability to store charge. It is measured in **farads (F)**. A one-farad capacitor attached to a 1-volt battery holds 1 coulomb of charge. A two-farad capacitor attached to the same battery holds 2 coulombs of charge.

Microfarads A coulomb is a huge amount of charge. Most capacitors hold much less than a coulomb of charge, and they have capacitances that are only a fraction of a farad. For this reason, capacitances are often measured in microfarads. One microfarad is 1×10^{-6} farad. A capacitor that supplies energy to a flash in a disposable camera is only about 200 microfarads and holds 0.02 coulombs of charge.

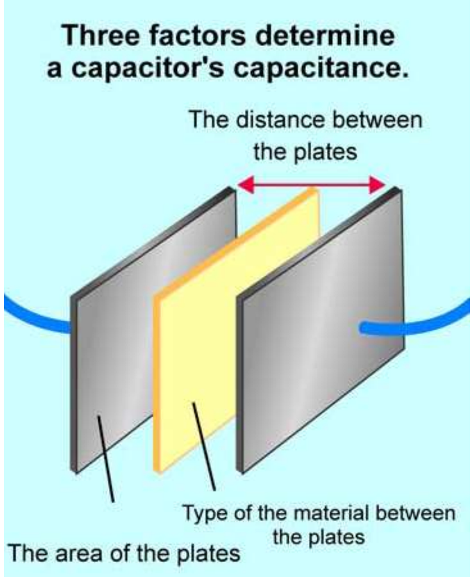


Figure 15.18: *Three factors determine a capacitor's capacitance.*

Factors determining capacitance The capacitance of a capacitor depends on three factors (Figure 15.18):

1. The greater the area of a capacitor's plates, the more charge it can hold, and the larger the capacitance.
2. The insulating material between the plates affects how much charge can be stored in a capacitor.
3. The smaller the separation distance between the plates, the greater the capacitance.

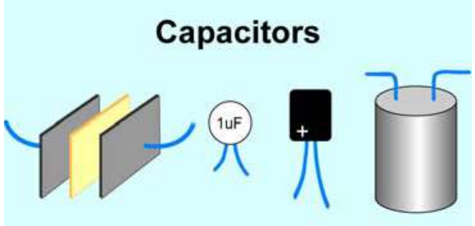


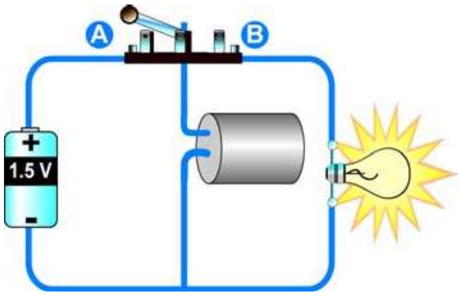
Figure 15.19: *There are many types of capacitors.*

Parallel plates are not practical Parallel plate capacitors are not practical to use in most devices because they must be large to store enough charge to be useful. If a capacitor's plates and insulating material are made of a flexible material, it can be rolled into the shape of a cylinder (Figure 15.19). This allows each plate to have a large area while the capacitor fits into a small space.

Discharging a capacitor

Discharging a capacitor A capacitor can be discharged by connecting it to any closed circuit that allows current to flow. A low-resistance circuit discharges the capacitor more quickly because the current is higher. Electrons are quickly removed from the negative plate and added to the positive plate. A capacitor is fully discharged when the two plates are both neutral and the voltage is zero.

Designing circuits When using a capacitor that will be charged and discharged, the circuit can be designed to change from charging to discharging with the flip of a switch. In the circuit shown at right, the capacitor charges when the switch is at position A. When it is flipped to position B, the battery is cut off and the capacitor discharges.



Capacitor safety If connected in a circuit with little resistance, a capacitor can discharge very quickly, creating a large amount of current. For this reason, capacitors can be very dangerous. When working with a capacitor, never hold it by its terminals. It is also important to always fully discharge a capacitor when you finish working with it.

15.3 Section Review

1. Traditionally, we say that current flows from positive to negative. Why is it more correct to say that current flows from negative to positive?
2. Explain, using electrons, why current flows.
3. Why does an insulator have high resistance? Why does a conductor allow current to flow? (Hint: use electrons to explain your answer)

Defibrillators

If you have ever seen doctors working in an emergency room on television or in a movie, you have probably seen a device called a *defibrillator*. A defibrillator uses an electric current to make a patient's heart start beating again after a heart attack or other trauma.

A defibrillator uses a capacitor to create a very quick but large current. Before using a defibrillator, doctors must wait a few seconds for the capacitor to charge. If a patient's heart doesn't start after one attempt, the voltage across the capacitor is increased. This provides more current to stimulate the heart.

Small portable defibrillators are being placed in schools, airports, and other public buildings. These devices have saved many lives by allowing trained people to help heart attack victims even before paramedics arrive.

Lightning

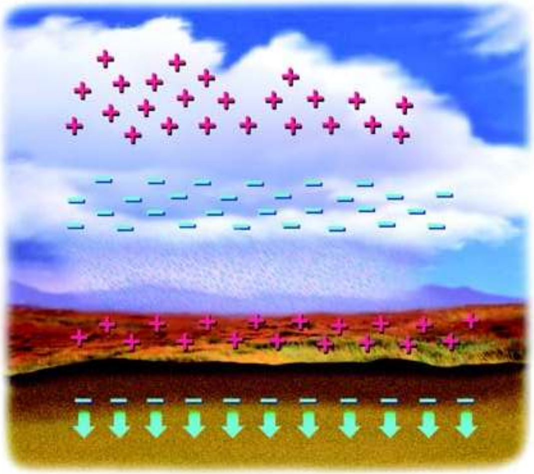
Have you ever scuffed your feet across a carpeted floor and then touched a metal doorknob?—Zap! You feel a static electric shock, and if the room is dark, you can see a quick flash of light.

The zap happens because contact between your shoes and the carpet transfers some of the carpet atoms' electrons to your feet. Your body acquires an excess negative charge. When you touch a conducting object like the doorknob, the excess charge moves from your hand to the metal in a flash.

Believe it or not, the same process that caused you to get zapped when you touched the doorknob creates the spectacular lightning displays you see on a stormy evening.

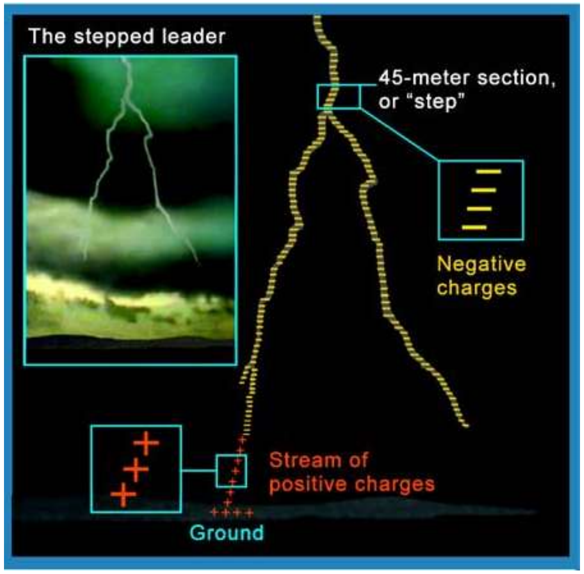
How does lightning get started?

Lightning originates in towering, dark storm clouds. Inside these clouds, charges begin to separate. Scientists still don't really understand how this happens. Some think that collisions between hailstones and ice crystals are responsible, while others speculate that friction between particles of ice and raindrops causes electrons to be ripped from some of the atoms.



While the mechanism is still a mystery, we do know that the bottom of the cloud acquires an excess negative charge (like your feet after you scuff them on the carpet). Warm updrafts carry the positively charged particles to the cloud's top.

The buildup of negative charges at the bottom of the cloud repels negative charges in the ground and attracts positive charges. The positively charged ground surface pulls the cloud's freed electrons downward. On their way down, these electrons crash into air molecules, knocking even more electrons out of place. All of these electrons would continue hurtling snowball-like toward the earth, if it weren't for a tug-of-war that begins with the positively charged particles in the top of the cloud.



The stepped leader

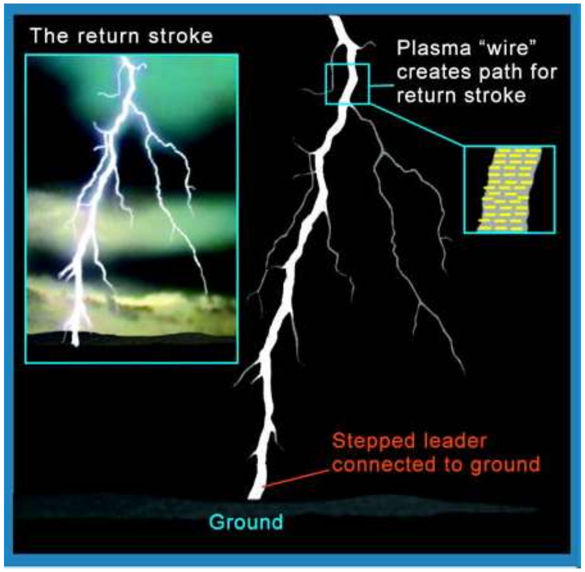
Those positive charges at the top of the cloud tend to pull slower-moving electrons back upward. But remember, as the storm develops, more charges separate in the cloud. Newly freed electrons pull the slow movers down again. This tug-of-war causes the initial downward path of electrons to move toward the ground in jerky 45-meter sections, or steps. This pathway is called the stepped leader.

Sometimes the stepped leader continues all the way down to the ground, but at other times, it will pull a stream of positive charges up to meet it about 100 meters above the ground. The stepped leader moves at about 390 kilometers per second, and takes about 5/1000 of a second to reach the ground. You can't see the stepped leader without using a special camera, because it moves so quickly and doesn't produce a lot of light.

A wire of plasma

The stepped leader is created as electrons knock other electrons off of air molecules. When these air molecules break apart, you end up with a pathway made of positive ions surrounded by a "sea" of electrons. That's a bit like what you find in a wire made of metal. The stepped leader creates a "wire" of *plasma* (a separate state of matter made up of ionized gas) in the atmosphere. This plasma wire, with all its freed electrons, conducts electricity extremely well.

The return stroke



Once the stepped leader is connected to the ground, an amazing surge of electrons moves along the plasma wire from cloud to ground, traveling 98,000 kilometers per second! The air glows like a super-bright fluorescent light. This "return stroke" is the lightning you see.

The return stroke drains the cloud of its freed electrons, but more charges are continually being separated in the cloud. As a result, an average of four lightning bolts in a row zing along a single path. That's why lightning sometimes seems to flicker.

Volts, amps, and lightning

Lightning bolts can deliver between 15,000,000 and 1,000,000,000 volts of electricity. Although the flow of charge is very brief, the current has been estimated at about 50,000 amps. That much current can cause a great deal of damage. If a lightning bolt strikes a tree, the sap may boil, and the buildup of vapor pressure can cause the tree to explode.

Questions:

1. Name two ways a lightning bolt is like a static shock.
2. How does the stepped leader create a "plasma wire" in the atmosphere?
3. Find out how to stay safe during a lightning storm. Create a poster with lightning safety tips.

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Chapter 15 Review

Understanding Vocabulary

Select the correct term to complete the sentences.

electric field
electrically neutral
electroscope
farads
coulomb
field lines
friction
induction
polarized
capacitor
static electricity
Coulomb's law

Section 15.1

1. The unit in which charge is measured is the _____.
2. An object is _____ when it has equal numbers of positive and negative charges.
3. _____ exists when there is an excess of one type of charge on an object.
4. _____ explains the relationship between electric force, charge, and distance.
5. Charging by _____ occurs when clothes brush against each other in the dryer.
6. A(n) _____ can be used to tell whether an object has a net charge.
7. If you use a charged balloon to charge a metal ball through _____, the balloon's net charge does not change.

Section 15.2

8. _____ are drawn to show the direction of the electric field.
9. An object is _____ if has a net positive charge on one side and a net negative charge on the other side.
10. There is a(n) _____ in the region around any charge.

Section 15.3

11. A _____ is used to store electrical energy by separating charge.
12. Capacitance is measured in _____.

Reviewing Concepts

Section 15.1

1. Protons are _____ charged, and electrons are _____ charged.
2. Like charges _____, and opposite charges _____.
3. What does it mean to say an object is electrically neutral?
4. In an object's net charge positive or negative if it loses electrons?
5. How many protons are needed to make one coulomb of charge?
6. How does the charge of an electron compare to the charge of a proton?
7. Why don't you usually notice electric forces between objects?
8. What two factors determine the amount of electric force between two objects?
9. What happens to the force between two charges as they are moved closer together?
10. Explain what happens to the force between two protons if each of the following occurs (consider each individually).
    a. The distance between them is cut in half.
    b. The distance between is doubled.
    c. The distance between them is tripled.
    d. One of the protons is replaced with an electron.
    e. One of the protons is replaced with two electrons.
11. Compare Coulomb's law to Newtons' law of gravitation.
12. Explain what happens inside an electroscope if a positively charged object is held above it without touching.
13. Explain how to charge an electroscope negatively through contact.
14. What happens to the charges in your hair and a balloon if you rub them together? What is this called?
15. Explain how to charge an electroscope positively through induction.

Section 15.2

16. How are the units *ampere* and *coulomb* related?

17. Ben Franklin defined current as going from _____ to _____. Now we know that electrons in a circuit move from _____ to _____.
18. Do all the electrons in a wire move to make the current in a circuit?
19. Does a battery supply the electrons to a circuit that create current in a circuit? Explain.
20. Why can current easily be created in a conductor but not in an insulator?
21. One volt equals one _____ of energy per _____ of charge. A volt is also equal to one _____ of power per _____ of current.

Section 15.3

22. What is a capacitor? What use do capacitors have?
23. What does it mean to say a capacitor is charged?
24. What happens to the current in a circuit as a capacitor charges? Why?
25. Which three factors affect a capacitor's capacitance?

Solving Problems

Section 15.1

1. What is the charge of 1000 electrons, measured in coulombs?
2. Find the net charge of an atom that contains
    a. 5 protons and 3 electrons
    b. 7 electrons and 6 protons
    c. 8 electrons and 8 protons
3. Six coulombs of charge pass through a wire in a time of two seconds. What is the current in the wire?
4. A wire carries a current of two amperes. How many coulombs of charge pass through the wire in 10 seconds?

Section 15.2

5. A circuit contains a 3 volt battery and a 2 ohm resistor.
    a. Calculate the current in the circuit.
    b. How many coulombs of charge pass by any point in the circuit in one second?
    c. How many coulombs of charge pass by any point in 2 seconds?
6. A battery provides 2 amperes of current in a circuit at a power of 6 watts. What is the battery's voltage?
7. A battery provides 6 joules of energy to 2 coulombs of charge in a circuit. What is the battery's voltage?

Section 15.3

8. How much charge does a 3 farad capacitor hold when charged with a 1.5 volt battery?
9. How much charge will a 6 farad capacitor hold if charged with a 1.5 volt battery?
10. How much charge will a 6 farad capacitor hold if charged with a 3 volt battery?

Applying Your Knowledge

Section 15.1

1. Static cling causes clothes to stick together when they come out of the dryer. What kinds of materials seem to stick together the most?
2. Static electricity is more often observed in dry weather than in damp weather. Why do you think this is?
3. How did Coulomb measure the force between electric charges? Research to find out the answer.
4. Conduct an experiment at home in which you charge an object by friction. You might use a balloon and hair or fleece, styrofoam and wool, or plastic and a tissue. Turn on a faucet so a narrow stream of water is created. Hold the charged object near the stream of water. What happens? What do you think is going on? Hint: water molecules are naturally polarized.

Section 15.2

5. Research superconductivity. Find out what it is and what applications it may have in the future.

Section 15.3

6. Research capacitors to find out how they are used in different electrical devices.