Lesson 1: Charge and Charge Interactions

Neutral vs. Charged Objects

As discussed in a previous section of Lesson 1, atoms are the building blocks of matter. There are different types of atoms, known as elements. Atoms of each element are distinguished from each other by the number of protons that are present in their nucleus. An atom containing one proton is a hydrogen atom (H). An atom containing 6 protons is a carbon atom. And an atom containing 8 protons is an oxygen atom.

The number of electrons which surround the nucleus will determine whether or not an atom is electrically charged or electrically neutral. The amount of charge on a single proton is equal to the amount of charge possessed by a single electron. A proton and an electron have an equal amount but an opposite type of charge. Thus, if an atom contains equal numbers of protons and electrons, the atom is described as being electrically neutral. On the other hand, if an atom has an unequal number of protons and electrons, then the atom is electrically charged (and in fact, is then referred to as an ion rather than an atom). Any particle, whether an atom, molecule or ion, which contains less electrons than protons is said to be positively-charged. Conversely, any particle which contains more electrons than protons is said to be negatively charged.

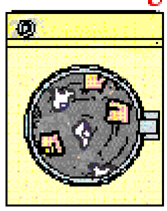
Charged versus Uncharged Particles

Positively Charged	Negatively Charged	Uncharged
Possesses more protons than electrons	Possesses more electrons than protons	Equal numbers of protons and electrons

Charged Objects as an Imbalance of Protons and Electrons

In the previous section of Lesson 1, an atom was described as being a small and dense core of positively-charged protons and neutral neutrons surrounded by shells of negatively charged electrons. The protons are tightly bound within the nucleus and not removable by ordinary measures. While the electrons are attracted to the protons of the nucleus, the addition of energy to an atom can persuade the electrons to leave an atom. Similarly, electrons within atoms of other materials can be persuaded to leave their own electron shells and become members of the electrons shells of other atoms of different materials. In short, electrons are migrants - constantly on the move and always ready to try out a new atomic environment.

Static Cling



The movement of electrons from material to material is the cause of static cling.

All objects are composed of these atoms. The electrons contained within the objects are prone to move or migrate to other objects. The process of an electron leaving one material object to reside (perhaps only temporarily) in another object is a common everyday occurrence. Even as you read the words of this web page, some electrons are likely moving through the monitor and adhering to your clothing (assuming that you are using this resource online) (and wearing clothes). If you were to walk across the carpeting towards the door of the room, electrons would likely be scuffed off the atoms of your shoes and moved onto the atoms of the carpet. And as clothes tumble in the dryer, it is highly likely that electrons on one piece of clothing will move from the atoms of the clothing onto the atoms of another piece of clothing. In general, for electrons to make a move from the atoms of one material to the atoms of another material, there must be an energy source, a motive, and a low-resistance pathway.

The cause and mechanisms by which this movement of electrons occur will be the subject of Lesson 2. For now, it is sufficient to say that objects that are charged contain unequal numbers of protons and electrons. Charged objects have an imbalance of charge - either more negative electrons than positive protons or vice versa. And neutral objects have a balance of charge - equal numbers of protons and electrons. The principle stated earlier for atoms can be applied to objects. Objects with more electrons than protons are charged negatively; objects with less electrons than protons are charged positively.

In this discussion of electrically charged versus electrically neutral objects, the neutron has been neglected. Neutrons, being electrically neutral play no role in this unit. Their presence (or absence) will have no direct bearing upon whether an object is charged or uncharged. Their role in the atom is merely to provide stability to the nucleus, a subject not discussed in The Physics Classroom. When it comes to the drama of static electricity, electrons and protons become the main characters.

Charge as a Quantity

Like mass, the charge of an object is a measurable quantity. The charge possessed by an object is often expressed using the scientific unit known as the Coulomb. Just as mass is measured in grams or kilograms, charge is measured in units of Coulombs (abbreviated C). Because one Coulomb of charge is an abnormally large quantity of charge, the units of microCoulombs (µC) or nanoCoulombs (nC) are more commonly used as the unit of measurement of charge. To illustrate the magnitude of 1 Coulomb, an object would need an excess of 6.25 x 1018 electrons to have a total charge of -1 C. And of course an object with a shortage of 6.25 x 1018 electrons would have a total charge of +1 C.

The charge on a single electron is -1.6 x 10 -19 Coulomb. The charge on a single proton is +1.6 x 10 -19 Coulomb. The quantity of charge on an object reflects the amount of imbalance between electrons and protons on that object. Thus, to determine the total charge of a positively charged object (an object with an excess of protons), one must subtract the total number of electrons from the total number of protons. This operation yields the number of excess protons. Since a single proton contributes a charge of +1.6 x 10 -19 Coulomb to the overall charge of an atom, the total charge can be computed by multiplying the number of excess protons by +1.6 x 10 -19 Coulomb. A similar process is used to determine the total charge of a negatively charged object (an object with an excess of electrons), except that the number of protons is first subtracted from the number of electrons.

This principle is illustrated in the following table.

Object	# of Excess Protons/Electrons	Quantity and Kind of Charge (Q) on Object in Coulombs (C)
A	1×10^{6} excess electrons	-1.6×10^{-13} C
B	1×10^{6} excess protons	$+1.6 \times 10^{-13}$ C

C	2 x 10^{10} excess electrons	-3.2 x 10^{-9} C
D	3.5 x 10^{8} excess protons	+5.6 x 10^{-11} C
E	4.67 x 10^{10} excess electrons	-7.5 x 10^{-9} C

In conclusion, an electrically neutral object is an object which has a balance of protons and electrons. In contrast, a charged object has an imbalance of protons and electrons. Determining the quantity of charge on such an object involves a counting process; the total number of electrons and protons are compared to determine the difference between the number of protons and electrons. This difference is multiplied by 1.6 x 10 -19 Coulombs to determine the overall quantity of charge on the object. The type of charge (positive or negative) is determined by whether the protons or the electrons are in excess.

Lesson 2: Electric Force

Coulomb's Law

The interaction between charged objects is a non-contact force which acts over some distance of separation. Charge, charge and distance. Every electrical interaction involves a force which highlights the importance of these three variables. Whether it is a plastic golf tube attracting paper bits, two like-charged balloons repelling or a charged Styrofoam plate interacting with electrons in a piece of aluminum, there is always two charges and a distance between them as the three critical variables which influence the strength of the interaction. In this section of Lesson 3, we will explore the importance of these three variables.

Force as a Vector Quantity

The electrical force, like all forces, is typically expressed in units of Newtons. Being a force, the strength of the electrical interaction is a vector quantity which has both magnitude and direction. The direction of the electrical force is dependent upon whether the charged objects are charged with like charge or opposite charge and upon their spatial orientation. By knowing the type of charge on the two objects, the direction of the force on either one of them can be determined with a little reasoning. In the diagram below, objects A and B have like charge causing them to repel each other. Thus, the force on object A is directed leftward (away from B) and the force on object B is directed rightward (away from A). On the other hand, objects C and D have opposite charge causing them to attract each other. Thus, the force on object C is directed rightward (toward object D) and the force on object D is directed leftward (toward object C). When it comes to the electrical force vector, perhaps the best way to determine the direction of it is to apply the fundamental rules of charge interaction (opposites attract and likes repel) using a little reasoning.

Determining the Direction of the Electrical Force Vector

Electrical force also has a magnitude or strength. Like most types of forces, there are a variety of factors which influence the magnitude of the electrical force. Two like-charged balloons will repel each other and the strength of their repulsive force can be altered by changing three variables. First, the quantity of charge on one of the balloons will affect the strength of the repulsive force. The more charged a balloon is, the greater the repulsive force. Second, the quantity of charge on the second balloon will affect the strength of the repulsive force. Gently rub two balloons with animal fur and they repel a little. Rub the two balloons vigorously to impart more charge to both of them, and they repel a lot. Finally, the distance between the two balloons will have a significant and noticeable affect upon the repulsive force. The electrical force is strongest when the balloons are closest together. Decreasing the separation distance increases the force. The magnitude of the force and the distance between the two balloons is said to be *inversely related*.

Coulomb's Law Equation

The quantitative expression for the affect of these three variables on electric force is known as Coulomb's law. Coulomb's law states that the electrical force between two charged objects is directly proportional to the product of the quantity of charge on the objects and inversely proportional to the square of the separation distance between the two objects. In equation form, Coulomb's law can be stated as

$$F = \frac{k \cdot Q_1 \cdot Q_2}{d^2}$$

where Q_1 represents the quantity of charge on object 1 (in Coulombs), Q_2 represents the quantity of charge on object 2 (in Coulombs), and **d** represents the distance of separation between the two objects (in meters). The symbol **k** is a proportionality constant known as the Coulomb's law constant. The value of this constant is dependent upon the medium that the charged objects are immersed in. In the case of air, the value is approximately 9.0×10^9 N • m^2 / C^2. If the charged objects are present in water, the value of **k** can be reduced by as much as a factor of 80. It is worthwhile to point out that the units on **k** are such that when substituted into the equation the units on charge (Coulombs) and the units on distance (meters) will be canceled, leaving a Newton as the unit of force.

The Coulomb's law equation provides an accurate description of the force between two objects whenever the objects act as **point charges**. A charged conducting sphere interacts with other charged objects as though all of its charge were located at its center. While the charge is uniformly spread across the surface of the sphere, the center of charge can be considered to be the center of the sphere. The sphere acts as a point charge with its excess charge located at its center. Since Coulomb's law applies to point charges, the distance **d** in the equation is the distance between the centers of charge for both objects (not the distance between their nearest surfaces).

The symbols Q_1 and Q_2 in the Coulomb's law equation represent the quantities of charge on the two interacting objects. Since an object can be charged positively or negatively, these quantities are often expressed as "+" or "-" values. The sign on the charge is simply representative of whether the object has an excess of electrons (a negatively charged object) or a shortage of electrons (a positively charged object). It might be tempting to utilize the "+" and "-" signs in the calculations of force. While the practice is not recommended, there is certainly no harm in doing so. When using the "+" and "-" signs in the calculation of force, the result will be that a "-" value for force is a sign of an attractive force and a "+" value for force signifies a repulsive force. Mathematically, the force value would be found to be positive when Q_1 and Q_2 are of like charge - either both "+" or both "-". And the force value would be found to be negative when Q_1 and Q_2 are of opposite charge - one is "+" and the other is "-". This is consistent with the concept that oppositely charged objects have an attractive interaction and like charged objects have a repulsive interaction. In the end, if you're thinking conceptually (and not merely mathematically), you would be very able to determine the nature of the force - attractive or repulsive - without the use of "+" and "-" signs in the equation.

Comparing Electrical and Gravitational Forces

Electrical force and gravitational force are the two non-contact forces discussed in The Physics Classroom tutorial. Coulomb's law equation for electrical force bears a strong resemblance to Newton's equation for universal gravitation.

$$F_{elect} = \frac{k \cdot Q_1 \cdot Q_2}{d^2} \qquad F_{grav} = \frac{G \cdot m_1 \cdot m_2}{d^2}$$

$$(k = 9.0 \times 10^9 \ N \cdot m^2/C^2) \qquad (G = 6.67 \times 10^{-11} \ N \cdot m^2/kg^2)$$

The two equations have a very similar form. Both equations show an inverse square relationship between force and separation distance. And both equations show that the force is proportional to the product of the quantity that causes the force - charge in the case of electrical force and mass in the case of gravitational force. Yet there are some striking differences between these two forces. First, a comparison of the proportionality constants - k versus G - reveals that the Coulomb's law constant (k) is significantly greater than Newton's universal gravitation constant (G). Subsequently a unit of charge will attract a unit of charge with significantly more force than a unit of mass will attract a unit of mass. Second, gravitational forces are only attractive; electrical forces can be either attractive or repulsive.

The inverse square relationship between force and distance which is woven into the equation is common to both non-contact forces. This relationship highlights the importance of separation distance when it comes to the electrical force between charged objects. It is the focus of the next section of Lesson 3.

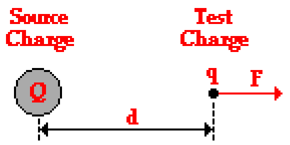
Lesson 3: Electric Field

Electric Field Intensity

In the previous section of Lesson 4, the concept of an electric field was introduced. It was stated that the electric field concept arose in an effort to explain action-at-a-distance forces. All charged objects create an electric field which extends outward into the space which surrounds it. The charge alters that space, causing any other charged object that enters the space to be affected by this field. The strength of the electric field is dependent upon how charged the object creating the field is and upon the distance of separation from the charged object. In this section of Lesson 4, we will investigate electric field from a numerical viewpoint - the electric field strength.

The Force per Charge Ratio

Electric field strength is a vector quantity; it has both magnitude and direction. The magnitude of the electric field strength is defined in terms of how it is measured. Let's suppose that an electric charge can be denoted by the symbol Q. This electric charge creates an electric field; since Q is the source of the electric field, we will refer to it as the source charge. The strength of the source charge's electric field could be



measured by any other charge placed somewhere in its surroundings. The charge that is used to measure the electric field strength is referred to as a test charge since it is used to test the field strength. The test charge has a quantity of charge denoted by the symbol q. When placed within the electric field, the test charge will experience an electric force - either attractive or repulsive. As is usually the case, this force will be denoted by the symbol F. The magnitude of the electric field is simply defined as the force per charge on the test charge.

$$\text{Electric Field Strength} = \frac{\text{Force}}{\text{Charge}}$$

If the electric field strength is denoted by the symbol E, then the equation can be rewritten in symbolic form as.

$$E = \frac{F}{q}$$

The standard metric units on electric field strength arise from its definition. Since electric field is defined as a force per charge, its units would be force units divided by charge units. In this case, the standard metric units are Newton/Coulomb or N/C.

In the above discussion, you will note that two charges are mentioned - the source charge and the test charge. Two charges would always be necessary to encounter a force. In the electric world, it takes two to attract or repel. The equation for electric field strength (E) has one of the two charge quantities listed in it. Since there are two charges involved, a student will have to be ultimately careful to use the correct charge quantity when computing the electric field strength. The symbol q in the equation is the quantity of charge on the test charge (not the source charge). Recall that the electric field strength is defined in terms of how it is measured or tested; thus, the test charge finds its way into the equation. Electric field is the force per quantity of charge on the test charge.

The electric field strength is not dependent upon the quantity of charge on the test charge. If you think about that statement for a little while, you might be bothered by it. (Of course if you don't think at all - ever - nothing really bothers you. Ignorance is bliss.) After all, the quantity of charge on the test charge (q) is in the equation for electric field. So how could electric field strength not be dependent upon q if q is in the equation? Good question. But if you think about it a little while longer, you will be able to answer your own question. (Ignorance might be bliss. But with a little extra thinking you might achieve insight, a state much better than bliss.) Increasing the quantity of charge on the test charge - say, by a factor of 2 - would increase the denominator of the equation by a factor of 2. But according to Coulomb's law, more charge also means more electric force (F). In fact, a twofold increase in q would be accompanied by a twofold increase in F. So as the denominator in the equation increases by a factor of two (or three or four), the numerator increases by the same factor. These two changes offset each other such that one can safely say that the electric field strength is not dependent upon the quantity of charge on the test charge. So regardless of what test charge is used, the electric field strength at any given location around the source charge Q will be measured to be the same.

Another Electric Field Strength Formula

The above discussion pertained to defining electric field strength in terms of how it is measured. Now we will investigate a new equation that defines electric field strength in terms of the variables which affect the electric field strength. To do so, we will have to revisit the Coulomb's law equation. Coulomb's law states that the electric force between two charges is directly proportional to the product of their charges and inversely proportional to the square of the distance between their centers. When applied to our two charges - the source charge (Q) and the test charge (q) - the formula for electric force can be written as

$$F = \frac{k \cdot q \cdot Q}{d^2}$$

where $k = 9.0 \cdot 10^9 \ N \cdot m^2/C^2$
d = separation distance between charges (meters)

If the expression for electric force as given by Coulomb's law is substituted for force in the above E =F/q equation, a new equation can be derived as shown below.

$$E = \frac{F}{q} = \frac{k \cdot \cancel{q} \cdot Q / d^2}{\cancel{q}} = \frac{k \cdot Q}{d^2}$$

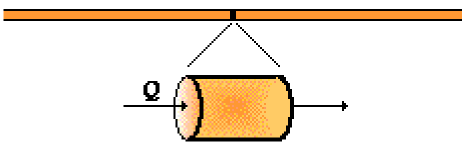
$$\boxed{E = \frac{k \cdot Q}{d^2}}$$

Note that the derivation above shows that the test charge q was canceled from both numerator and denominator of the equation. The new formula for electric field strength (shown inside the box) expresses the field strength in terms of the two variables which affect it. The electric field strength is dependent upon the quantity of charge on the source charge (Q) and the distance of separation (d) from the source charge.

Electric Current

If the two requirements of an electric circuit are met, then charge will flow through the external circuit. It is said that there is a current - a flow of charge. Using the word current in this context is to simply use it to say that something is happening in the wires - charge is moving. Yet current is a physical quantity which can be measured and expressed numerically. As a physical quantity, current is the rate at which charge flows past a point on a circuit. As depicted in the diagram below, the current in a circuit can be determined if the quantity of charge Q passing through a cross section of a wire in a time t can be measured. The current is simply the ratio of the quantity of charge and time.

Definition of Current



Current is the rate at which charge passes by a point on the circuit. If a small cross section of a wire could be isolated and the quantity of charge (Q) passing through this cross section in a certain amount of time (t) could be measured, then the current would be the Q / t ratio.

Current is a rate quantity. There are several rate quantities in physics. For instance, velocity is a rate quantity - the rate at which an object changes its position. Mathematically, velocity is the position change per time ratio. Acceleration is a rate quantity - the rate at which an object changes its velocity. Mathematically, acceleration is the velocity change per time ratio. And power is a rate quantity - the rate at which work is done on an object. Mathematically, power is the work per time ratio. In every case of a rate quantity, the mathematical equation involves some quantity over time. Thus, current as a rate quantity would be expressed mathematically as

$$\text{Current} = I = \frac{Q}{t}$$

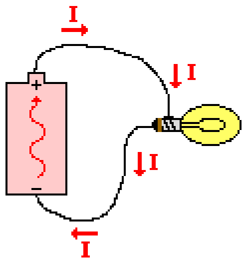
Note that the equation above uses the symbol I to represent the quantity current. As is the usual case, when a quantity is introduced in The Physics Classroom, the standard metric unit used to express that quantity are introduced as well. The standard metric unit for current is the ampere.

Ampere is often shortened to Amp and is abbreviated by the unit symbol A. A current of 1 ampere means that there is 1 coulomb of charge passing through a cross section of a wire every 1 second.

1 ampere = 1 coulomb / 1 second

Conventional Current Direction

The particles which carry charge through wires in a circuit are mobile electrons. The electric field direction within a circuit is by definition the direction which positive test charges are pushed. Thus, these negatively charged electrons move in the direction opposite the electric field. But while electrons are the charge carriers in metal wires, the charge carriers in other circuits can be positive charges, negative charges or both. In fact, the charge carriers in semiconductors, street lamps and fluorescent lamps are simultaneously both positive and negative charges traveling in opposite directions.

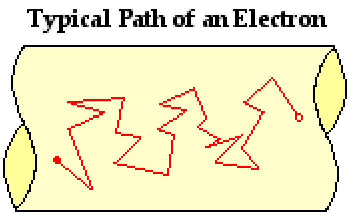


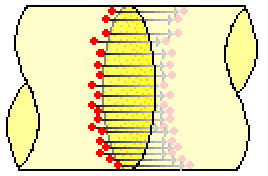
Electric current in the external circuit is directed from the positive to the negative terminal.

Ben Franklin, who conducted extensive scientific studies in both static and current electricity, envisioned positive charges as the carriers of charge. As such, an early convention for the direction of an electric current was established to be in the direction which positive charges would move. The convention has stuck and is still used today. The direction of an electric current is by convention the direction in which a positive charge would move. Thus, the current in the external circuit is directed away from the positive terminal and toward the negative terminal of the battery. Electrons would actually move through the wires in the opposite direction. Knowing that the actual charge carriers in wires are negatively charged electrons may make this convention seem a bit odd and outdated. Nonetheless, it is the convention which is used world wide and one that a student of physics can easily become accustomed to.

Current versus Drift Speed

Current has to do with the number of coulombs of charge which pass a point in the circuit per unit of time. Because of its definition, it is often confused with the quantity drift speed. Drift speed refers to the average distance traveled by a charge carrier per unit of time. Like the speed of any object, the drift speed of an electron moving through a wire is the distance to time ratio. The path of a typical electron through a wire could be described as a rather chaotic, zigzag path characterized by collisions with fixed atoms. Each collision results in a change in direction of the electron. Yet because of collisions with atoms in the solid network of the metal conductor, there are two steps backwards for every three steps forward. With an electric potential established across the two ends of the circuit, the electron continues to migrate forward. Progress is always made towards the positive terminal. Yet the overall affect of the countless collisions and the high between-collision speeds is that the overall drift speed of an electron in a circuit is abnormally low. A typical drift speed might be 1 meter per hour. That is slow!





A high current results from many charge carriers passing through a given cross section of wire on a circuit.

One might then ask: How can there by a current on the order of 1 or 2 ampere in a circuit if the drift speed is only about 1 meter per hour? The answer is: there are many, many charge carriers moving at once throughout the whole length of the circuit. Current is the rate at which charge crosses a point on a circuit. A high current is the result of several coulombs of charge crossing over a cross section of a wire on a circuit. If the charge carriers are densely packed into the wire, then there does not have to be a high speed to have a high current. That is, the charge carriers do not have to travel a long distance in a second, there just has to be a lot of them passing through the cross section. Current does not have to do with how far charges move in a second but rather with how many charges pass through a cross section of wire on a circuit.

To illustrate how densely packed the charge carriers are, we will consider a typical wire found in household lighting circuits - a 14-gauge copper wire. In a 0.01 cm-long (very thin) cross-sectional slice of this wire, there would be as many as 3.51 x 1020 copper atoms. Each copper atom has 29 electrons; it would be unlikely that even the 11 valence electrons would be in motion as charge carriers at once. If we assume that each copper atom contributes just a single electron, then there would be as much as 56 coulombs of charge within a thin 0.01-cm length of the wire. With that much mobile charge within such a small space, a small drift speed could lead to a very large current.

To further illustrate this distinction between drift speed and current, consider this racing analogy. Suppose that there was a very large turtle race with millions and millions of turtles on a very wide race track. Turtles do not move very fast - they have a very low drift speed. Suppose that the race was rather short - say 1 meter in length - and that a large percentage of the turtles reached the finish line at the same time - 30 minutes after the start of the race. In such a case, the current would be very large - with millions of turtles passing a point in a short amount of time. In this analogy, speed has to do with how far the turtles move in a certain amount of time; and current has to do with how many turtles cross the finish line in a certain amount of time.

The Nature of Charge Flow

Once it has been established that the average drift speed of an electron is very, very slow, the question soon arises: Why does the light in a room or in a flashlight light immediately after the switched is turned on? Wouldn't there be a noticeable time delay before a charge carrier moves from the switch to the light bulb filament? The answer is NO! and the explanation of why reveals a significant amount about the nature of charge flow in a circuit.

As mentioned above, charge carriers in the wires of electric circuits are electrons. These electrons are simply supplied by the atoms of copper (or whatever material the wire is made of) within the metal wire. Once the switch is turned to on, the circuit is closed and there is an electric potential difference is established across the two ends of the external circuit. The electric field signal travels at nearly the speed of light to all mobile electrons within the circuit, ordering them to begin marching. As the signal is received, the electrons begin moving along a zigzag path in their usual direction. Thus, the flipping of the switch causes an immediate response throughout every part of the circuit, setting charge carriers everywhere in motion in the same net direction. While the actual motion of charge carriers occurs with a slow speed, the signal which informs them to start moving travels at a fraction of the speed of light.

The electrons which light the bulb in a flashlight do not have to first travel from the switch through 10 cm of wire to the filament. Rather, the electrons which light the bulb immediately after the switch is turned to on are the electrons which are present in the filament itself. As the switch is flipped, all mobile electrons everywhere begin marching; and it is the mobile electrons present in the filament whose motion are immediately responsible for the lighting of its bulb. As those electrons leave the filament, new electrons enter and become the ones which are responsible for lighting the bulb. The electrons are moving together much like the water in the pipes of a home move. When a faucet is turned on, it is the water in the faucet which emerges from the spigot. One does not have to wait a noticeable time for water from the entry point to your home to travel through the pipes to the spigot. The pipes are already filled with water and water everywhere within the water circuit is set in motion at the same time.

The picture of charge flow being developed here is a picture in which charge carriers are like soldiers marching along together, everywhere at the same rate. Their marching begins immediately in response to the establishment of an electric potential across the two ends of the circuit. There is no place in the electrical circuit where charge carriers become consumed or used up. While the energy possessed by the charge may be used up (or a better way of putting this is to say that the electric energy is transformed to other forms of energy), the charge carriers themselves do not disintegrate, disappear or otherwise become removed from the circuit. And there is no place in the circuit where charge carriers begin to pile up or accumulate. The rate at which charge enters the external circuit on one end is the same as the rate at which charge exits the external circuit on the other end. Current - the rate of charge flow - is everywhere the same. Charge flow is like the movement of soldiers marching in step together, everywhere at the same rate.

Electrical Resistance

An electron traveling through the wires and loads of the external circuit encounters resistance. Resistance is the hindrance to the flow of charge. For an electron, the journey from terminal to terminal is not a direct route. Rather, it is a zigzag path which results from countless collisions with fixed atoms within the conducting material. The electrons encounter resistance - a hindrance to their movement. While the electric potential difference established between the two terminals encourages the movement of charge, it is resistance which discourages it. The rate at which charge flows from terminal to terminal is the result of the combined affect of these two quantities.

Variables Affecting Electrical Resistance

The flow of charge through wires is often compared to the flow of water through pipes. The resistance to the flow of charge in an electric circuit is analogous to the frictional affects between water and the pipe surfaces as well as the resistance offered by obstacles which are present in its path. It is this resistance which hinders the water flow and reduces both its flow rate and its drift speed. Like the resistance to water flow, the total amount of resistance to charge flow within a wire of an electric circuit is affected by some clearly identifiable variables.

First, the total length of the wires will affect the amount of resistance. The longer the wire, the more resistance that there will be. There is a direct relationship between the amount of resistance encountered by charge and the length of wire it must traverse. After all, if resistance occurs as the result of collisions between charge carriers and the atoms of the wire, then there is likely to be more collisions in a longer wire. More collisions means more resistance.

Second, the cross-sectional area of the wires will affect the amount of resistance. Wider wires have a greater cross-sectional area. Water will flow through a wider pipe at a higher rate than it will flow through a narrow pipe. This can be attributed to the lower amount of resistance which is present in the wider pipe. In the same manner, the wider the wire, the less resistance that there will be to the flow of electric charge. When all other variables are the same, charge will flow at higher rates through wider wires with greater cross-sectional areas than through thinner wires.

A third variable which is known to affect the resistance to charge flow is the material that a wire is made of. Not all materials are created equal in terms of their conductive ability. Some materials are better conductors than others and offer less resistance to the flow of charge. Silver is one of the best conductors but is never used in wires of household circuits due to its cost. Copper and aluminum are among the least expensive materials with suitable conducting ability to permit their use in wires of household circuits. The conducting ability of a material is often indicated by its resistivity. The resistivity of a material is dependent upon the material's electronic structure and its temperature. For most (but not all) materials, resistivity increases with increasing temperature. The table below lists resistivity values for various materials at temperatures of 20 degrees Celsius.Material   Resistivity

(ohm•meter)

Silver	1.59 x 10-8	Copper	1.7 x 10-8	Gold	2.4 x 10-8	Aluminum	2.8 x 10-8
Tungsten	5.6 x 10-8	Iron	10 x 10-8	Platinum	11 x 10-8	Lead	22 x 10-8
Nichrome	150 x 10-8	Carbon	3.5 x 105	Polystyrene	107 – 1011		
Polyethylene	108 – 109	Glass	1010 – 1014	Hard Rubber	1013		

As seen in the table, there is a broad range of resistivity values for various materials. Those materials with lower resistivities offer less resistance to the flow of charge; they are better conductors. The materials shown in the last five rows of the above table have such high resistivity that they would not even be considered to be conductors.

Mathematical Nature of Resistance

Resistance is a numerical quantity which can be measured and expressed mathematically. The standard metric unit for resistance is the ohm, represented by the Greek letter omega - . An electrical device having a resistance of 5 ohms would be represented as R = 5 . The equation representing the dependency of the resistance (R) of a cylindrically shaped conductor (e.g., a wire) upon the variables which affect it is

$$R = \rho \frac{L}{A}$$

where L represents the length of the wire (in meters), A represents the cross-sectional area of the wire (in meters2), and represents the resistivity of the material (in ohm•meter). Consistent with the discussion above, this equation shows that the resistance of a wire is directly proportional to the length of the wire and inversely proportional to the cross-sectional area of the wire. As shown by the equation, knowing the length, cross-sectional area and the material that a wire is made of (and thus, its resistivity) allows one to determine the resistance of the wire.

Ohm's Law

There are certain formulas in Physics that are so powerful and so pervasive that they reach the state of popular knowledge. A student of Physics has written such formulas down so many times that they have memorized it without trying to. Certainly to the professionals in the field, such formulas are so central that they become engraved in their minds. In the field of Modern Physics, there is E = m • c2. In the field of Newtonian Mechanics, there is Fnet = m • a. In the field of Wave Mechanics, there is v = f • . And in the field of current electricity, there is V = I • R.

The predominant equation which pervades the study of electric circuits is the equation

V = I • R

In words, the electric potential difference between two points on a circuit (V) is equivalent to the product of the current between those two points (I) and the total resistance of all electrical devices present between those two points (R). Through the rest of this unit of The Physics Classroom, this equation will become the most common equation which we see. Often referred to as the Ohm's law equation, this equation is a powerful predictor of the relationship between potential difference, current and resistance.

Ohm's Law as a Predictor of Current

The Ohm's law equation can be rearranged and expressed as

$I = \frac{\Delta V}{R}$ As an equation, this serves as an algebraic recipe for calculating the current if the electric potential difference and the resistance are known. Yet while this equation serves as a powerful recipe for problem-solving, it is much more than that. This equation indicates the two variables which would affect the amount of current in a circuit. The current in a circuit is directly proportional to the electric potential difference impressed across its ends and inversely proportional to the total resistance offered by the external circuit. The greater the battery voltage (i.e., electric potential difference), the greater the current. And the greater the resistance, the less the current. Charge flows at the greatest rates when the battery voltage is increased and the resistance is decreased. In fact, a twofold increase in the battery voltage would lead to a twofold increase in the current (if all other factors are kept equal). And an increase in the resistance of the load by a factor of two would cause the current to decrease by a factor of two to one-half its original value.