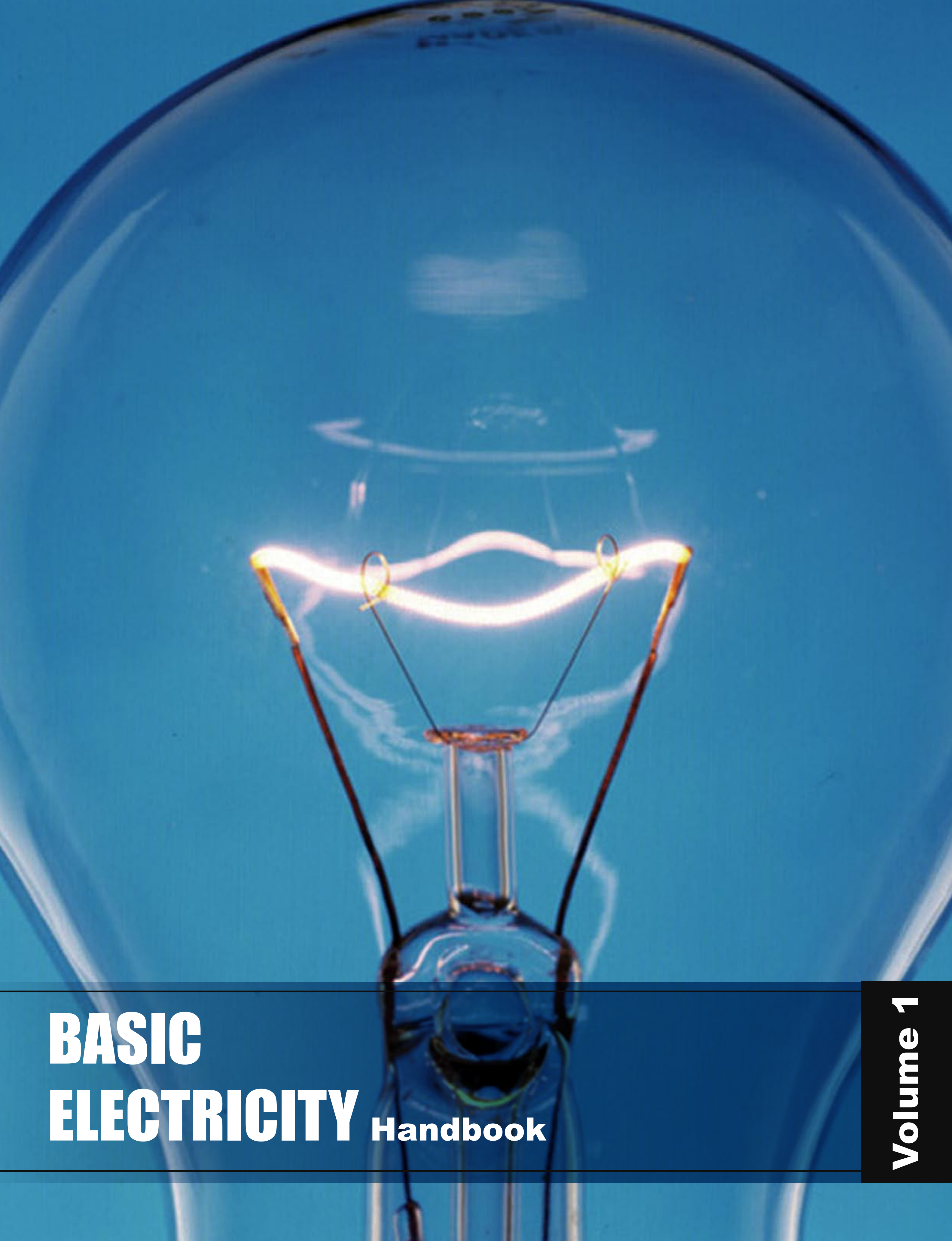

BASIC ELECTRICITY Handbook

Volume 1

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Handbook

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Handbook

Volume 1

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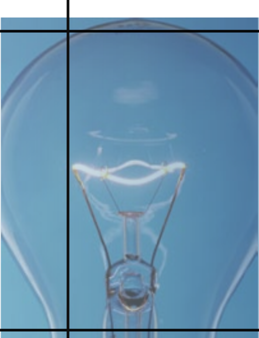

Introduction

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FUNDAMENTALS OF ELECTRICITY CHAPTER 1

Introduction

Electricity is a form of energy characterized by the presence and motion of elementary charged particles generated by friction, induction, or chemical change. Electricity is a secondary energy source which means that we get it from the conversion of other sources of energy, like coal, natural gas, oil, nuclear power and other natural sources, which are called primary sources. The energy sources we use to make electricity can be renewable or non-renewable, but electricity itself is neither renewable nor non-renewable.

SCIENCE OF ELECTRICITY BASICS EVERYTHING IS MADE OF ATOMS

In order to understand electricity, we need to know something about atoms. Everything in the universe is made of atoms — every star, every tree, every animal. The human body is made of atoms. Air and water are, too. Atoms are the building blocks of the universe. Atoms are so small that millions of them would fit on the head of a pin.

ATOMS ARE MADE OF EVEN SMALLER PARTICLES

The center of an atom is called the nucleus. It is made of particles called protons and neutrons. The protons and neutrons are very small, but electrons are much, much smaller. Electrons spin around the nucleus in shells a great distance from the nucleus. If the nucleus were the size of a tennis ball, the atom would be the size of the Empire State Building. Atoms are mostly empty space.

If you could see an atom, it would look a little like a tiny center of balls surrounded by giant invisible bubbles (or shells). The electrons would be on the surface of the bubbles, constantly spinning and moving to stay as far away from each other as possible. Electrons are held in their shells by an electrical force.

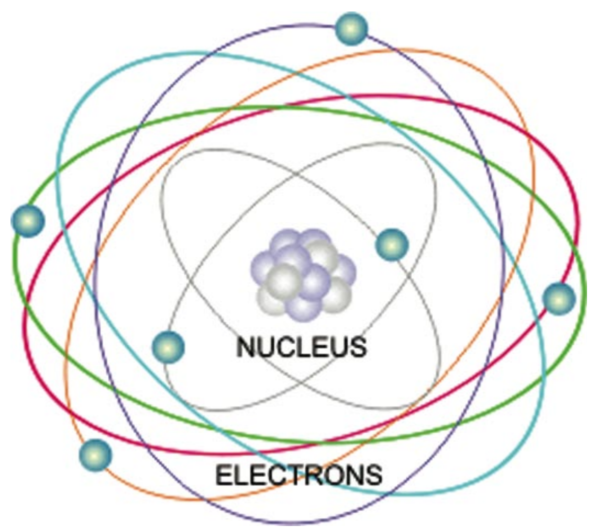
The protons and electrons of an atom are attracted to each other. They both carry an electrical charge. Protons have a positive charge (+) and electrons have a negative charge (-). The positive charge of the protons is equal to the negative charge of the electrons. Opposite charges attract each other. An atom is in balance when it has an equal number of protons and electrons. The neutrons carry no charge and their number can vary.

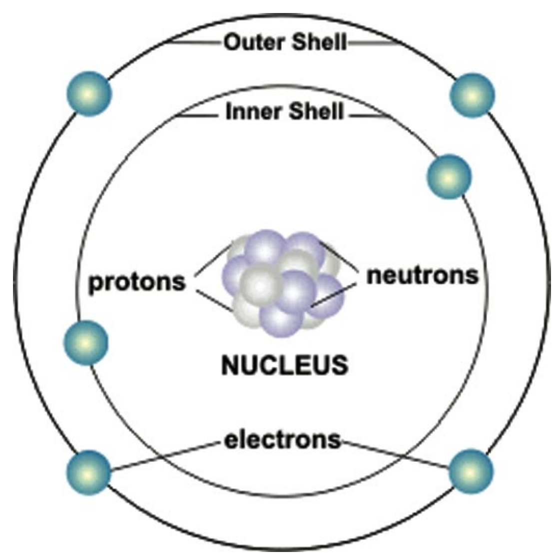
The number of protons in an atom determines the kind of atom, or element, it is. An element is a substance consisting of one type of atom (the Periodic Table shows all the known elements), all with the same number of protons. Every atom of hydrogen, for example, has one proton, and every atom of carbon has six protons. The number of protons determines which element it is.

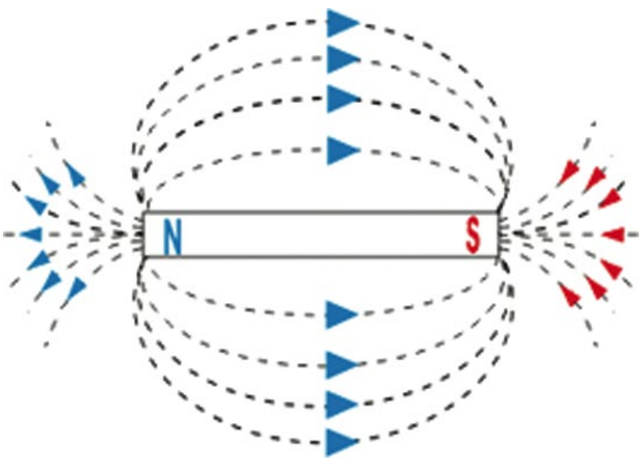
ELECTRICITY IS THE MOVEMENT OF ELECTRONS BETWEEN ATOMS

Electrons usually remain a constant distance from the nucleus in precise shells. The shell closest to the nucleus can hold two electrons. The next shell can hold up to eight. The outer shells can hold even more. Some atoms with many protons can have as many as seven shells with electrons in them.

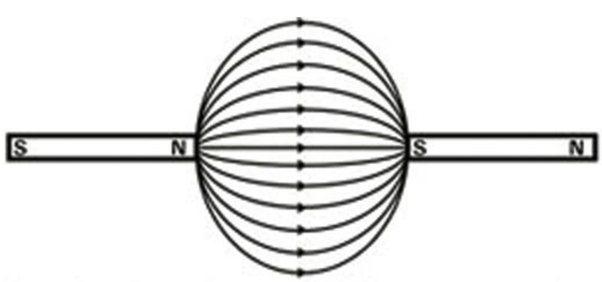
The electrons in the shells closest to the nucleus have a strong force of attraction to the protons. Sometimes, the electrons in an atom's outermost shells do not. These electrons can be pushed out of their orbits. Applying a force can make them move from one atom to another. These moving electrons are electricity.







Like poles of magnets (N-N or S-S) repel each other.



Opposite poles of magnets (N-S) attract each other.

STATIC ELECTRICITY EXISTS IN NATURE

Lightning is a form of electricity. It is electrons moving from one cloud to another or jumping from a cloud to the ground. Have you ever felt a shock when you touched an object after walking across a carpet? A stream of electrons jumped to you from that object. This is called static electricity.

Have you ever made your hair stand straight up by rubbing a balloon on it? If so, you rubbed some electrons off the balloon. The electrons moved into your hair from the balloon. They tried to get far away from each other by moving to the ends of your hair. They pushed against each other and made your hair move — they repelled each other. Just as opposite charges attract each other, like charges repel each other.

MAGNETS AND ELECTRICITY

The spinning of the electrons around the nucleus of an atom creates a tiny magnetic field. Most objects are not magnetic because their electrons spin in different, random directions, and cancel out each other.

Magnets are different; the molecules in magnets are arranged so that their electrons spin in the same direction. This arrangement of atoms creates two poles in a magnet, a North-seeking pole and a South-seeking pole.

MAGNETS HAVE MAGNETIC FIELDS

The magnetic force in a magnet flows from the North pole to the South pole. This creates a magnetic field around a magnet.

Have you ever held two magnets close to each other? They don't act like most objects. If you try to push the South poles together, they repel each other. Two North poles also repel each other.

Turn one magnet around, and the North (N) and the South (S) poles are attracted to each other. Just like protons and electrons — opposites attract.

MAGNETIC FIELDS CAN BE USED TO MAKE ELECTRICITY

Properties of magnets can be used to make electricity. Moving magnetic fields can pull and push electrons. Metals such as copper have electrons that are loosely held. So electrons in copper wires can easily be pushed from their shells by moving magnets.

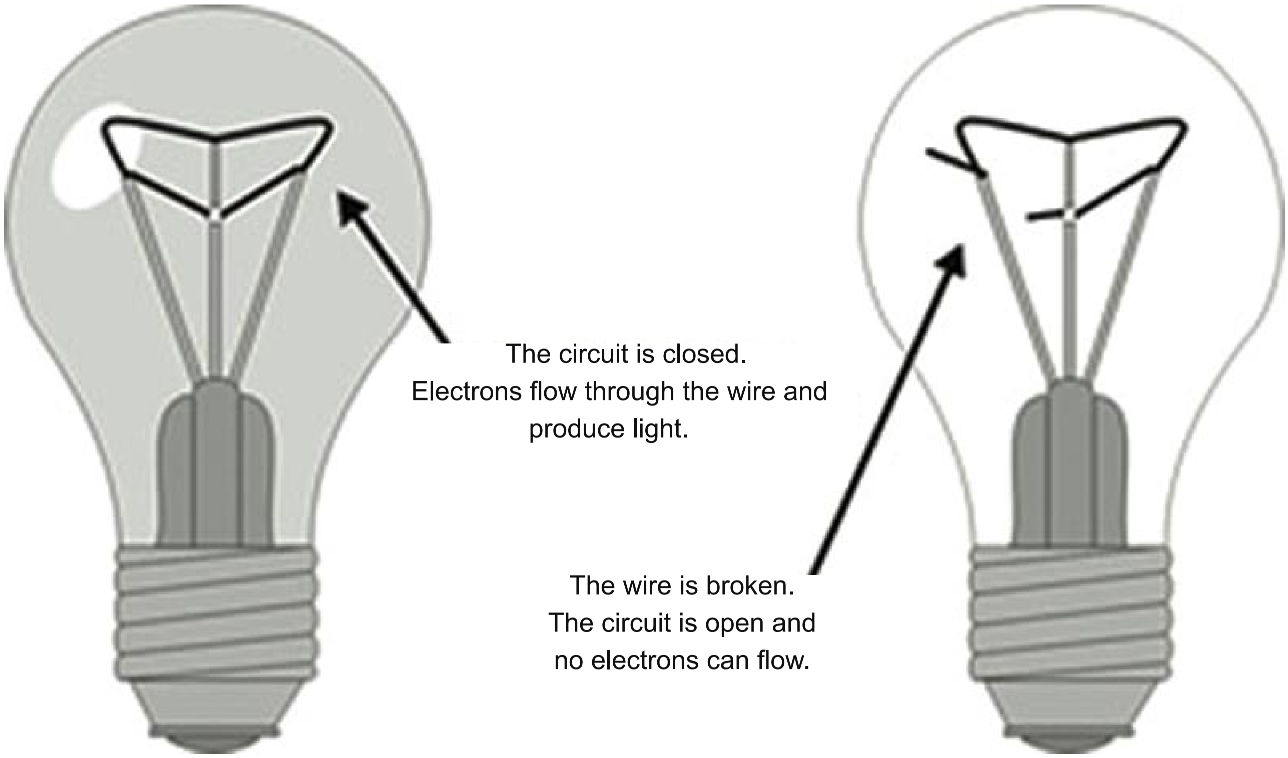
By using moving magnets and copper wire together, electric generators create electricity. Electric generators essentially convert kinetic energy (the energy of motion) into electrical energy.

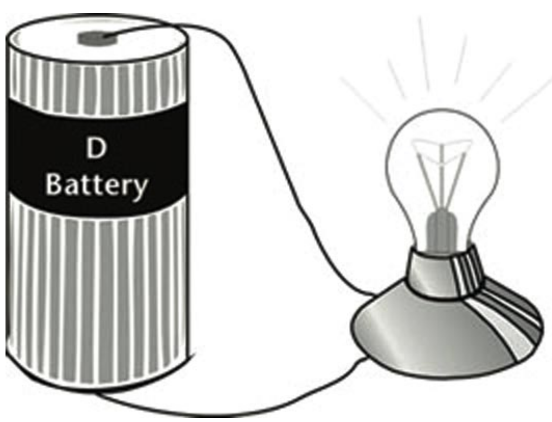
BATTERIES, CIRCUITS, & TRANSFORMERS BATTERIES PRODUCE ELECTRICITY

A battery produces electricity using two different metals in a chemical solution. A chemical reaction between the metals and the chemicals frees more electrons in one metal than in the other. One end of the battery is attached to one of the metals; the other end is attached to the other metal.

The end that frees more electrons develops a positive charge and the other end develops a negative charge. If a wire is attached from one end of the battery to the other, electrons flow through the wire to balance the electrical charge.

A load is a device that does work or performs a job. If a load -- such as a light bulb -- is placed along the wire, the electricity can do work as it flows through the wire. Electrons flow from the negative end of the battery through the wire to the light bulb.





The electricity flows through the wire in the light bulb and back to the positive end of the battery.

ELECTRICITY TRAVELS IN CIRCUITS

Electricity travels in closed loops, or circuits. It must have a complete path before the electrons can move. If a circuit is open, the electrons cannot flow. When we flip on a light switch, we close a circuit. The electricity flows from an electric wire, through the light bulb, and back out another wire.

When we flip the switch off, we open the circuit. No electricity flows to the light. When we turn a light switch on, electricity flows through a tiny wire in the bulb. The wire gets very hot. It makes the gas in the bulb glow. When the bulb burns out, the tiny wire has broken. The path through the bulb is gone.

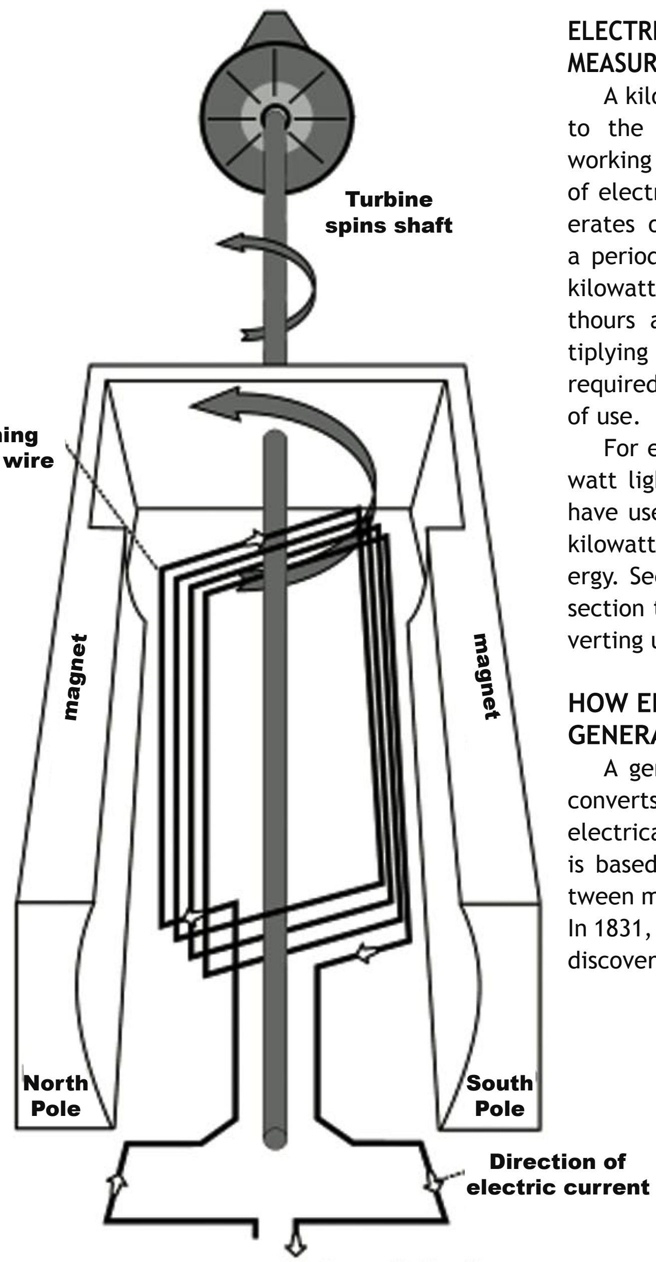
When we turn on the TV, electricity flows through wires inside the TV set, producing pictures and sound. Sometimes electricity runs motors — in washers or mixers. Electricity does a lot of work for us many times each day.

TRANSFORMERS HELP TO MOVE ELECTRICITY EFFICIENTLY OVER LONG DISTANCES

To solve the problem of sending electricity over long distances, William Stanley developed a device called a transformer. The transformer allowed electricity to be efficiently transmitted over long distances. This increased delivery range made it possible to supply electricity to homes and businesses located far from the electric generating plant.

The electricity produced by a generator travels along cables to a transformer, which changes electricity from low voltage to high voltage. Electricity can be moved long distances more efficiently using high voltage. Transmission lines are used to carry the electricity to a substation. Substations have transformers that change the high voltage electricity into lower voltage electricity. From the substation, distribution lines carry the electricity to homes, offices, and factories, which require low voltage electricity.

TURBINE GENERATOR



MEASURING ELECTRICITY

Electricity Is Measured in Watts and Kilowatts

Electricity is measured in units of power called watts. It was named to honor James Watt, the inventor of the steam engine. One watt is a very small amount of power. It would require nearly 750 watts to equal one horsepower.

A kilowatt is the same as 1,000 watts.

ELECTRICITY USE OVER TIME IS MEASURED IN KILOWATTHOURS

A kilowatthour (kWh) is equal to the energy of 1,000 watts working for one hour. The amount of electricity a power plant generates or a customer uses over a period of time is measured in kilowatthours (kWh). Kilowatthours are determined by multiplying the number of kilowatts required by the number of hours of use.

For example, if you use a 40-watt light bulb for 5 hours, you have used 200 watthours, or 0.2 kilowatthours, of electrical energy. See EIA's Energy Calculator section to learn more about converting units.

HOW ELECTRICITY IS GENERATED

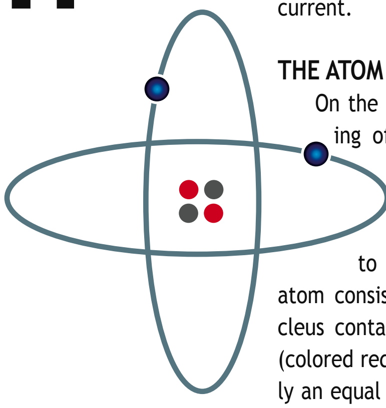
A generator is a device that converts mechanical energy into electrical energy. The process is based on the relationship between magnetism and electricity. In 1831, scientist Michael Faraday discovered that when a magnet is moved inside a coil of wire, electrical current flows in the wire.

A typical generator at a power plant uses an electromagnet — a magnet produced by electricity — not a traditional magnet. The generator has a series of insulated coils of wire that form a stationary cylinder. This cylinder surrounds a rotary electromagnetic shaft. When the electromagnetic shaft rotates, it induces a small electric current in each section of the wire coil. Each section of the wire becomes a small, separate electric conductor. The small currents of individual sections are added together to form one large current. This current is the electric power that is transmitted from the power company to the consumer.

An electric utility power station uses either a turbine, engine, water wheel, or other similar machine to drive an electric generator — a device that converts mechanical or chemical energy to electricity. Steam turbines, internal-combustion engines, gas combustion turbines, water turbines, and wind turbines are the most common methods to generate electricity.

Steam turbine power plants powered by coal and nuclear energy produce about 70% of the electricity used in the United States. These plants are about 35% efficient. That means that for every 100 units of primary heat energy that go into a plant, only 35 units are converted to useable electrical energy.

ELECTRICITY TUTORIAL



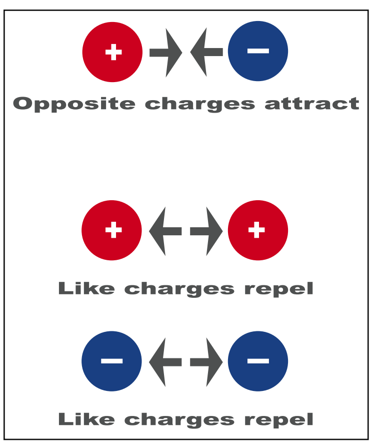
This tutorial is a brief introduction to the concepts of charge, voltage, and current.

THE ATOM

On the right is a conceptual drawing of an atom. Atoms are the building blocks of matter. Everything is made of atoms, from rocks, to trees, to stars, to even yourself. An atom consists of a tightly packed nucleus containing one or more protons (colored red in the picture), and usually an equal number of neutrons (gray). Electrons (blue) surround the nucleus, forming an electron cloud. The number of electrons in an electrically stable atom is always equal to the number of protons in the nucleus.

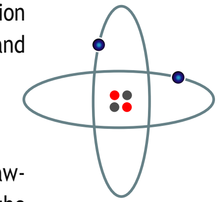
ELECTRIC CHARGE

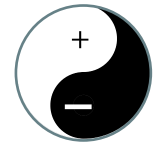
A strange thing happens between protons and electrons: a proton and an electron are always attracted to one another, while a proton will repel other protons, and an electron will repel other electrons. This behavior is caused by something called the electric force. Protons are said to have a positive electric charge, while electrons have a negative electric charge. Two objects with the same type of charge push away from each other, while two objects with opposite charges attract to each other. Since a proton and an electron have opposite electric charges, they are attracted to each other. Two protons, however, move away from each other because of their equal electric charges. The same is true of two electrons, which push away from each other because of their equal negative charges.



ELECTRIC BALANCE

Most matter contains an equal number of protons and electrons. The negative electrons balance out the positive protons, and the matter has no overall electrical charge. The word overall is important, since the charges are still there, bouncing around inside the matter. Electrical charges are everywhere, but we just can't sense them because they are in balance. In fact, in chemistry, you learn that the electric force is the very thing that holds matter together. The next time you pick something up, just think that whatever you are holding is literally filled with electric charge. This is an important fact that many people miss when they study electricity.

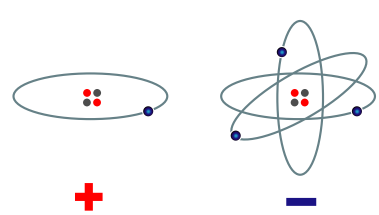




STATIC ELECTRICITY

Let's say we steal an electron from one atom and give the electron to another atom. One atom will have an overall positive charge and the other will have an overall negative charge. When this happens, the two atoms are called ions. Because ions have an overall electric charge, they can interact with other charged objects. Since like charges repel and opposite charges attract, a positive ion will attract negatively charged objects, such as electrons or other ions, and will repel positively charged objects. A negatively charged ion will attract positively charged objects, and will repel other negatively charged objects.

The same is true for larger objects. If you take electrons from one object and place them on another object, the first object will have an overall positive charge while the second will have an overall negative charge. Depending on



the types of objects and the amount of charge involved, the electric force may be enough to cause the objects to stick together. This phenomenon is often referred to as "static electricity".

There are several ways to steal electrons from one object and give them to another. Some of the ways include chemical reactions, mechanical motion, light, and even heat. If you rub a glass rod with silk, the electrons in the glass rod will be knocked off and collected on the silk. The glass rod gains an overall positive charge, and the silk gains an overall negative charge. In a battery, chemical reactions are used to force electrons from the positive terminal and place them on the negative terminal.

MEASURING CHARGES

The amount of overall electric charge possessed by an object is measured in coulombs. One coulomb is roughly equal to the amount of charge possessed by 6,000,000,000,000,000,000 (six billion billion) electrons. While this may seem like a huge number at first, it is not really that much, since electrons are so tiny. Just to give you an idea, one coulomb is roughly the amount of charge that flows through a 12-watt automotive light bulb in one second.

If the amount of charge possessed by two objects and the distance between them are known, it is possible to calculate the amount of force between the objects using a formula known as Coulomb's law. This law was discovered by Charles Augustin de Coulomb in 1784, and states that the force between two charged objects varies directly as the charges of the objects and inversely as the square of the distance between them. Coulomb's law looks like this in formula form:

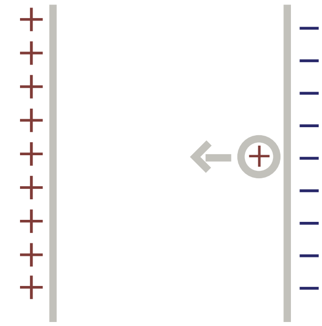
$$F = k\,\frac{qq^1}{r^2}$$

F is the force, in Newtons.
q and q' are the charges of the two objects, in coulombs.
r is the distance between the objects, in meters.
k is a constant equal to 8.98755x109 N m2 C-2

VOLTAGE

Whenever electrons are taken from one object and placed on another object, causing an imbalance of charge, we say that a voltage exists. That is what somebody means when they say that something has so many volts of electricity. They are describing a difference of charge in two different places. A standard AA battery has a difference of 1.5 volts between its positive and negative terminal, while a car battery has a difference of 12 volts between its two terminals, and the everyday type of static electricity that causes things to stick together and occasionally gives you a jolt when you touch a metal object is usually measured in thousands of volts.

Another way to understand voltage is to think of an "electric field". Imagine a positively charged plate next to a negatively charged plate. If you place a positively charged object between these plates, the plates' electric field will attract the object to the negative side. Imagine that you place an object with 1 Coulomb of positive charge next to the negative plate, and then pull the object towards the positive plate. Because the electric field creates a force in the opposite direction, moving the charged object requires energy. The amount of energy depends on the distance between the plates and the strength of the electric field created by the plates. This energy is called the electric field's "voltage". One volt is the amount of energy in joules required to move an object with 1 coulomb of charge through an electric field. Mathematically, 1 Volt = 1 Joule / 1 Coulomb.



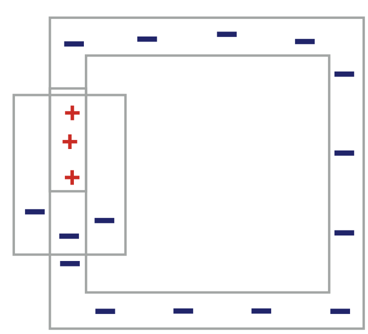
Volts are useful, because they neatly describe the size and strength of any electric field. Visualizing the electric field between two simple plates is easy, but visualizing the field in a complicated circuit with batteries, motors, light bulbs, and switches is very difficult. Voltage simplifies circuits like these by describing the entire electric field with a single number.

ELECTRIC CURRENT

The word current comes from the Latin word currere, which means to run or to flow. An electric current is nothing more than the flow of electric charges. Electric charges can only flow through certain materials, called conductors. Although the electrons in most materials are confined to fixed orbits, some materials, including most metals, have many loose electrons that are free to wander around through the material. Materials with this property act as conductors. When a conductor is placed between two charged objects, these loose electrons are pushed away by the negatively charged object and are sucked into the positively charged object. The result is that there is a flow of charge, called a current, and the two object's charges become balanced. The amount of current flowing through a conductor at any given time in measured in amperes, or amps for short. When you read that something uses so many amps, what you are being told is the amount of current flowing through the device. One ampere is equal to the flow of one coulomb of charge in one second.

BATTERIES AND CURRENT

In the previous section, we looked at how current flows from one charged object to another, canceling out the charges of the two objects. Once the charges were canceled, the current stopped. If current were always this short-lived, it would be very impractical. Imagine a flashlight that only lasted a fraction of a second before needing to be recharged! While current does tend to cancel out charges on two objects and then stop flowing, if a charge can be placed on the objects faster than the current can drain the charge, it is possible to keep a current flowing continu



ously. That is what happens in a battery. Chemical reactions within the battery pump electrons from the positive terminal to the negative terminal faster than the device connected to the battery can drain them. The battery will continue to supply as much current as the device requires until the chemicals within the battery are used up, at which point the battery is dead and must be replaced.

RESISTANCE

All conductors offer some degree of resistance to the flow of electric current. What happens is this: As electrons travel through the conductor, they bump into atoms, losing some of their movement in jiggling the atom. The result is that the current flowing through the conductor is slowed down, and the conductor is heated. The amount that a given conductor resists the flow of electric current is measured in ohms.

POWER

Whenever current flows, work is done. A conductor may be heated, a motor may be spun, a bulb might give off light, or some other form of energy may be released. There is a simple law that tells exactly how much work may be done by a flowing current. The amount of work done is equal to the voltage of the supply times the current flowing through the wire. This law is expressed in the form P=IV, where P is the power in watts, I is the current in amps, and V is the voltage in volts. For example, if we find that a light bulb draws half of an amp at 120 volts, we simply multiply the 120 volts by half an amp to find that the bulb draws 60 watts of power.

V=IR

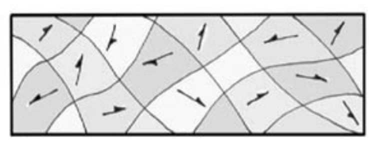
OHM'S LAW

Let's say you have a six volt battery and you need to draw two amps of current. What resistance should you make the conductor? Or let's say you have a three volt power supply and a thousand ohm resistor. How much current would flow through the resistor if you were to connect the resistor to the power supply? In order to find the answers to these questions, all you need to do is to use a simple mathematical formula called ohm's law. Ohm's law states that the amount of current flowing through a conductor times the resistance of the conductor is equal to voltage of the power supply. This law is often expressed in the form V=IR, where V is the voltage measured in volts, I is the current measured in amps, and R is the resistance measured in ohms.

MAGNETISM & ELECTRICITY

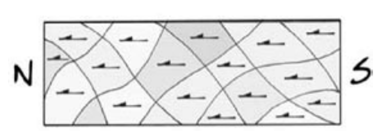
Magnetism is a natural phenomenon first documented by the Greeks who observed that a naturally occurring substance, magnetite would attract pieces of iron. Later on, the Chinese discovered that this naturally magnetic material could be used to induce a magnetic state in the iron itself, and that a sliver of magnetized iron floated on water would align itself along the north and south poles of the Earth. Iron and its steel alloys are the only common metals that are attracted by magnets.

Magnetically, iron and steel are made up of many discrete sections known as domains. Each domain has an inherent magnetic force, but the forces are unorganized.



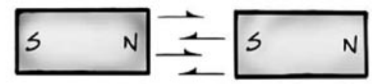
AN IRON BAR IS DIVIDED INTO UNORGANIZED MAGNETIC "DOMAINS"

Passing a magnet over the steel will organize the domains so that they all attract in the same direction, and the steel is then rendered magnetic by that action. In addition, a magnet that is placed in contact with a piece of steel will transfer its magnetic quality to that piece of steel, but only for the length of time the contact remains.

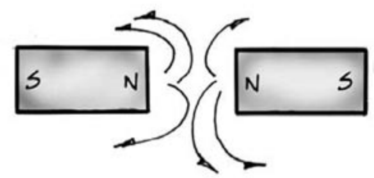


MAGNETIZING THE BAR ORGANIZES THE DOMAINS

Each magnet has a north and south pole. The north pole of one magnet will attract the south pole of another magnet. The north pole of any one magnet will repel the north pole of any other magnet. Opposites attract, like poles repel.

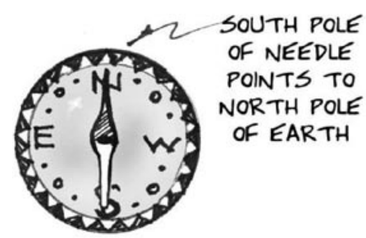


UNLIKE POLES OF A MAGNET ATTRACT ONE ANOTHER



LIKE POLES OF A MAGNET REPEL ONE ANOTHER

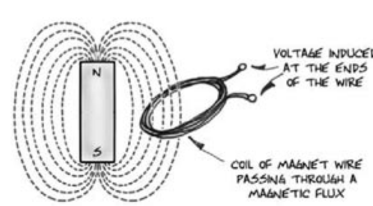
needle is attracted to the north pole of the earth. The core of the Earth is largely made up of molten iron. The North and South poles of the Earth form the approximate magnetic north and south poles, which is skewed a bit by large iron ore deposits in Siberia.



THE NEEDLE ON A COMPASS MUST BE VERY FREE TO ROTATE

INDUCTION:

There is a very important relationship between magnetism and electricity that is crucial to the operation of many common electrical devices. The reaction of current flow to magnetic force is called induction. Placing a coil wire near a magnet will induce a



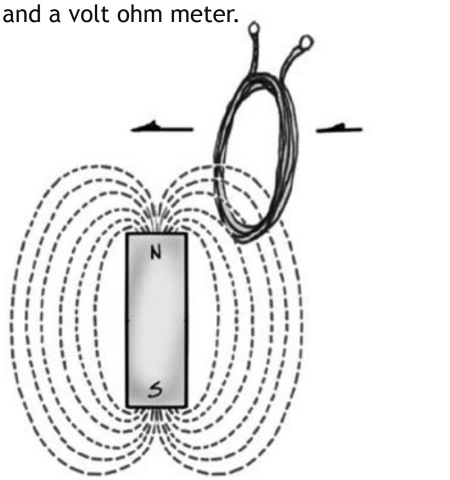
The force of the current, or voltage, induced in the wire is largely dependent on these factors:

1 The strength of the magnetic force

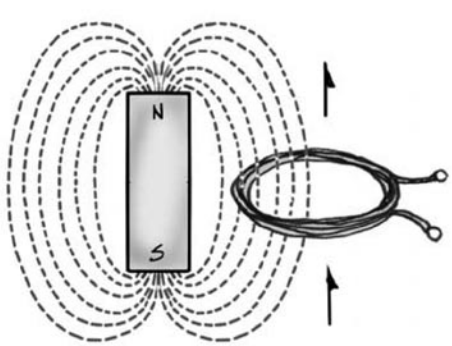
2 The proximity of the wire and the magnetic force.

3 The direction of movement through the lines of magnetic force.

More voltage is induced when the wire is passing at an angle to the lines of magnetic force rather than when the wire is passing along the lines of magnetic force. This is an important factor that governs the way alternating current is produced in a generator because it creates a fluctuation in the current that is extremely useful. In addition, a backward motion through the lines of magnetic force will induce the electrons to flow in the opposite direction. This phenomenon is easily observed using a magnet, coil of wire, and a volt ohm meter.

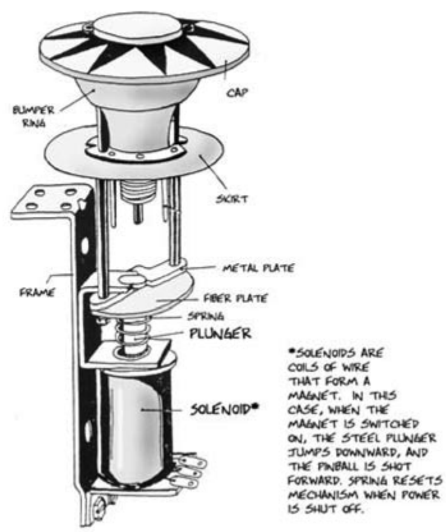


MOVING THROUGH THE LINES OF FORCE INDUCES MUCH MORE CURRENT



MOVING ALONG THE LINES OF FORCE INDUCES LITTLE, IF ANY, CURRENT

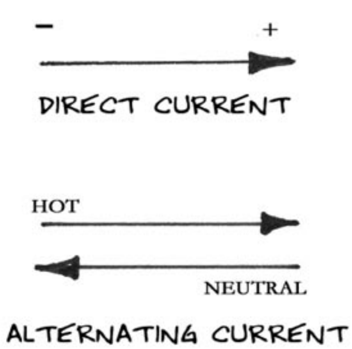
As demonstrated, magnets induce electron flow when wire is passed through the magnetic field, but the reverse is also true. A voltage flowing through a wire can be used to form a magnetic field, especially when the wire is wrapped around an iron core. The intensity of the magnetic field depends upon the voltage of the current flow, the number of wraps of wire around the core, and the diameter/proximity of wire to the core. Some common uses for this principle are motors, solenoids, and relays.



OLENOID USED IN A PINBALL MACHINE

ALTERNATING CURRENT:

So far we have used only direct current (DC) to discuss circuit theories pertaining to Ohm's laws of resistance as it is used to explain the relationship between voltage, current, and resistance using the formula E = IxR. In direct current, electrons in a battery flow in only one direction from a source of surplus negative ions to a source of positive ions.



Alternating current or AC, is formed by a generator using magnetic force and the principles of induction. In this type of current, electrons flow first in one direction, and then reverse that direction to flow the opposite way, hence the name alternating. AC has a number of distinct advantages over DC, mostly due to its easy manipulation through induction, which in most cases is not really possible with a DC current. DC power for homes and offices was developed by Thomas Edison and was the earliest type of power distribution used. Edison found a way to make generators produce a form of DC current, which was more commonly understood at the time because of the historical dependence on batteries for any sort of electrical work. Although resistance loads like light bulbs or heaters can easily work with direct current, there are serious problems associated with the long-range transmission of DC power that makes large-scale distribution difficult.

In Edison's day, using DC current, it was necessary to have a power generating station every few blocks because the resistance of the distribution wires themselves, in series with the intended load in a home or business, would seriously degrade the voltage available to the end user. As you will recall, all conductors like wires have a certain built-in resistance that is in series with the intended load of something like a light bulb. The amount of this resistance is generally expressed as a certain number of ohms per foot of conductor. Even though Edison's power company used extremely large conductors, the distances they could effectively span were quite short by modern standards. Today, power transmission lines can be up to hundreds of miles long because AC power is used rather than DC.

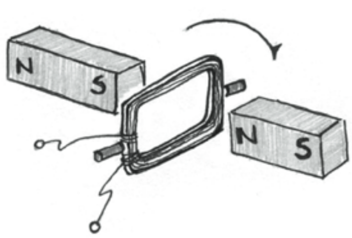
Alternating Current is able to overcome the difficulty of power loss by using a very high voltage in long transmission lines. Power loss in a circuit is determined by the formula Ploss = P2R/E2. Since the value of E is present in the denominator, the higher that number is, the smaller the total power loss will be. The current running through the line is actually quite small.

COPPER WIRE

RESISTANCE TABLE

AWG	Feet/Ω	Ω/100ft	Ampacity*
10	490.2	.204	30
12	308.7	.324	20
14	193.8	.516	15
16	122.3	.818	10
18	76.8	1.30	5
20	48.1	2.08	3.3
22	30.3	3.30	2.1
24	19.1	5.24	1.3
26	12.0	8.32	0.8
28	7.55	13.2	0.5

These Ohms / Distance figures are for a round trip circuit. Specifications are for copper wire at 77 degrees Fahrenheit or 25 degrees Celsius.



AS THE COIL OF WIRE ROTATES BETWEEN TWO MAGNETS, A VOLTAGE IS INDUCED. ELECTRONS FLOW FIRST IN ONE DIRECTION, AND THEN IN THE OTHER

AC as a general power source was developed by George Westinghouse and Nicola Tesla. Tesla worked for Edison at one time, but was fired for being too avant-garde. AC power is easily produced by a generator. Although DC generators are also possible, they require extra components to change the naturally formed Alternating Current into DC, and even so the current is more like a pulsating voltage rather than the steady voltage that comes from a battery. Alternating current is somewhat more dangerous to work with than DC power is because of the capacitor-like function of the neutral conductor. Capacitors temporarily store electrons, and will be covered later.

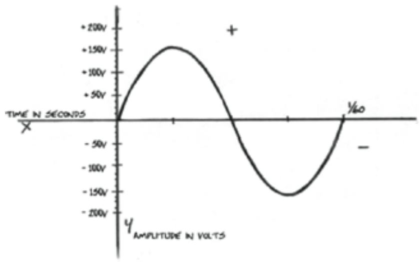
Edison tried to make safety an overriding issue for the power industry in order to promote his DC power companies over the more efficient AC system. Because Edison was a famous inventor, he was asked to design a "more humane" execution device; one that would replace hangings, and as a result designed an electric chair which he specified should use Alternating Current. He hoped this would create a public fear of that type of power generation. Although AC power is indeed more likely to harm people by means of a possible fatal electric shock, its ability to function better in transmission lines, and in other ways, far outweighs the dangers. (At least until you are the one shocked!)

AC is formed by a generator using magnetic force and electrical induction to create a voltage in a coil of wire. Electric motors and generators are very similar in construction. In fact, if a permanent magnet motor is turned by an external force, it will produce an electric current. Generators can be powered by wind, falling water, or steam from coal/gas/nuclear reactor, or any other mechanical means that will turn the coils of wire.

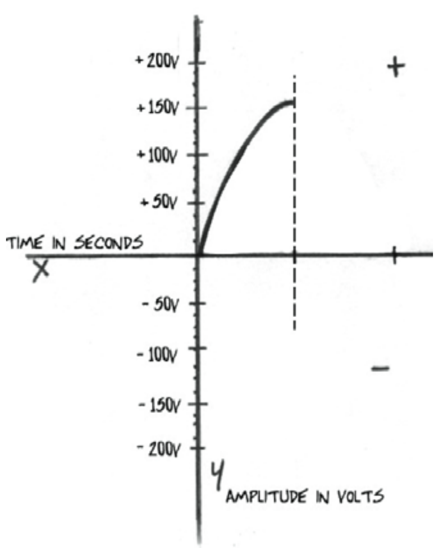
For our purposes we will imagine a theoretical generator that has inside of it permanent magnets of the type you have experimented with earlier. In reality, most power company generators use a more complicated, but more controllable system of electrically charged magnets. For our purposes, it is easier to visualize the action of a generator without concerning ourselves too much with the source of the magnetic fields.

A mechanical means is used to rotate a coil of wire in the presence of the magnetic field, and as the generator rotor spins, the coil of wire passes through different parts of that field. As discussed earlier, the voltage pressure induced by this action is at its peak when the coil is passing at an angle directly through the lines of magnetic force. It is at its weakest when passing along the lines of magnetic force. Reversing the motion of the wire coil will induce a voltage pushing in the opposite direction of the first one. Of course producing power this way would mean repeatedly stopping and starting the entire machine, which wouldn't work very well. Although in a practical generator the coil is always spinning in the same direction, electrically, it appears to have changed direction after turning 180°. At that point, the polarity of the magnetic force is the mirror image of what it was in the beginning. The net effect is to pull electrons in the opposite direction through the wire.

A graph is typically used to display the manner in which Alternating Current produces a voltage. In the graph below, the x axis represents time in seconds, while the y axis represents the strength of the EMF, given in volts.

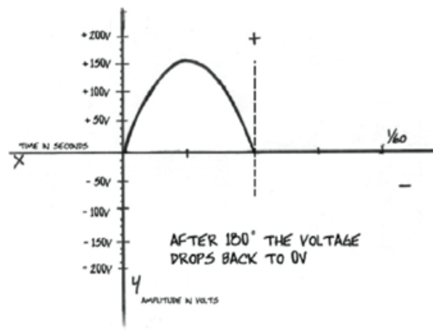


The induced voltage begins at 0, which is one of the points at which the coil of wire is moving directly along the lines of magnetic force. As the coil rotates 90˚, it passes directly across the lines of magnetic force, and the voltage is at its peak, with electrons moving in what we will call the first direction. Remember that voltage is a measurement of the force with which electrons are being pushed.

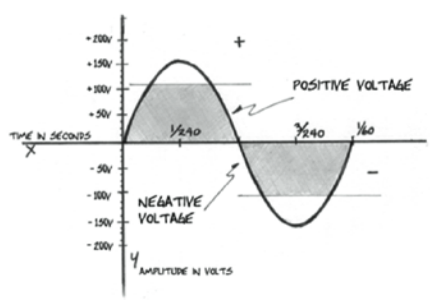


AS THE COIL OF WIRE ROTATES, FIRST IT PASSES ALONG THE LINES OF FORCE. THEN IT BEGINS TO CURVE INTO A LINE THAT CUTS ACROSS THE LINES OF MAGNETIC FORCE, WHICH INCREASES ITS VALUE.

As the coil of wire moves another 90˚, it again reaches a point where it is moving in the same direction as the lines of magnetic force, and at this precise moment no voltage is induced. This is represented on the graph as the place where the sine curve line touches the x axis for the second time.



At this point on the graph the voltage line dips below the x axis, as a result of the coil of wire continuing its movement through the magnetic field. But now its orientation is the mirror image of where it began. Flipping the coil of wire over produces the same effect as moving it in the opposite direction through the magnetic field as it was on the first half of its rotation. The induced current flow is in the opposite direction through the wire, and electron movement is in the opposite direction. This is shown on the graph as a line that dips below the x axis.



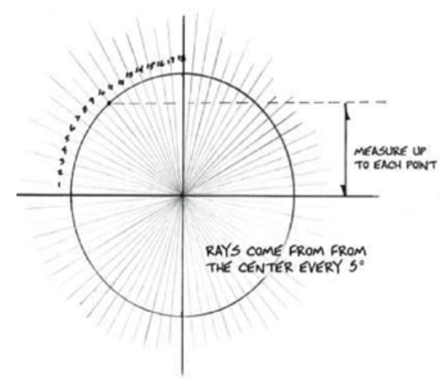
ONE CYCLE OF ALTERNATING CURRENT

THE USEFUL VOLTAGE THAT IS APPLIED TO THE LOAD IS THE AVERAGE VOLTAGE. THE RMS AVERAGE VOLTAGE IS INDICATED BY THE SHADED-IN AREA. THE ACTUAL PEAK VOLTAGE IS MUCH HIGHER.

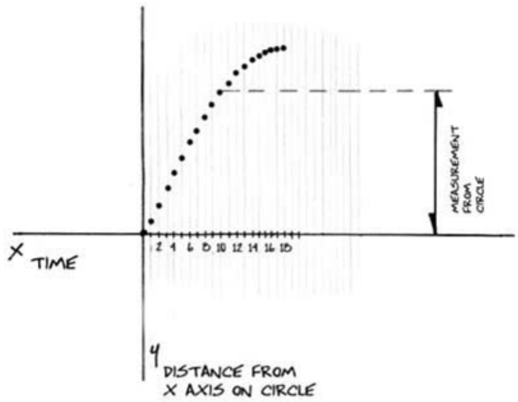
VOLTAGE TRAVELS ONE DIRECTION WHEN THE CURVE IS IN THE POSITIVE QUADRANT, AND THE OPPOSITE DIRECTION WHEN THE CURVE IS IN THE NEGATIVE QUADRANT

Electrons are now moving in the opposite direction through the wire, so the electro motive force or EMF becomes a negative value. The strength of the voltage in this opposite direction is again determined by the angle at which the coil of wire is passing through the lines of magnetic force. Since the same magnetic force is used, and the coil of wire has the same number of turns in it, the opposite flow of electrons should be equal to the right hand flow in every dimension other than being negative instead of positive. So the size and shape of the sine curve below the x axis is the same as the size and shape of the curve above the x axis. A sine curve is a specific shape. You may have noticed that it appears to slope upward most rapidly near the x axis, and that its rate of change slows dramatically near the top of the curve. A sine curve actually represents the passage of a point placed on a rotating circle with reference to a horizontal line. Note the position of the point as the circle spins. At first, close to the horizontal line, the point is moving almost straight up and the gap between the line and the point increases rapidly.

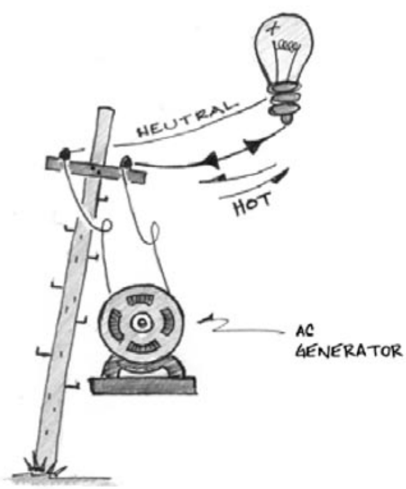
As the point reaches its furthermost distance from the horizontal line, the rate of change in its upward movement begins to slow, then stops entirely, then begins the same relative process for the next 90˚, moving downward as a mirror image. This process very closely mimics the passage of the coil of wire in a circle through the magnetic field. You can work this problem yourself by dividing a circle into 5˚ segments, and then measuring up from the horizontal line to specific points on the circle. Transfer these measurements to a graph using time as the x axis, and your measurements as the distance along the y axis. The result should plot out a sine wave.



In North America, generators spin at a speed of 60 revolutions per second, so the complete sine curve up and down motion is produced 60 times per second. For this reason, our alternating current is said to operate at 60 cycles. Hertz is the unit of measurement used to express one cycle, so another way of saying 60 cycles per second is 60Hertz or 60Hz.



CONNECTING THE DOTS WILL FORM A SINE CURVE



ALTERNATING CURRENT

AC HAS A HOT AND A NEUTRAL RATHER THAN A PLUS AND MINUS LIKE IN DIRECT CURRENT

Direct current like that from a battery has a negative terminal and a positive terminal, named for the way that type of current is formed. A different nomenclature is used for AC. Since the process of producing alternating current is by a generator and the current flow is so different, it is described as having a hot terminal and a neutral terminal. The hot wire is connected to the generator on the side where electrons are being pushed because of the inductive force. The neutral wire is used to complete the electrical circuit, but in many ways mimics the action of a capacitor.

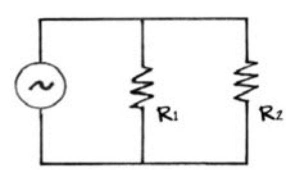
In electronics, capacitors are used to store electrons, and will be studied in more detail later on. Electrons can be "bunched up" inside a capacitor, and released later on. They are used in many different ways. It is also possible to store electrons in the earth, which can itself serve as a capacitor. If a wire is run from the neutral terminal of an electrical device to a grounding pole placed in the earth, this wire can take the place of the neutral, and electrons will still flow through the electrical circuit. They are pushed through the hot wire, stored in the earth, and then allowed to snap back during the negative half of the cycle as represented on the sine curve graph.

This phenomenon is at the heart of what makes alternating current more dangerous than direct current. Normally, a ground wire is used to make AC current safer, by providing an alternate path or circuit for electrons to take that has less resistance than the pathway through a person's body. Since the body acts as a resistor in series with a short circuit, and the ground wire has only the very small resistance of the wire, it will naturally draw off most of the current. This can be easily shown using Ohm's law.

In DC circuits there must be a direct connection back to the positive terminal in order to complete a pathway. You can still receive a shock from DC, but your body must interrupt the circuit. With AC, your body only need form an alternate route.

Many other materials can, in effect, take the place of the neutral conductor and if a person is placed in that alternative circuit a serious electrical shock will result. In this case the human body becomes a resistor, converting current into heat, causing damage to its cells. The higher the voltage, the more dangerous AC can be. At lower voltages, one will likely experience only a tingling sensation. The possibility of electric shock is greatly increased if a person is grounded to a metal structure, or if water is present. Water can be an excellent conductor when ions are in it.

OHM'S LAW AND GROUNDING



R1 = HUMAN BODY = 1,000 OHMS
R2 = GROUNDWIRE = 1 OHM
E = 120 VAC

I = E/R $\frac{E}{I \cdot R}$

HUMAN BODY

I = 120/1000 = .12 AMPERES

GROUND WIRE CIRCUIT

I = 120/1 = 120 AMPERES

IF A 20 AMP CIRCUIT BREAKER IS IN PLACE, THE 120 AMPS DOWN THE GROUND WIRE SHOULD TRIP THE CIRCUIT BREAKER IMMEDIATELY

STATIC ELECTRICITY

You walk across the rug, reach for the doorknob and zap! You get a static shock.

Or, you come inside from the cold, pull off your hat and surprise! Static hair - that static electricity makes your hair stand straight out from your head.

What is going on here? And why is static more of a problem in the winter?

To understand static electricity, we have to learn a little bit about the nature of matter. Or in other words, what is all the stuff around us made of?

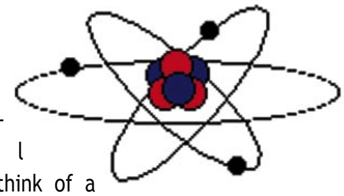
EVERYTHING IS MADE OF ATOMS

Imagine a pure gold ring. Divide it in half and give one of the halves away. Keep dividing and dividing and dividing. Soon you will have a piece so small you will not be able to see it without a microscope. It may be very, very small, but it is still a piece of gold. If you could keep dividing it into smaller and smaller pieces, you would finally get to the smallest piece of gold possible. It is called an atom. If you divided it into smaller pieces, it would no longer be gold.

Everything around us is made of atoms. Scientists so far have found only 115 different kinds of atoms. Everything you see is made of different combinations of these atoms.

PARTS OF AN ATOM

So what are atoms made of? In the middle of each atom is a "nucleus." The nucleus contains two kinds of tiny particles, called protons and neutrons. Orbiting around the nucleus are even smaller particles called electrons. The 115 kinds of atoms are different from each other because they have different numbers of protons, netrons and electrons.



t is useful to think of a model of the atom as similar to the solar system. The nucleus is in the center of the atom, like the sun in the center of the solar system. The electrons orbit around the nucleus like the planets around the sun. Just like in the solar system, the nucleus is large compared to the electrons. The atom is mostly empty space. And the electrons are very far away from the nucleus. While this model is not completely accurate, we can use it to help us understand static electricity.

ELECTRICAL CHARGES

Protons, neutrons and electrons are very different from each other. They have their own properties, or characteristics. One of these properties is called an electrical charge. Protons have what we call a "positive" (+) charge. Electrons have a "negative" (-) charge. Neutrons have no charge, they are neutral. The charge of one proton is equal in strength to the charge of one electron. When the number of protons in an atom equals the number of electrons, the atom itself has no overall charge, it is neutral.

ELECTRONS CAN MOVE

The protons and neutrons in the nucleus are held together very tightly. Normally the nucleus does not change. But some of the outer electrons are held very loosely. They can move from one atom to another. An atom that looses electrons has more positive charges (protons) than negative charges (electrons). It is positively charged. An atom that gains electrons has more negative than positive particles. It has a negative charge. A charged atom is called an "ion."

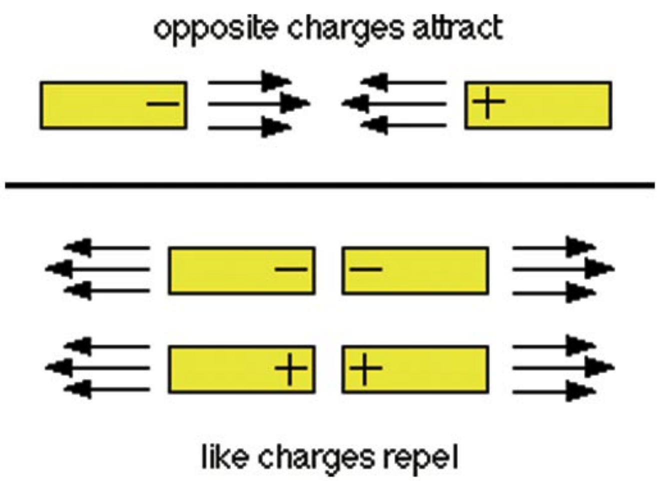
Some materials hold their electrons very tightly. Electrons do not move through them very well. These things are called insulators. Plastic, cloth, glass and dry air are good insulators. Other materials have some loosely held electrons, which move through them very easily. These are called conductors. Most metals are good conductors.

How can we move electrons from one place to another? One very common way is to rub two objects together. If they are made of different materials, and are both insulators, electrons may be transferred (or moved) from one to the other. The more rubbing, the more electrons move, and the larger the static charge that builds up. (Scientists believe that it is not the rubbing or friction that causes electrons to move. It is simply the contact between two different materials. Rubbing just increases the contact area between them.)

Static electricity is the imbalance of positive and negative charges.

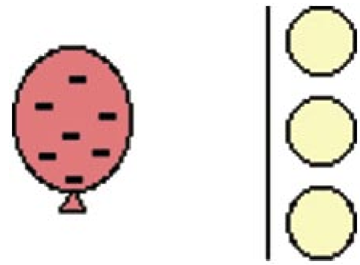
OPPOSITES ATTRACT

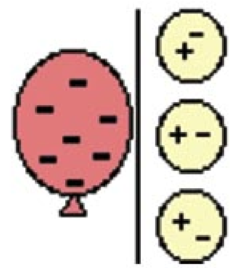
Now, positive and negative charges behave in interesting ways. Did you ever hear the saying that opposites attract? Well, it's true. Two things with opposite, or different charges (a positive and a negative) will attract, or pull towards each other. Things with the same charge (two positives or two negatives) will repel, or push away from each other.



A charged object will also attract something that is neutral. Think about how you can make a balloon stick to the wall. If you charge a balloon by rubbing it on your hair, it picks up extra electrons and has a negative charge. Holding it near a neutral object will make the charges in that object move. If it is a conductor, many electrons move easily to the other side, as far from the balloon as possible. If it is an insulator, the electrons in the atoms and molecules can only move very slightly to one side, away from the balloon. In either case, there are more positive charges closer to the negative balloon. Opposites attract. The balloon sticks. (At least until the electrons on the balloon slowly leak off.) It works the same way for neutral and positively charged objects.

So what does all this have to do with static shocks? Or static electricity in hair? When you take off your wool hat, it rubs against your hair. Electrons move from your hair to the hat. A static charge builds up and now each of the hairs has the same positive charge. Remember, things with the same charge repel each other. So the hairs try to get as far from each other as possible. The farthest they can get is by standing up and away from the others. And that is how static electricity causes a bad hair day!





As you walk across a carpet, electrons move from the rug to you. Now you have extra electrons and a negative static charge. Touch a door knob and ZAP! The door knob is a conductor. The electrons jump from you to the knob, and you feel the static shock.

We usually only notice static electricity in the winter when the air is very dry. During the summer, the air is more humid. The water in the air helps electrons move off you more quickly, so you can not build up as big a static charge.

TRIBOELECTRIC SERIES

When we rub two different materials together, which becomes positively charged and which becomes negative? Scientists have ranked materials in order of their ability to hold or give up electrons. This ranking is called the triboelectric series. A list of some common materials is shown here. Under ideal conditions, if two materials are rubbed together, the one higher on the list should give up electrons and become positively charged.

TRIBOELECTRIC SERIES

- your hand
- glass
- your hair
- nylon
- wool
- fur
- silk
- paper
- cotton
- hard rubber
- polyester
- polyvinylchloride plastic

CONSERVATION OF CHARGE

When we charge something with static electricity, no electrons are made or destroyed. No new protons appear or disappear. Electrons are just moved from one place to another. The net, or total, electric charge stays the same. This is called the principle of conservation of charge.

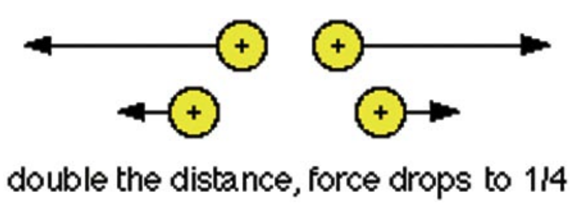
COULOMB'S LAW

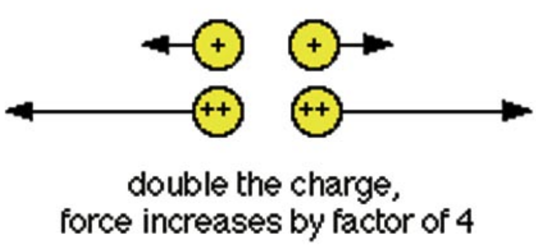
Charged objects create an invisible electric force field around themselves. The strength of this field depends on many things, including the amount of charge, distance involved, and shape of the objects. This can become very complicated. We can simplify things by working with "point sources" of charge. Point sources are charged objects which are much, much smaller than the distance between them.

Charles Coulomb first described electric field strengths in the 1780's. He found that for point charges, the electrical force varies directly with the product of the charges. In other words, the greater the charges, the stronger the field. And the field varies inversely with the square of the distance between the charges. This means that the greater the distance, the weaker the force becomes. This can be written as the formula:

$$F = k (q_1 X q_2) / d^2$$

where **F** is the force, q_1 and q_2 are the charges, and **d** is the distance between the charges. **k** is the proportionality constant, and depends on the material separating the charges.





DANGERS OF ELECTRICITY

Dangers of Electricity include a variety of hazards that include Electric Shock, Psychological Damage, Physical Burns, Neurological Damage and Ventricular fibrillation resulting in death.

Any form of energy, when not properly controlled or harnessed, can result in serious danger to those who use it. The risks inherent with electric power can generally be divided into two categories: direct and indirect. The direct danger is the damage that the power itself can do to the human body, such as stoppage of breathing or regular heartbeats, or burns. The indirect dangers of electricity include the damages that can result to the human body as a result of something caused by electric shock, such as a fall, an explosion, or a fire.

Electricity at any voltage can be dangerous and should always be approached with caution. An electric shock can occur upon contact of a human or animal body with any source of voltage high enough to cause sufficient current flow through the muscles or nerves. The minimum current a human can feel is thought to be about 1 milliampere (mA). As little as 80 milliampere, can seize the heart muscle. The current may cause tissue damage or heart fibrillation if it is sufficiently high. A fatal electric shock is referred to as electrocution.

PSYCHOLOGICAL

The perception of electric shock can be different depending on the voltage, duration, current, path taken, frequency, etc. Current entering the hand has a threshold of perception of about 5 to 10 mA (milliampere) for DC and about 1 to 10 mA for AC at 60 Hz. Shock perception declines with increasing frequency, ultimately disappearing at frequencies above 15-20 kHz.

BURNS

Dangers of Electricity include physical burns. High-voltage (> 500 to 1000 V) shocks tend to cause internal burns due to the large energy (which is proportional to the duration multiplied by the square of the voltage) available from the source. Damage due to current is through tissue heating. In some cases 16 volts might be fatal to a human being when the electricity passes through organs such as the heart.

VENTRICULAR FIBRILLATION

A low-voltage (110 to 220 V), 50 or 60-Hz AC current traveling through the chest for a fraction of a second may induce ventricular fibrillation at currents as low as 60mA. With DC, 300 to 500 mA is required. If the current has a direct pathway to the heart (e.g., via a cardiac catheter or other kind of electrode), a much lower current of less than 1 mA, (AC or DC) can cause fibrillation. Fibrillations are usually lethal because all the heart muscle cells move independently. Above 200mA, muscle contractions are so strong that the heart muscles cannot move at all.

NEUROLOGICAL EFFECTS

Other Dangers of Electricity cause interference with nervous control, especially over the heart and lungs. Repeated or severe electric shock which does not lead to death has been shown to cause neuropathy.

When the current path is through the head, it appears that, with sufficient current, loss of consciousness almost always occurs swiftly.

ARC FLASH

Arc flash and arc blast will always be present on the job, but proper awareness, training and the development of arc flash safety personal protection strategies can minimize the likelihood of injury and fatality.

The leading standard governing the calculation and determination of explosive hazard is the NFPA 70E - Electrical Safety in the Workplace. This electrical safety standard covers the full range of electrical safety issues from work practices to maintenance, special equipment requirements, and installation. In fact, OSHA in the United States already bases its electrical safety mandates on the comprehensive information in this important Standard.

Electrical safety is the leading subject in the North American power industry. Electrical accidents, when they occur (and they occur every day) are extremely debilitating and often fatal, depending on the voltage and amperage involved, as well as the conditions of electrocution. As little as 80 milliamps of electricity is enough energy to put the human heart into defibrillation and death. So, this subject should be addressed with commitment from electrical workers and their management.

HOW DOES ELECTRICITY WORK? CHAPTER 2

Learning The Terms

Electrical Circuits

Circuit Connections

Electrical Resistance

Current Electricity

Learning The Terms

WHAT ARE VOLTS / WATTS / AMPS?

The three most basic units in electricity are voltage (V), current (I, uppercase "i") and resistance (r). Voltage is measured in volts, current is measured in amps and resistance is measured in ohms.

A neat analogy to help understand these terms is a system of plumbing pipes. The voltage is equivalent to the water pressure, the current is equivalent to the flow rate, and the resistance is like the pipe size.

There is a basic equation in electrical engineering that states how the three terms relate. It says that the current is equal to the voltage divided by the resistance.

$$I = V/r$$

Let's see how this relation applies to the plumbing system. Let's say you have a tank of pressurized water connected to a hose that you are using to water the garden.

What happens if you increase the pressure in the tank? You probably can guess that this makes more water come out of the hose. The same is true of an electrical system: Increasing the voltage will make more current flow.

Let's say you increase the diameter of the hose and all of the fittings to the tank. You probably guessed that this also makes more water come out of the hose. This is like decreasing the resistance in an electrical system, which increases the current flow.

Electrical power is measured in watts. In an electrical system power (P) is equal to the voltage multiplied by the current.

$$P = VI$$

The water analogy still applies. Take a hose and point it at a waterwheel like the ones that were used to turn grinding stones in watermills. You can increase the power generated by the waterwheel in two ways. If you increase the pressure of the water coming out of the hose, it hits the waterwheel with a lot more force and the wheel turns faster, generating more power. If you increase the flow rate, the waterwheel turns faster because of the weight of the extra water hitting it.

ELECTRICAL EFFICIENCY

Electrical systems are more efficient when a higher voltage is used to reduce current.

In an electrical system, increasing either the current or the voltage will result in higher power. Let's say you have a system with a 6-volt light bulb hooked up to a 6-volt battery. The power output of the light bulb is 100 watts. Using the equation above, we can calculate how much current in amps would be required to get 100 watts out of this 6-volt bulb.

You know that P = 100 W, and V = 6 V. So you can rearrange the equation to solve for I and substitute in the numbers.

$$I = P/V = 100\ W / 6\ V = 16.66\ amps$$

What would happen if you use a 12-volt battery and a 12-volt light bulb to get 100 watts of power?

$$100\ W / 12\ V = 8.33\ amps$$

So this system produces the same power, but with half the current. There is an advantage that comes from using less current to make the same amount of power. The resistance in electrical wires consumes power, and the power consumed increases as the current going through the wires increases. You can see how this happens by doing a little rearranging of the two equations. What you need is an equation for power in terms of resistance and current. Let's rearrange the first equation:

I = V / R can be restated as V = I R

Now you can substitute the equation for V into the other equation:

P = V I substituting for V we get P = IR I, or P = I2R

What this equation tells you is that the power consumed by the wires increases if the resistance of the wires increases (for instance, if the wires get smaller or are made of a less conductive material). But it increases dramatically if the current going through the wires increases. So using a higher voltage to reduce the current can make electrical systems more efficient. The efficiency of electric motors also improves at higher voltages.

This improvement in efficiency is what is driving the automobile industry to adopt a higher voltage standard. Carmakers are moving toward a 42-volt electrical system from the current 12-volt electrical systems. The electrical demand on cars has been steadily increasing since the first cars were made. The first cars didn't even have electrical headlights; they used oil lanterns. Today cars have thousands of electrical circuits, and future cars will demand even more power. The change to 42 volts will help cars meet the greater electrical demand placed on them without having to increase the size of wires and generators to handle the greater current.

To help you remember, you can call it the West Virginia Law:

W = VA

That is, Watts = Volts * Amps.

Watts are a measure of power, which is work being done at a particular rate. That's why the power company charges you for kilowatt-hours: the rate of work per hour, times the number of hours. "Power" can be a little bit of work done quickly, like one small light bulb glowing very brightly, or a lot of work done slowly, like gradually charging up a car battery.

"Work" happens when something gives off light or heat, or when it moves. A light bulb or hair dryer is measured in watts: the higher the wattage, the faster it's doing its work, putting out more light or heat.

A Watt is defined as 1 joule/second. A "joule" is a unit of energy. In the case of electricity, it means you've pushed a certain number of electrons (measured in "coulombs", which I'll get back to in a second) across a certain voltage. The more electrons you push, and the harder you push them, the more light you get out of your light bulb.

"How hard you push" is measured in Volts. Voltage is like gravity, for electrical force. It's measured as the difference between two places. When you push a car off a cliff, the total amount of energy it gets is the difference between the cliff and the ground. With electricity, you have two wires from the power company, and the voltage is the electrical force between them. Connect them together, and current will flow with a particular force.

That "current" is how many electrons are moving past a point at a particular point in time. "How many electrons" is those coulombs again. The current is measured in amperes, which is a coulomb per second.

This is a lot of things to take in all at once, and it helps to think of it by analogy with water:

- A coulomb (number of electrons) is like a gallon of water
- An ampere (current) is like a gallon of water moving by in one second, just like water current
- A volt (voltage) is like a cliff that a waterfall is going over
- A watt (that is, volts * amps, voltage * current) is how fast work can be done by water going over the waterfall: how many gallons per second, and how hard they hit the bottom.
- A watt-second (or kilowatt-hour; same thing on a different scale) is the amount of work done by that water hitting the ground in 1 second.

People often used amps and watts interchangeably because for houses, the voltage is always the same: 110V. So if I tell you that this microwave draws 15 amps, you know how much power it uses: 15 amps * 110 V = ~1,500 W. Run your 1,500W microwave for an hour, and they'll charge you for 1.5 kilowatt-hours.

Looking at it in terms of electrons is just a bit more complicated, because there are two kinds of electricity. (Well, two main kinds) The simple kind is "Direct current", which really is just electrons flowing through a wire. That's the kind used inside electronic devices.

But that's not what comes into your house. What you get in your house is Alternating Current (AC). You don't actually get a flow of electrons. Instead, you get electrons pushed back and forth, a lot like the wave of the ocean. Thus, the actual power, voltage, and current actually vary cyclically, 60 times a second.

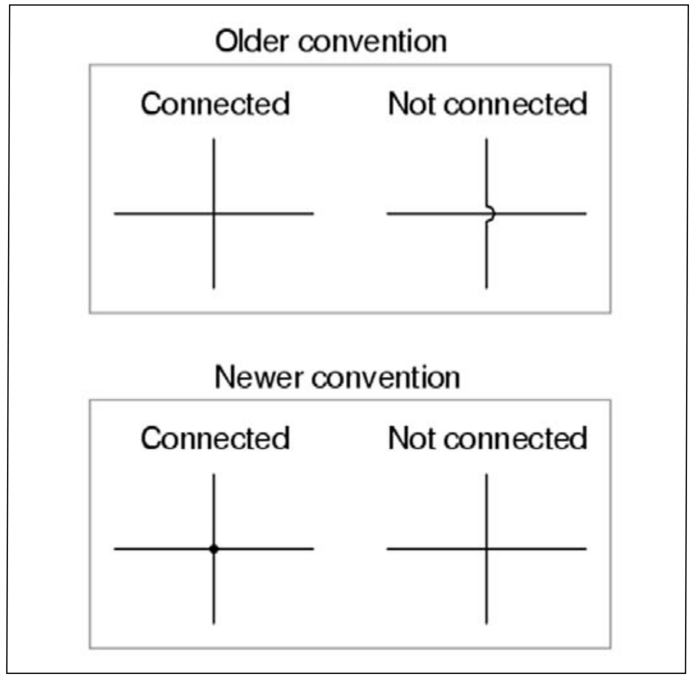
It turns out, though, that averaged over time, they're still doing about the same amount of work. Both the up-flows and down-flows of the wave are doing work. That's easiest to see in the case of a light bulb. The filament gets hot when electrons flow through it, but it doesn't matter which way the electrons are flowing. Strictly speaking, there's an instant (two instants, really) in each cycle where there are no electrons flowing, but the bulb stays hot through that instant. The bulb fluctuates very, very, very faintly because of it, but too faintly for your eyes to see and far too fast.

The wall wart that you use to connect electronic objects to the socket both converts electricity from high voltage to a reasonable amount, and sometimes converts it from AC to DC. It turns out that's not hard. You just send the current through one wire when it's going up, and another wire that reverses it when it's going down, and you get a continuous stream with a constant voltage.

Remember: the voltage is how much force the electrons move with. A small device like a calculator can't handle a lot of force, even if it's a small amount of electricity. It would be like trying to water a flower pot with your finger over the hose: the water squirts out in a very sharp stream, knocking over the plant. The same amount of water in the same time is more controllable when it comes out with less force.

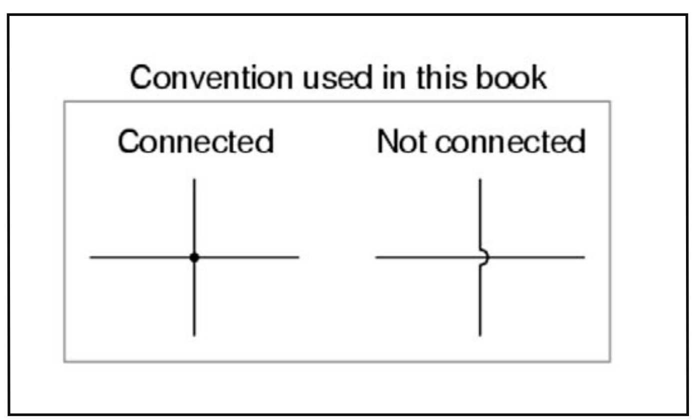
ELECTRICAL CIRCUITS

WIRES AND CONNECTIONS

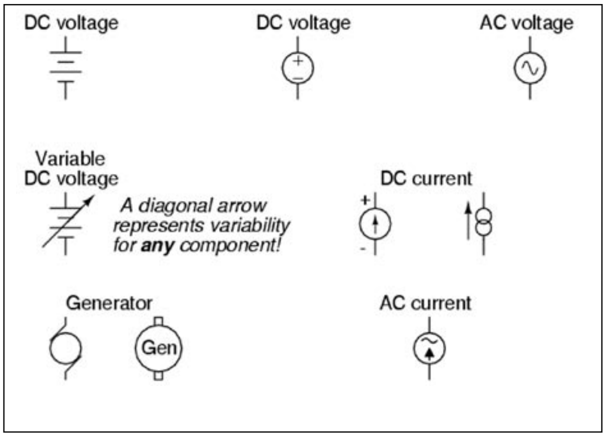


Older electrical schematics showed connecting wires crossing, while non-connecting wires "jumped" over each other with little half-circle marks. Newer electrical schematics show connecting wires joining with a dot, while non-connecting wires cross with no dot. However, some people still use the older convention of connecting wires crossing with no dot, which may create confusion.

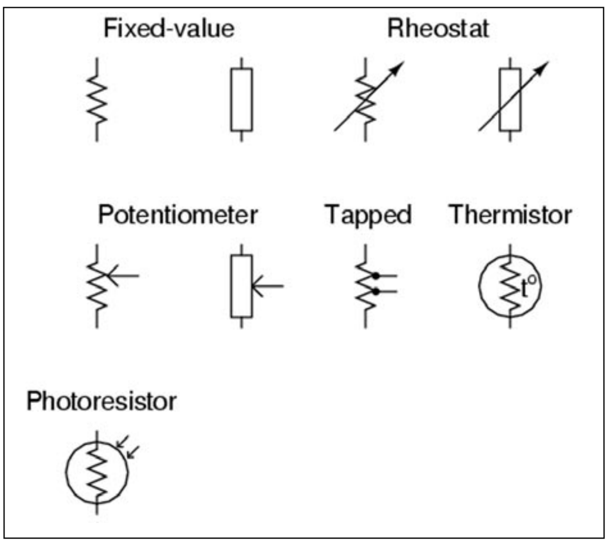
For this reason, I opt to use a hybrid convention, with connecting wires unambiguously connected by a dot, and non-connecting wires unambiguously "jumping" over one another with a half-circle mark. While this may be frowned upon by some, it leaves no room for interpretational error: in each case, the intent is clear and unmistakable:



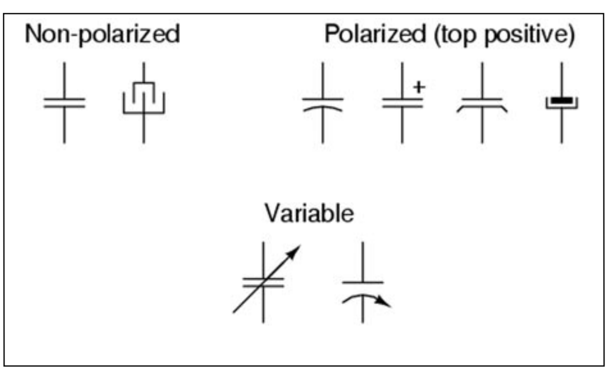
POWER SOURCES



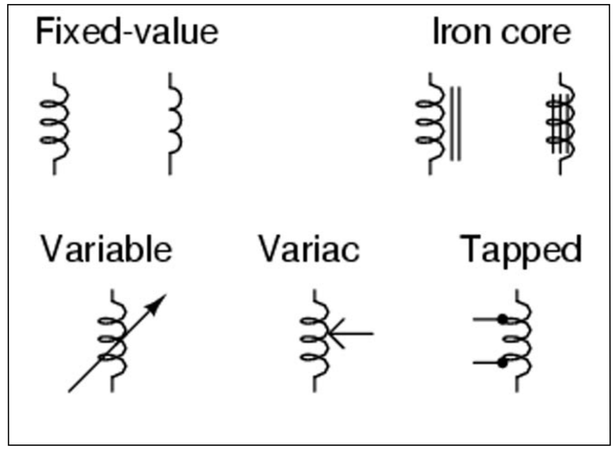
RESISTORS



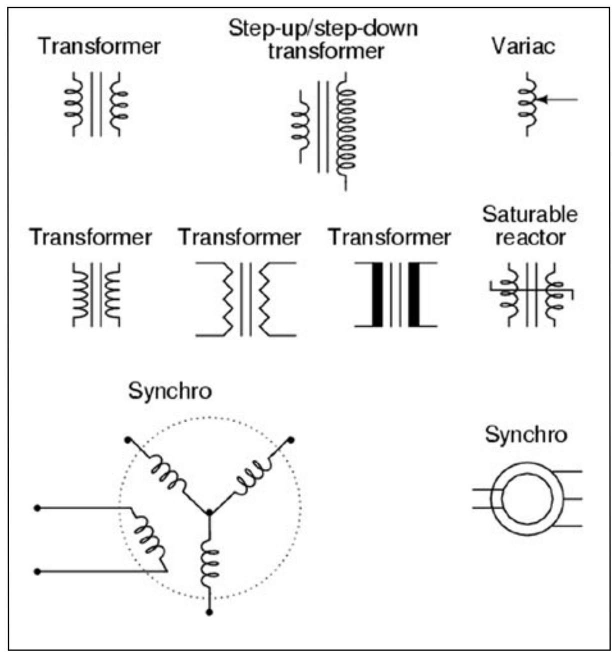
CAPACITORS



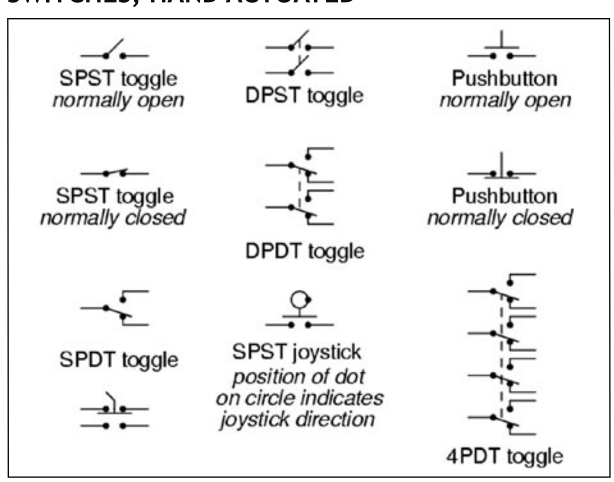
INDUCTORS



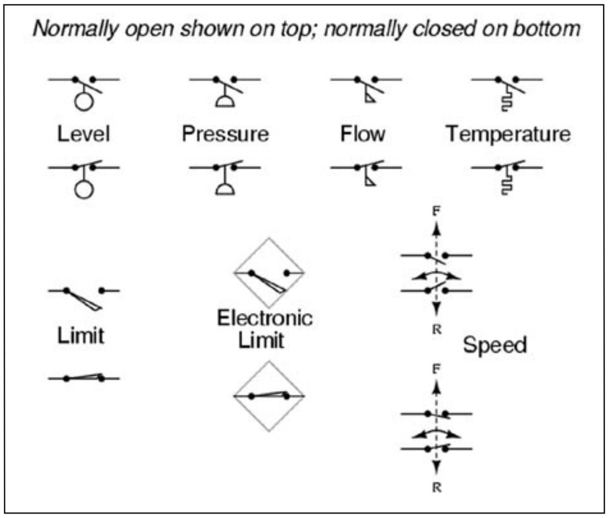
MUTUAL INDUCTORS



SWITCHES, HAND ACTUATED



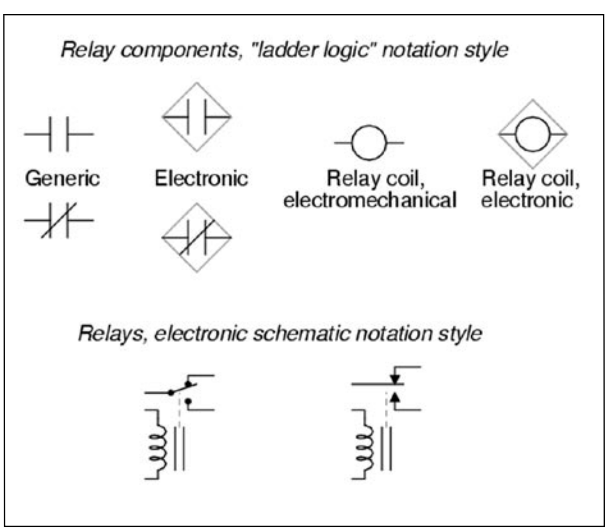
SWITCHES, PROCESS ACTUATED



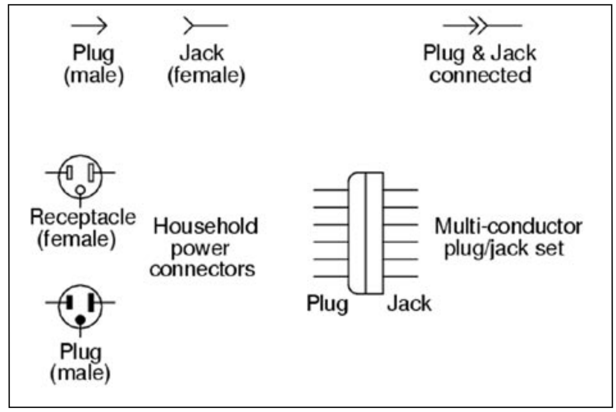
It is very important to keep in mind that the "normal" contact status of a process-actuated switch refers to its status when the process is absent and/or inactive, not "normal" in the sense of process conditions as expected during routine operation. For instance, a normally closed low-flow detection switch installed on a coolant pipe will be maintained in the actuated state (open) when there is regular coolant flow through the pipe. If the coolant flow stops, the flow switch will go to its "normal" (unactuated) status of closed.

A limit switch is one actuated by contact with a moving machine part. An electronic limit switch senses mechanical motion, but does so using light, magnetic fields, or other non-contact means.

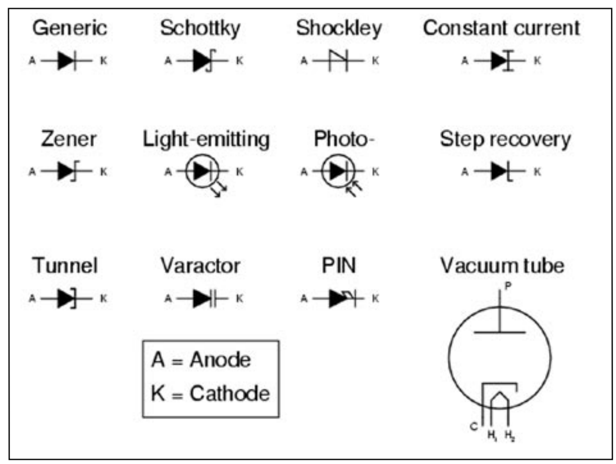
SWITCHES, ELECTRICALLY ACTUATED (RELAYS)



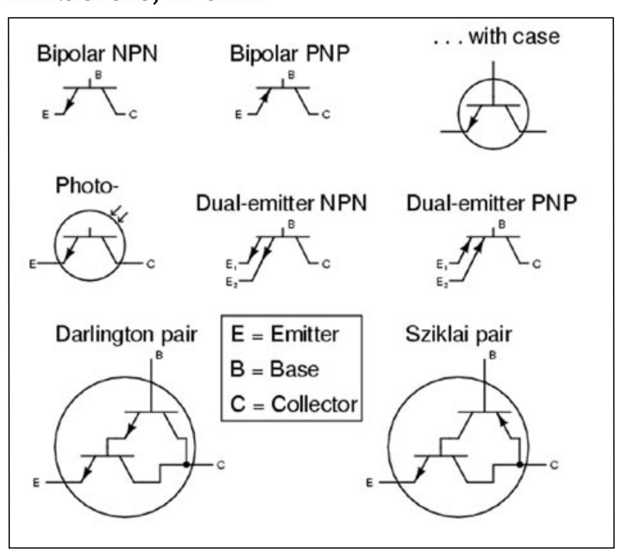
CONNECTORS



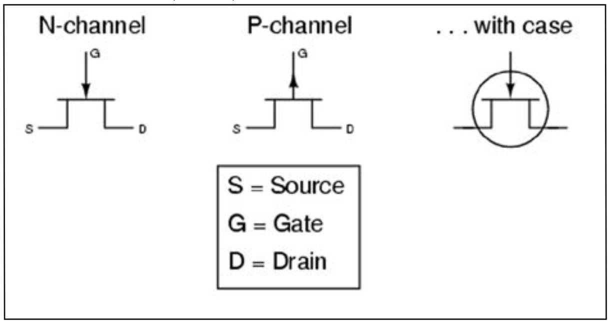
DIODES



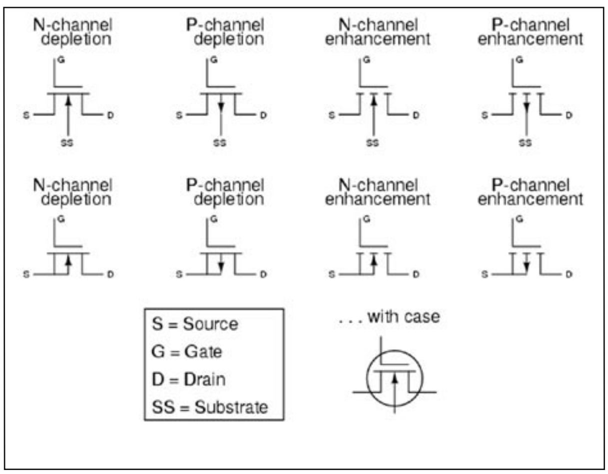
TRANSISTORS, BIPOLAR



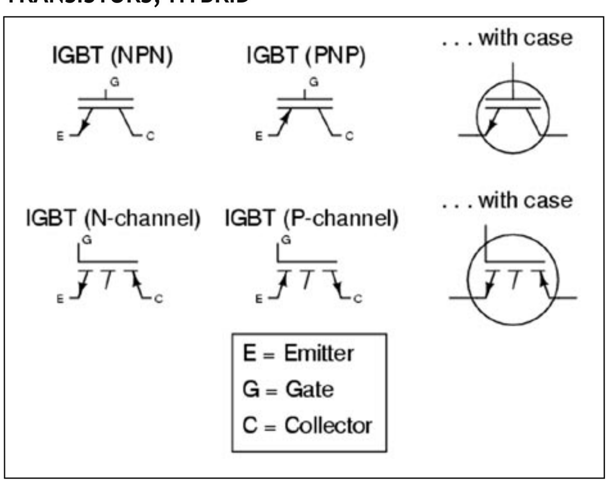
TRANSISTORS, JUNCTION FIELD-EFFECT (FJET)



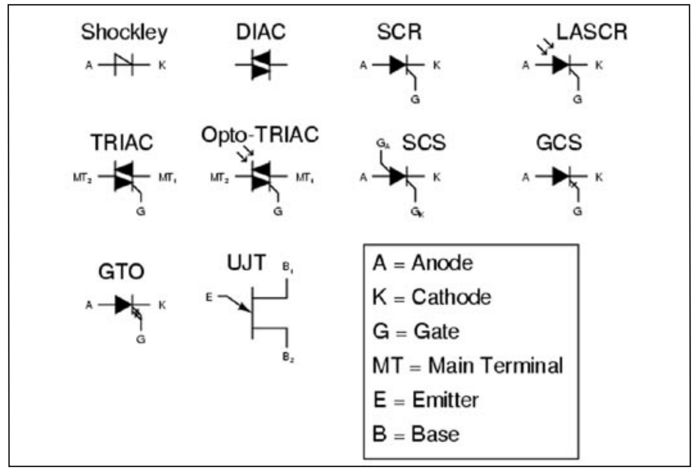
TRANSISTORS, INSULATED-GATE FIELD-EFFECT (IGFET OR MOSFET)



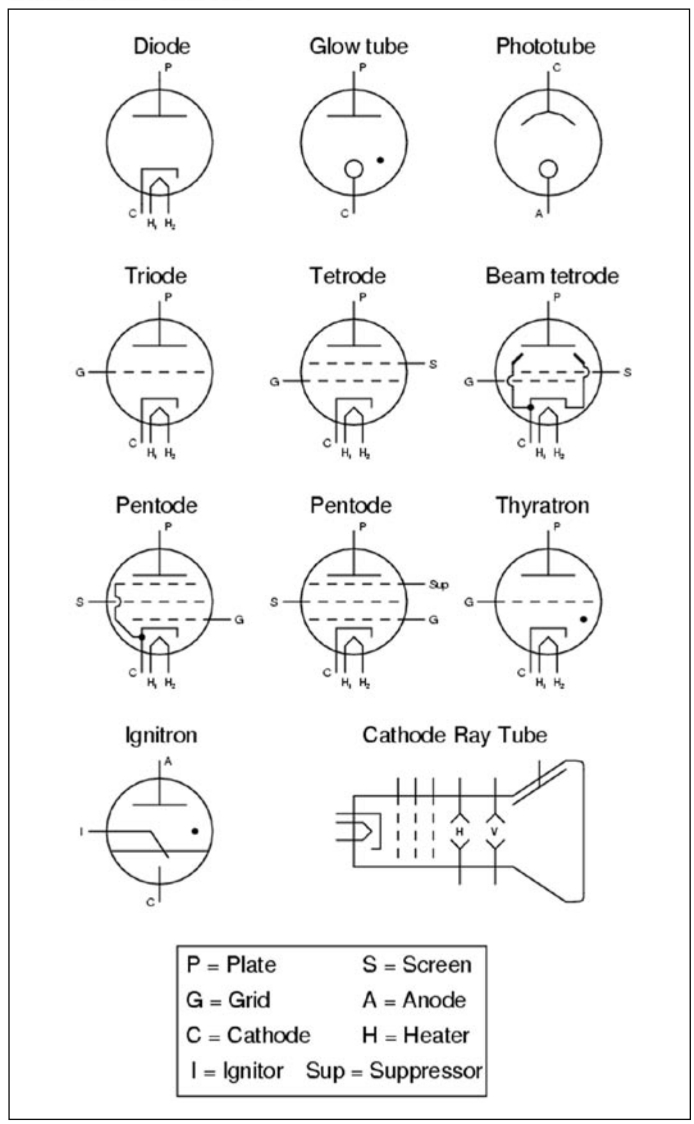
TRANSISTORS, HYBRID



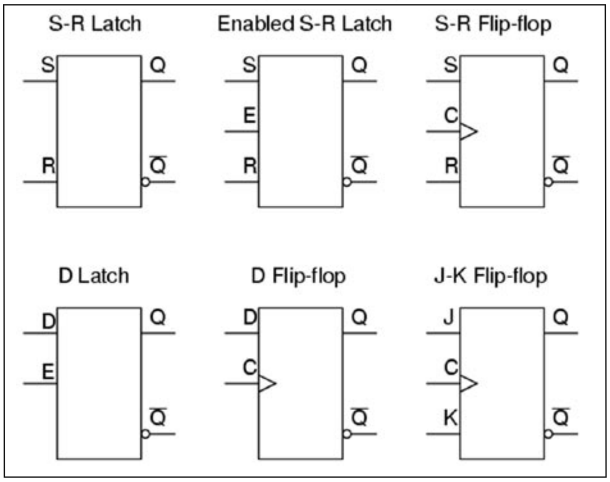
THYRISTORS



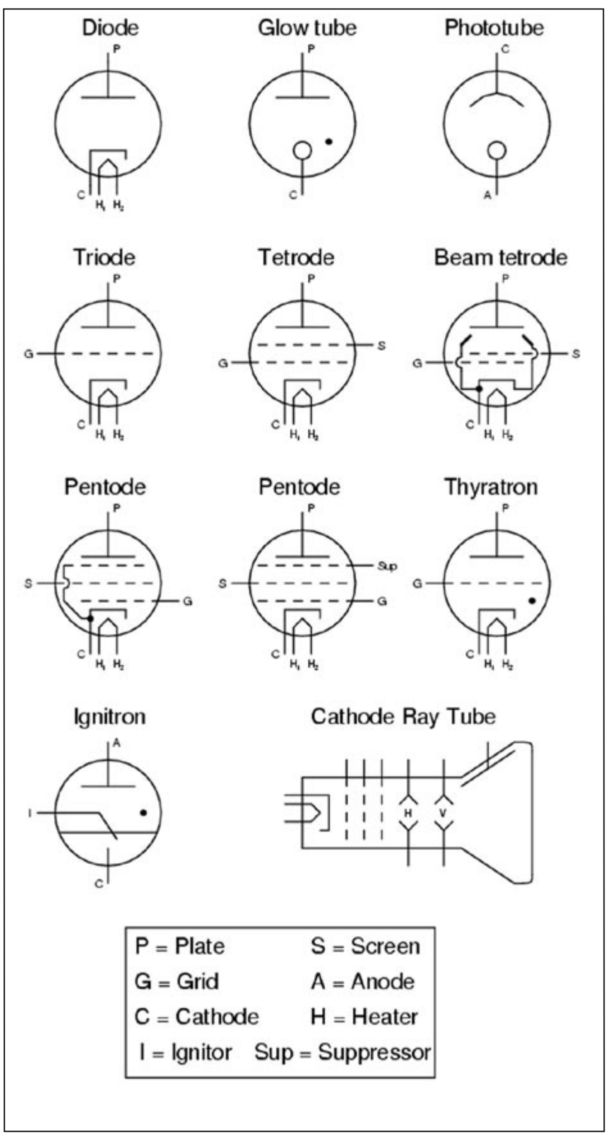
INTEGRATED CIRCUITS



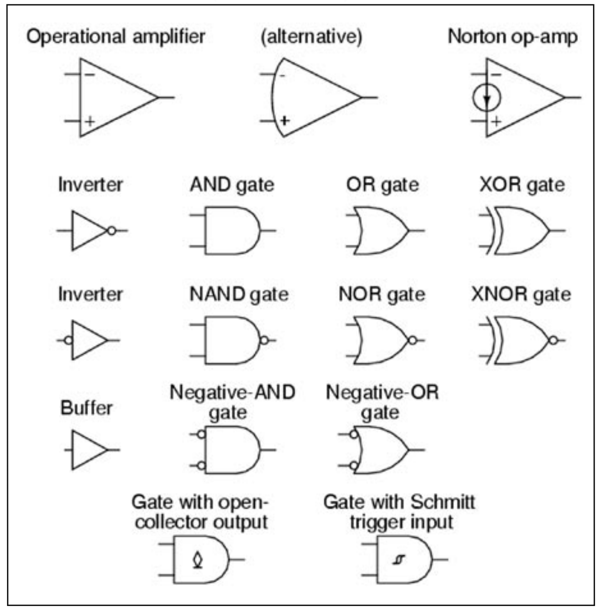
INTEGRATED CIRCUITS (CONTINUED)



ELECTRON TUBES



ELECTRON TUBES (CONTINUED)



Circuit Connections

CIRCUIT CONNECTIONS

CIRCUIT SYMBOLS AND CIRCUIT DIAGRAMS

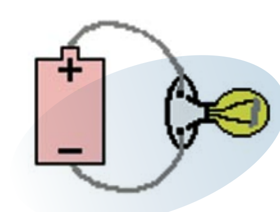
Thus far, this section has focused on the key ingredients of an electric circuit and upon the concepts of electric potential difference, current and resistance. Conceptual meaning of terms have been introduced and applied to simple circuits. Mathematical relationships between electrical quantities have been discussed and their use in solving problems have been modeled.

This section will focus on the means by which two or more electrical devices can be connected to form an electric circuit. Our discussion will progress from simple circuits to mildly complex circuits. Former principles of electric potential difference, current and resistance will be applied to these complex circuits and the same mathematical formulas will be used to analyze them.

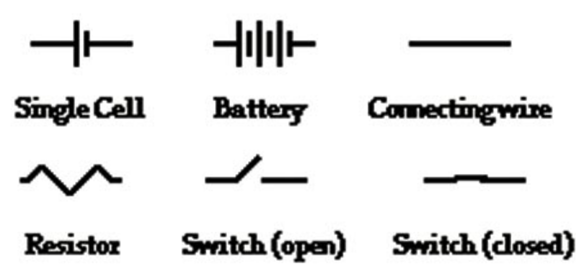
Electric circuits, whether simple or complex, can be described in a variety of ways. An electric circuit is commonly described with mere words. Saying something like "A light bulb is connected to a D-cell" is a sufficient amount of words to describe a simple circuit. On many occasions in this book, words have been used to describe simple circuits. Upon hearing (or reading) the words, a person grows accustomed to quickly picturing the circuit in their mind. But another means of describing a circuit is to simply draw it. Such drawings provide a quicker mental picture of the actual circuit. Circuit drawings like the one below have been used many times in this handbook.

Describing Circuits with Words
"A circuit contains a light bulb and a 1.5-Volt D-cell."

Describing Circuits with Drawings



A final means of describing an electric circuit is by use of conventional circuit symbols to provide a schematic diagram of the circuit and its components. Some circuit symbols used in schematic diagrams are shown here.



The + and - terminals of a battery.

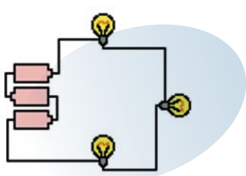
A single cell or other power source is represented by a long and a short parallel line. A collection of cells or battery is represented by a collection of long and short parallel lines.
In both cases, the long line is representative of the positive terminal of the energy source and the short line represents the negative terminal. A straight line is used to represent a connecting wire between any two components of the circuit. An electrical device which offers resistance to the flow of charge is generically referred to as a resistor and is represented by a zigzag line. An open switch is generally represented by providing a break in a straight line by lifting a portion of the line upward at a diagonal. These circuit symbols will be frequently used throughout the remainder of of the book as electric circuits are represented by schematic diagrams. It will be important to either memorize these symbols or to refer to this short listing frequently until you become accustomed to their use.

As an illustration of the use of electrical symbols in schematic diagrams, consider the following two examples.

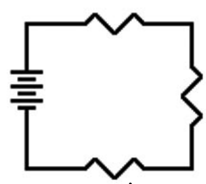
EXAMPLE 1:

Description with Words: Three D-cells are placed in a battery pack to power a circuit containing three light bulbs.

Drawing of Circuit



Schematic Diagram of Circuit



Using the verbal description, one can acquire a mental picture of the circuit being described. This verbal description can then be represented by a drawing of three cells and three light bulbs connected by wires. Finally, the circuit symbols presented above can be used to represent the same circuit. Note that three sets of long and short parallel lines have been used to represent the battery pack with its three D-cells. And note that each light bulb is represented by its own individual resistor symbol. Straight lines have been used to connect the two terminals of the battery to the resistors and the resistors to each other.

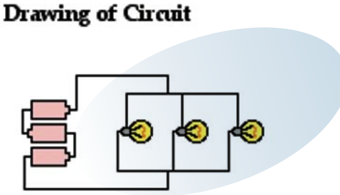
The above circuits presumed that the three light bulbs were connected in such a way that the charge flowing through the circuit would pass through each one of the three light bulbs in consecutive fashion. The path of a positive test charge leaving the positive terminal of the battery and traversing the external circuit would involve a passage through each one of the three connected light bulbs before returning to the negative terminal of the battery.

But is this the only way that three light bulbs can be connected? Do they have to be connected in consecutive fashion as shown above? Absolutely not! In fact, example 2 below contains the same verbal description with the drawing and the schematic diagrams being drawn differently.

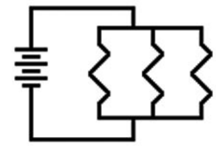
EXAMPLE 2:

Description with Words: Three D-cells are placed in a battery pack to power a circuit containing three light bulbs.

Drawing of Circuit



Schematic Diagram of Circuit



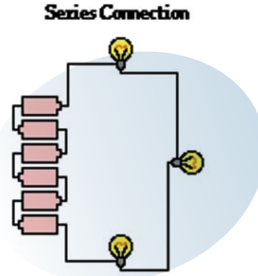
ture of the circuit being described. But this time, the connections of light bulbs is done in a manner such that there is a point on the circuit where the wires branch off from each other. The branching location is referred to as a node. Each light bulb is placed in its own separate branch. These branch wires eventually connect to each other to form a second node. A single wire is used to connect this second node to the negative terminal of the battery.

These two examples illustrate the two common types of connections made in electric circuits. When two or more resistors are present in a circuit, they can be connected in series or in parallel.

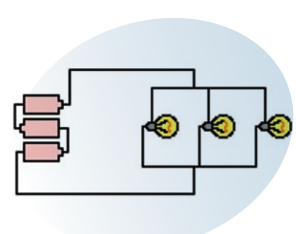
TWO TYPES OF CONNECTIONS

When there are two or more electrical devices present in a circuit with an energy source, there are a couple of basic means by which to connect them. They can be connected in series or connected in parallel. Suppose that there are three light bulbs connected together in the same circuit. If connected in series, then they are connected in such a way that an individual charge would pass through each one of the light bulbs in consecutive fashion. When in series, charge passes through every light bulb. If connected in parallel, a single charge passing through the external circuit would only pass through one of the light bulbs. The light bulbs are placed within a separate branch line, and a charge traversing the external circuit will pass through only one of the branches during its path back to the low potential terminal. The means by which the resistors are connected will have a major affect upon the overall resistance of the circuit, the total current in the circuit, and the current in each resistor. In Section 4, we will explore the effect of the type of connection upon the overall current and resistance of the circuit.

Series Connection



Parallel Connection



A common physics lab activity involves constructing both types of circuits with bulbs connected in series and bulbs connected in parallel. A comparison and contrast is made between the two circuits.

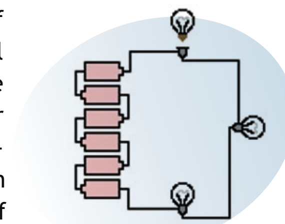
The main questions of concern in a lab activity such as this are typically the following:

- As the number of resistors (light bulbs) increases, what happens to the overall current within the circuit?
- As the number of resistors (light bulbs) increases, what happens to the overall resistance within the circuit?
- If one of the resistors is turned off (i.e., a light bulb goes out), what happens to the other resistors (light bulbs) in the circuit? Do they remain on (i.e., lit)?

In conducting the lab activity, distinctly different observations are made for the two types of circuits. A series circuit can be constructed by connecting light bulbs in such a manner that there is a single pathway for charge flow; the bulbs are added to the same line with no branching point. As more and more light bulbs are added, the brightness of each bulb gradually decreases. This observation is an indicator that the current within the circuit is decreasing.

So for series circuits, as more resistors are added, the overall current within the circuit decreases. This decrease in current is consistent with the conclusion that the overall resistance increases.

A final observation which is unique to series circuits is the effect of removing a bulb from a socket. If one of three bulbs in a series circuit is unscrewed from its socket, then it is observed that the other bulbs immediately go out. In order for the devices in a series circuit to work, each device must work. If one goes out, they all go out. Suppose that all the appliances in a household kitchen were all connected in series. In order for the refrigerator to work in that kitchen, the toaster oven, dishwasher, garbage disposal and overhead light would all have to be on. In order for one device in series to work, they all must work. If current is cut from any one of them, it is cut from all of them. Quite obviously, the appliances in the kitchen are not connected in series.



When one bulb is removed from its socket, the other bulbs in series "go out."

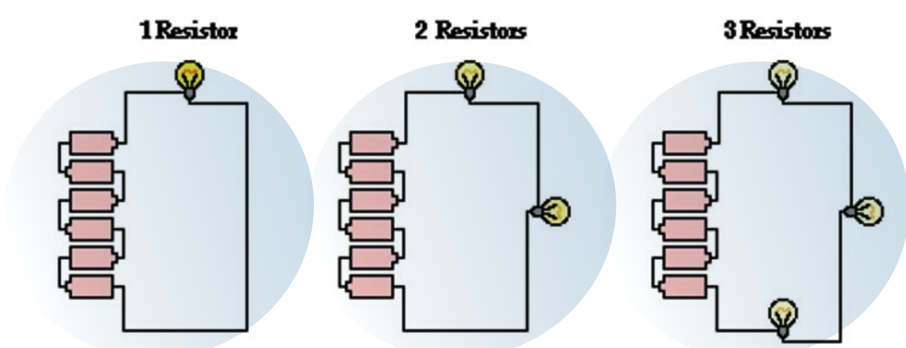
Using the same collection of wires, D-cells and bulbs, parallel circuits can be explored in the same manner. The effect of the number of resistors upon the overall current and the overall resistance can be investigated. The next set of diagrams depict the usual means of constructing the circuit with parallel connections of light bulbs. One will note that a study of the overall current for parallel connections requires the addition of an indicator bulb. The indicator bulb is placed outside of the branches and allows one to observe the effect of additional resistors upon the overall current. The bulbs which are placed in the parallel branches only provide an indicator of the current through that particular branch. So if investigating the effect of the number of resistors upon the overall current and resistance, one must make careful observations of the indicator bulb, not the bulbs which are placed in the branches. The diagram below depicts the typical observations.

It is clear from observing the indicator bulbs in the above diagrams that the addition of more resistors causes the indicator bulb to get brighter. For parallel circuits, as the number of resistors increases, the overall current also increases. This increase in current is consistent with a decrease in overall resistance. Adding more resistors in a separate branch has the unexpected result of decreasing the overall resistance!

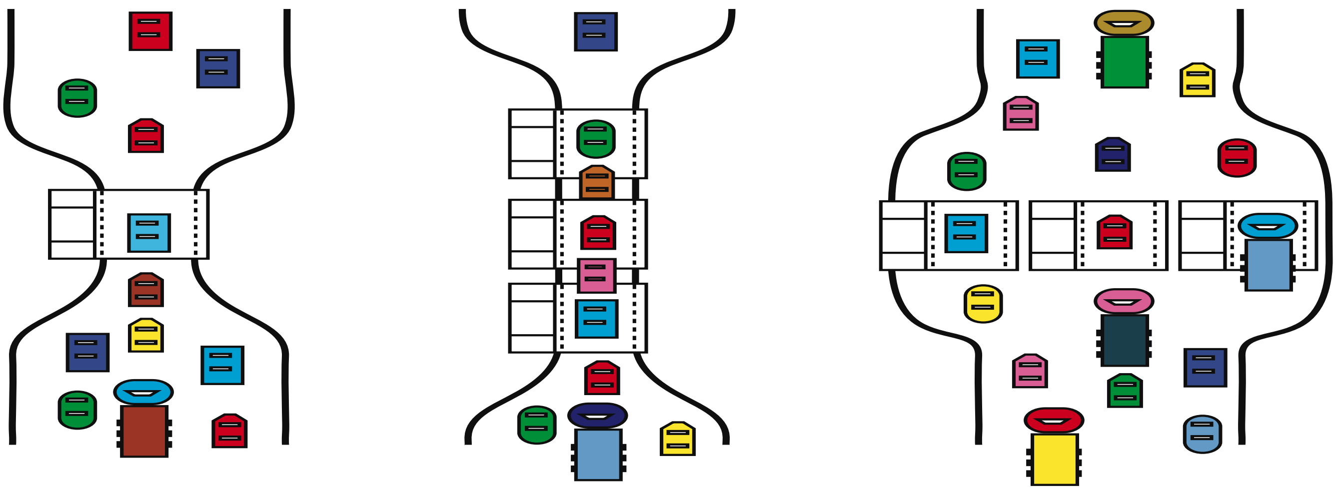
If an individual bulb in a parallel branch is unscrewed from its socket, then there is still current in the overall circuit and current in the other branches. Removing the third bulb from its socket has the effect of transforming the circuit from a three-bulb parallel circuit to a two-bulb parallel circuit. If the appliances in a household kitchen were connected in parallel, then the refrigerator could function without having to have the dishwasher, toaster, garbage disposal and overhead lights on. One appliance can work without the other appliances having to be on. Since each appliance is in its own separate branch, turning that appliance off merely cuts off the flow of charge to that branch. There will still be charge flowing through the other branches to the other appliances. Quite obviously, the appliances in a home are wired with parallel connections.

The effect of adding resistors is quite different if added in parallel compared to adding them in series. Adding more resistors in series means that there is more overall resistance; yet adding more resistors in parallel means that there is less overall resistance. The fact that one can add more resistors in parallel and produce less resistance is quite bothersome to many. An analogy may help to clarify

Series Connection of Light Bulbs



Influencing the Flow Rate on a Tollway



A Single Resistor | **Three Resistors Placed in Series** | **Three Resistors Placed in Parallel**

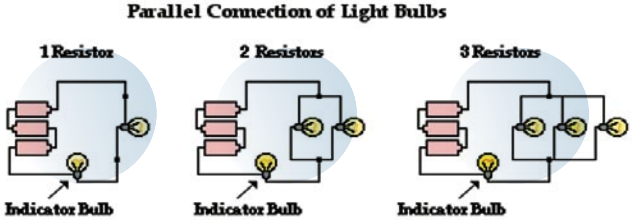
the reason behind this initially bothersome truth.

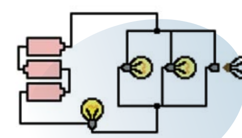
The flow of charge through the wires of a circuit can be compared to the flow of cars along a tollway system in a very crowded metropolitan area. The main source of resistance on a tollway system are the tollbooths. Stopping cars and forcing them to pay a toll at a tollbooth not only slows the cars down, but in a highly trafficked area, will also cause a bottleneck with a backup for miles. The rate at which cars flow past a point on that tollway system is reduced significantly by the presence of a tollbooth. Clearly, tollbooths are the main resistor to car flow.

Now suppose that in an effort to increase the flow rate the Tollway Authority decides to add two more tollbooths at a particular toll station where the bottleneck is troublesome to travelers. They consider two possible means of connecting their tollbooths - in series versus in parallel. If adding the tollbooths (i.e., resistors) in series, they would add them in a manner that every car flowing along the highway would have to stop at each tollbooth in consecutive fashion. With only one pathway through the tollbooths, each car would have to stop and pay a toll at each booth. Instead of paying 60 cents one time at one booth, they would now have to pay 20 cents three times at each of the three tollbooths. Quite obviously, adding tollbooths in series would have the overall affect of increasing the total amount of resistance and decreasing the overall car flow rate (i.e., current).

The other means of adding the two additional tollbooths at this particular toll station would be to add the tollbooths in parallel fashion. Each tollbooth could be placed in a separate branch. Cars flowing along the tollway would stop at only one of the three booths. There would be three possible pathways for cars to flow through the toll station and each car would chose only one of the pathways. Quite obviously, adding tollbooths in parallel would have the overall effect of decreasing the total amount of resistance and increasing the overall car flow rate (i.e., current) along the tollway. Just as is the case for adding more electrical resistors in parallel, adding more tollbooths in parallel branches creates less overall resistance. By allowing for more pathways (i.e., branches) by which charge and cars can flow through the bottleneck areas, the flow rate can be increased.

Parallel Connection of Light Bulbs



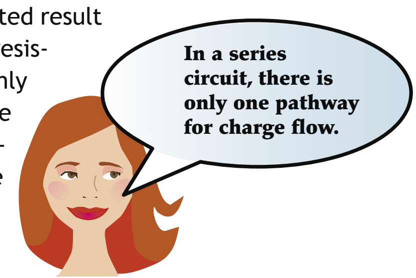


When one bulb is removed from its socket, the other bulbs in the parallel branches remain lit.

SERIES CIRCUITS

As mentioned earlier, two or more electrical devices in a circuit can be connected by series connections or by parallel connections. When all the devices are connected using series connections, the circuit is referred to as a series circuit. In a series circuit, each device is connected in a manner such that there is only one pathway by which charge can traverse the external circuit. Each charge passing through the loop of the external circuit will pass through each resistor in consecutive fashion.

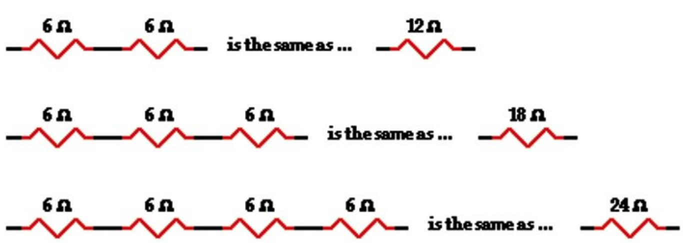
A short comparison and contrast between series and parallel circuits has been made in this handbook. There, it was emphasized that the act of adding more resistors to a series circuit results in the rather expected result of having more overall resistance. Since there is only one pathway through the circuit, every charge encounters the resistance of every device; so adding more devices results in more overall resistance. This increased resistance serves to reduce the rate at which charge flows (also known as the current).



EQUIVALENT RESISTANCE AND CURRENT

Charge flows together through the external circuit at a rate which is everywhere the same. The current is no greater at one location as it is at another location. The actual amount of current varies inversely with the amount of overall resistance. There is a clear relationship between the resistance of the individual resistors and the overall resistance of the collection of resistors. As far as the battery which is pumping the charge is concerned, the presence of two 6-Ω resistors in series would be equivalent to having one 12-Ω resistor in the circuit. The presence of three 6-Ω resistors in series would be equivalent to having one 18-W resistor in the circuit. And the presence of four 6-Ω resistors in series would be equivalent to having one 24-Ω resistor in the circuit.

Equivalent Resistance



This is the concept of equivalent resistance. The equivalent resistance of a circuit is the amount of resistance which a single resistor would need in order to equal the overall affect of the collection of resistors which are present in the circuit. For series circuits, the mathematical formula for computing the equivalent resistance (Req) is:

$$R_{eq} = R_1 + R_2 + R_3 + \ldots$$

where R_1, R_2, and R_3 are the resistance values of the individual resistors which are connected in series.

The current in a series circuit is the same everywhere. Charge does NOT pile up and begin to accumulate at any given location such that the current at one location is more than at other locations. Charge does NOT become used up by resistors such that there is less of it at one location compared to another. The charges can be thought of as marching together through the wires of an electric circuit, everywhere marching at the same rate. Current - the rate at which charge flows - is the same everywhere. It is the same at the first resistor as it is at the last resistor as it is in the battery. Mathematically, one might write:

$$I_{battery} = I_1 = I_2 = I_3 = \ldots$$

where I1, I2, and I3 are the current values at the individual resistor locations.

These current values are easily calculated if the battery voltage is known and the individual resistance values are known. Using the individual resistor values and the equation above, the equivalent resistance can be calculated. And using Ohm's law ($\Delta V = I \bullet R$), the current in the battery and thus through every resistor can be determined by finding the ratio of the battery voltage and the equivalent resistance.

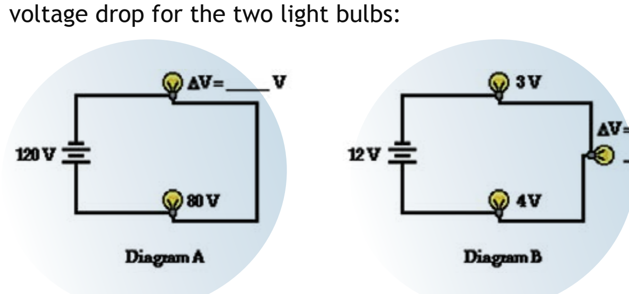
$$I_{battery} = I_1 = I_2 = I_3 = \Delta V_{battery} / R_{eq}$$

ELECTRIC POTENTIAL DIFFERENCE AND VOLTAGE DROPS

As discussed in Section 1, the electrochemical cell of a circuit supplies energy to the charge to move it through the cell and to establish an electric potential difference across the two ends of the external circuit. A 1.5-volt cell will establish an electric potential difference across the external circuit of 1.5 volts. This is to say that the electric potential at the positive terminal is 1.5 volts greater than at the negative terminal. As charge moves through the external circuit, it encounters a loss of 1.5 volts of electric potential. This loss in electric potential is referred to as a voltage drop. It occurs as the electrical energy of the charge is transformed to other forms of energy (thermal, light, mechanical, etc.) within the resistors or loads. If an electric circuit powered by a 1.5-volt cell is equipped with more than one resistor, then the cumulative loss of electric potential is 1.5 volts. There is a voltage drop for each resistor, but the sum of these voltage drops is 1.5 volts - the same as the voltage rating of the power supply. This concept can be expressed mathematically by the following equation:

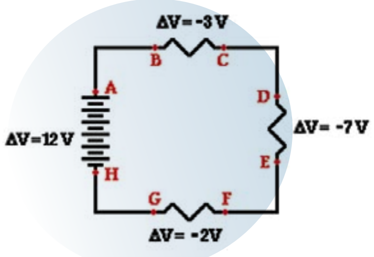
$$\Delta V_{battery} = \Delta V_1 + \Delta V_2 + \Delta V_3 + \ldots$$

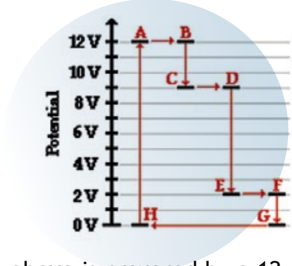
To illustrate this mathematical principle in action, consider the two circuits shown in Diagrams A and B. Suppose that you were to asked to determine the two unknown values of the electric potential difference across the light bulbs in each circuit. To determine their values, you would have to use the equation above. The battery is depicted by its customary schematic symbol and its voltage is listed next to it. Determine the voltage drop for the two light bulbs:



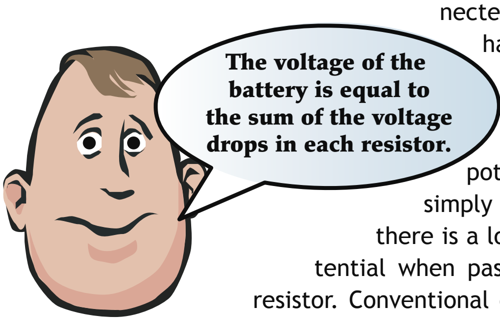
Answer: 40 volts (Diagram A) and 5 volts (Diagram B). The missing values can be determined by applying the principle that the sum of the voltage drops for each resistor is equal to the battery voltage.

Earlier in Section 1, the use of an electric potential diagram was discussed. An electric potential diagram is a conceptual tool for representing the electric potential difference between several points on an electric circuit. Consider the next circuit diagram and its corresponding electric potential diagram.





The circuit shown in the diagram above is powered by a 12-volt energy source. There are three resistors in the circuit connected in series, each having its own voltage drop. The negative sign for the electric potential difference simply denotes that there is a loss in electric potential when passing through the resistor. Conventional current is directed through the external circuit from the positive terminal to the negative terminal. Since the schematic symbol for a voltage source uses a long bar to represent the positive terminal, location A in the diagram is at the positive terminal or the high potential terminal. Location A is at 12 volts of electric potential and location H (the negative terminal) is at 0 volts. In passing through the battery, the charge gains 12 volts of electric potential. And in passing through the external circuit, the charge loses 12 volts of electric potential as depicted by the electric potential diagram shown to the right of the schematic diagram.



This 12 volts of electric potential is lost in three steps with each step corresponding to the flow through a resistor. In passing through the connecting wires between resistors, there is little loss in electric potential due to the fact that a wire offers relatively little resistance to the flow of charge. Since locations A and B are separated by a wire, they are at virtually the same electric potential of 12 V. When a charge passes through its first resistor, it loses 3 V of electric potential and drops down to 9 V at location C. Since location D is separated from location C by a mere wire, it is at virtually the same 9 V electric potential as C. When a charge passes through its second resistor, it loses 7 V of electric potential and drops down to 2 V at location E. Since location F is separated from location E by a mere wire, it is at virtually the same 2 V electric potential as E. Finally, as a charge passes through its last resistor, it loses 2 V of electric potential and drops down to 0 V at G. At locations G and H, the charge is out of energy and needs an energy boost in order to traverse the external circuit again. The energy boost is provided by the battery as the charge is moved from H to A.

In Section 3, Ohm's law ($\Delta V = I \bullet R$) was introduced as an equation which relates the voltage drop across a resistor to the resistance of the resistor and the current at the resistor. The Ohm's law equation can be used for any individual resistor in a series circuit. When combining Ohm's law with some of the principles already discussed, a big idea emerges.

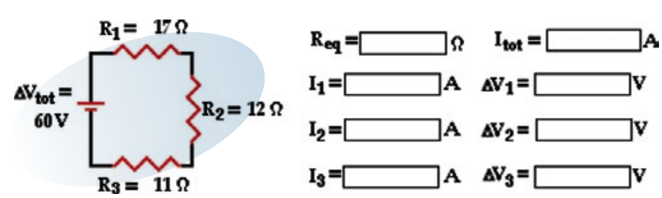
In series circuits, the resistor with the greatest resistance has the greatest voltage drop.

Since the current is everywhere the same within a series circuit, the I value of $\Delta V = I \bullet R$ is the same in each of the resistors of a series circuit. So the voltage drop (ΔV) will vary with varying resistance. Wherever the resistance is greatest, the voltage drop will be greatest about that resistor. The Ohm's law equation can be used to not only predict which resistor in a series circuit will have the greatest voltage drop, it can also be used to calculate the actual voltage drop values.

$$\Delta V_1 = I \bullet R_1 \quad \Delta V_2 = I \bullet R_2 \quad \Delta V_3 = I \bullet R_3$$

MATHEMATICAL ANALYSIS OF SERIES CIRCUITS

The above principles and formulae can be used to analyze a series circuit and determine the values of the current at and electric potential difference across each of the resistors in a series circuit. Their use will be demonstrated by the mathematical analysis of the circuit shown below. The goal is to use the formulae to determine the equivalent resistance of the circuit (Req), the current at the battery (Itot), and the voltage drops and current for each of the three resistors.



The analysis begins by using the resistance values for the individual resistors in order to determine the equivalent resistance of the circuit.

$$R_{eq} = R_1 + R_2 + R_3 = 17\ \Omega + 12\ \Omega + 11\ \Omega = 40\ \Omega$$

Now that the equivalent resistance is known, the current at the battery can be determined using the Ohm's law equation. In using the Ohm's law equation ($\Delta V = I \bullet R$) to determine the current in the circuit, it is important to use the battery voltage for ΔV and the equivalent resistance for R. The calculation is shown here:

$$I_{tot} = \Delta V_{battery} / R_{eq} = (60V) / (40\ \Omega) = 1.5\ amp$$

The 1.5 amp value for current is the current at the battery location. For a series circuit with no branching locations, the current is the same everywhere. The current at the battery location is the same as the current at each resistor location. Subsequently, the 1.5 amp is the value of I^1, I^2, and I^3.

$1_{battery} = I_1 = I_2 = I_3 = 1.5$ amp

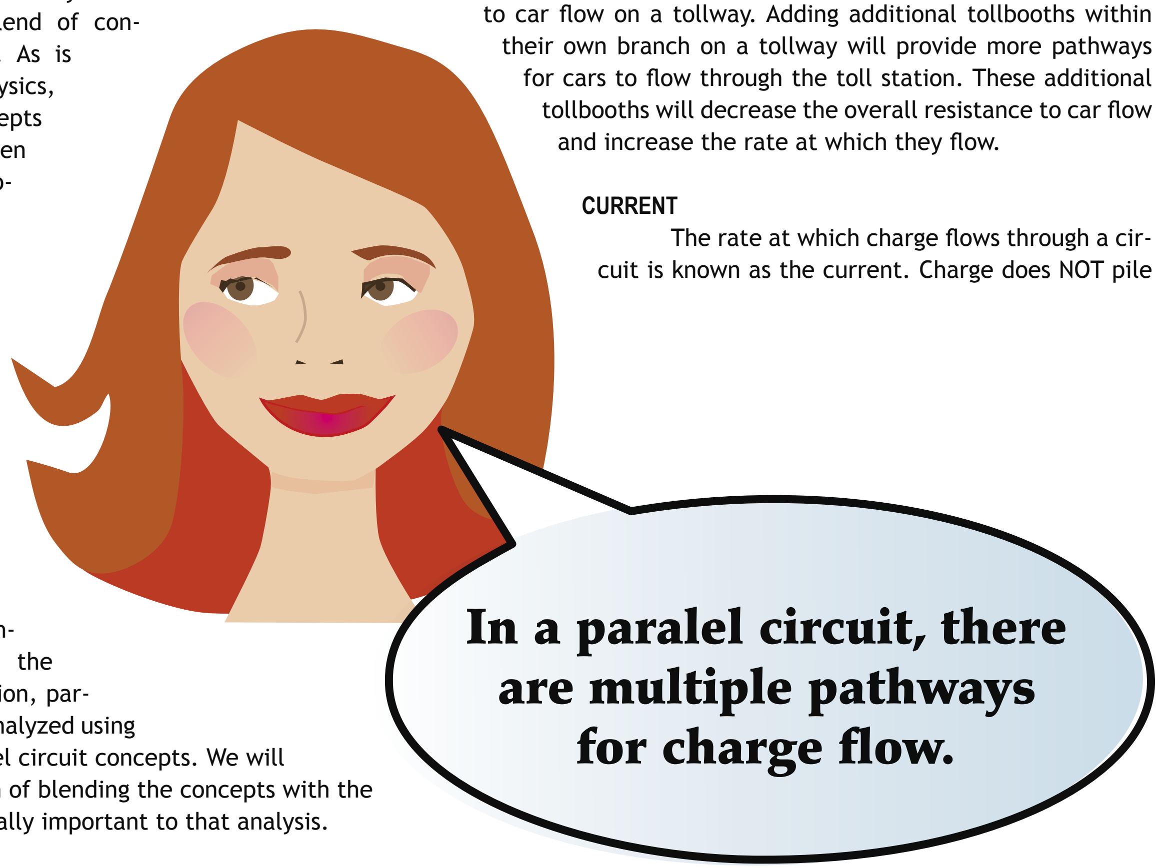
There are three values left to be determined - the voltage drops across each of the individual resistors. Ohm's law is used once more to determine the voltage drops for each resistor - it is simply the product of the current at each resistor (calculated earlier as 1.5 amp) and the resistance of each resistor (given in the problem statement). The calculations are shown here.

$\Delta V_1 = I_1 \cdot R_1$	$\Delta V_2 = I_2 \cdot R_2$	$\Delta V_3 = I_3 \cdot R_3$
$\Delta V_1 = (1.5A) \cdot (17\Omega)$	$\Delta V_2 = (1.5\ A) \cdot (12\Omega)$	$\Delta V_3 = (1.5A) \cdot (11\Omega)$
$\Delta V_1 = 25.5$ V	$\Delta V_2 = 18$ V	$\Delta V_3 = 16.5$ V

As a check of the accuracy of the mathematics performed, it is wise to see if the calculated values satisfy the principle that the sum of the voltage drops for each individual resistor is equal to the voltage rating of the battery. In other words,

Is $\Delta V_{battery} = \Delta V_1 + \Delta V_2 + \Delta V_3$?
Is 60 V = 25.5 V + 18 V + 16.5 V?
Is 60 V = 60 V?
Yes!!

The mathematical analysis of this series circuit involved a blend of concepts and equations. As is often the case in physics, the divorcing of concepts from equations when embarking on the solution to a physics problem is a dangerous act. Here, one must consider the concepts that the current is everywhere the same and that the battery voltage is equivalent to the sum of the voltage drops across each resistor in order to complete the mathematical analysis. In the next part of this section, parallel circuits will be analyzed using Ohm's law and parallel circuit concepts. We will see that the approach of blending the concepts with the equations will be equally important to that analysis.



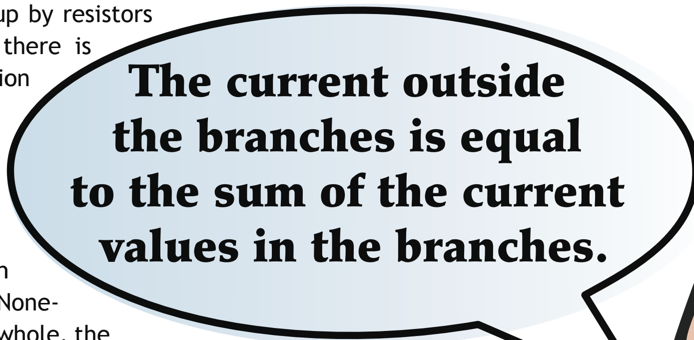
PARALLEL CIRCUITS

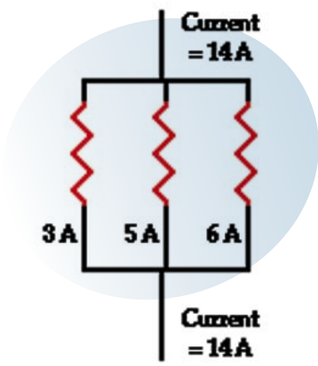
As mentioned earlier, two or more electrical devices in a circuit can be connected by series connections or by parallel connections. When all the devices are connected using parallel connections, the circuit is referred to as a parallel circuit. In a parallel circuit, each device is placed in its own separate branch. The presence of branch lines means that there are multiple pathways by which charge can traverse the external circuit. Each charge passing through the loop of the external circuit will pass through a single resistor present in a single branch. When arriving at the branching location or node, a charge makes a choice as to which branch to travel through on its journey back to the low potential terminal.

A short comparison and contrast between series and parallel circuits was made earlier in this section. There, it was emphasized that the act of adding more resistors to a parallel circuit results in the rather unexpected result of having less overall resistance. Since there are multiple pathways by which charge can flow, adding another resistor in a separate branch provides another pathway by which to direct charge through the main area of resistance within the circuit. This decreased resistance resulting from increasing the number of branches will have the effect of increasing the rate at which charge flows (also known as the current). In an effort to make this rather unexpected result more reasonable, a tollway analogy was introduced. A tollbooth is the main location of resistance to car flow on a tollway. Adding additional tollbooths within their own branch on a tollway will provide more pathways for cars to flow through the toll station. These additional tollbooths will decrease the overall resistance to car flow and increase the rate at which they flow.

CURRENT

The rate at which charge flows through a circuit is known as the current. Charge does NOT pile up and begin to accumulate at any given location such that the current at one location is more than at other locations. Charge does NOT become used up by resistors in such a manner that there is less current at one location compared to another. In a parallel circuit, charge divides up into separate branches such that there can be more current in one branch than there is in another. Nonetheless, when taken as a whole, the total amount of current in all the branches when added together is the same as the amount of current at locations outside the branches. The rule that current is everywhere the same still works, only with a twist. The current outside the branches is the same as the sum of the current in the individual branches. It is still the same amount of current, only split up into more than one pathway.





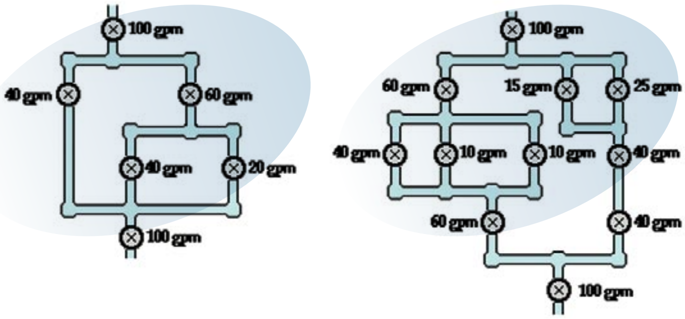
In equation form, this principle can be written as

$$I_{total} = I_1 + I_2 + I_3 + \ldots$$

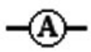
where Itotal is the total amount of current outside the branches (and in the battery) and I^1,1^2 and I^3 represent the current in the individual branches of the circuit.

Throughout this unit, there has been an extensive reliance upon the analogy between charge flow and water flow. Once more, we will return to the analogy to illustrate how the sum of the current values in the branches is equal to the amount outside of the branches. The flow of charge in wires is analogous to the flow of water in pipes. Consider the diagrams below in which the flow of water in pipes becomes divided into separate branches. At each node (branching location), the water takes two or more separate pathways. The rate at which water flows into the node (measured in gallons per minute) will be equal to the sum of the flow rates in the individual branches beyond the node. Similarly, when two or more branches feed into a node, the rate at which water flows out of the node will be equal to the sum of the flow rates in the individual branches which feed into the node.

The same principle of flow division applies to electric circuits. The rate at which charge flows into a node is equal to



the sum of the flow rates in the individual branches beyond the node. This is illustrated in the examples shown below. In the examples a new circuit symbol is introduced - the letter A enclosed within a circle.



Ammeter

This is the symbol for an ammeter - a device used to measure the current at a specific point. An ammeter is capable of measuring the current while offering negligible resistance to the flow of charge.

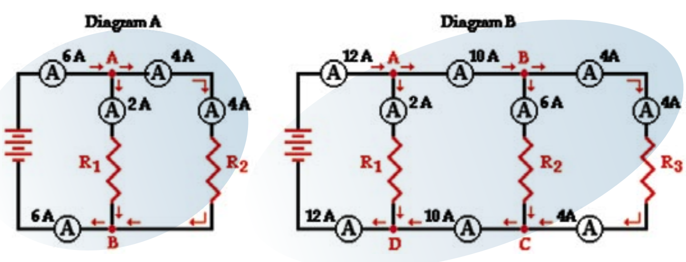


Diagram A displays two resistors in parallel with nodes at point A and point B. Charge flows into point A at a rate of 6 amps and divides into two pathways - one through resistor 1 and the other through resistor 2. The current in the branch with resistor 1 is 2 amps and the current in the branch with resistor 2 is 4 amps. After these two branches meet again at point B to form a single line, the current again becomes 6 amps. Thus we see the principle that the current outside the branches is equal to the sum of the current in the individual branches holds true.

$$I_{total} = I_1 + I_2$$
6 amps = 2 amps + 4 amps

Diagram B above may be slightly more complicated with its three resistors placed in parallel. Four nodes are identified on the diagram and labeled A, B, C and D. Charge flows into point A at a rate of 12 amps and divides into two pathways - one passing through resistor 1 and the other heading towards point B (and resistors 2 and 3). The 12 amps of current is divided into a 2 amp pathway (through resistor 1) and a 10 amp pathway (heading toward point B). At point B, there is further division of the flow into two pathways - one through resistor 2 and the other through resistor 3. The 10 amps of current approaching point B is divided into a 6 amp pathway (through resistor 2) and a 4 amp pathway (through resistor 3). Thus, it is seen that the current values in the three branches are 2 amps, 6 amps and 4 amps and that the sum of the current values in the individual branches is equal to the current outside the branches.

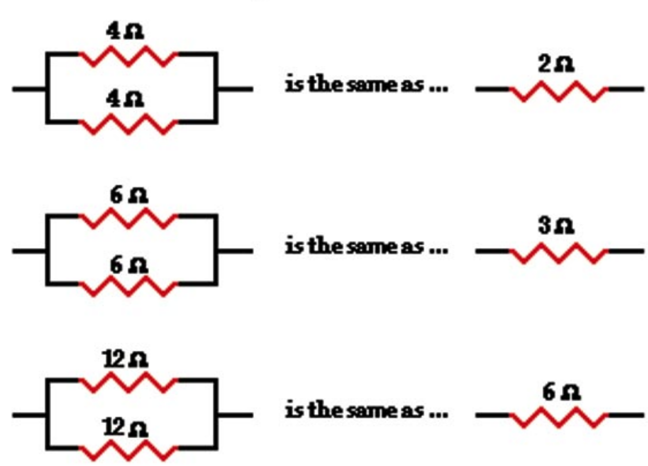
$$I_{total} = I_1 + I_2$$
12 amps = 2 amps + 6 amps + 4 amps

A flow analysis at points C and D can also be conducted and it is observed that the sum of the flow rates heading into these points is equal to the flow rate which is found immediately beyond these points.

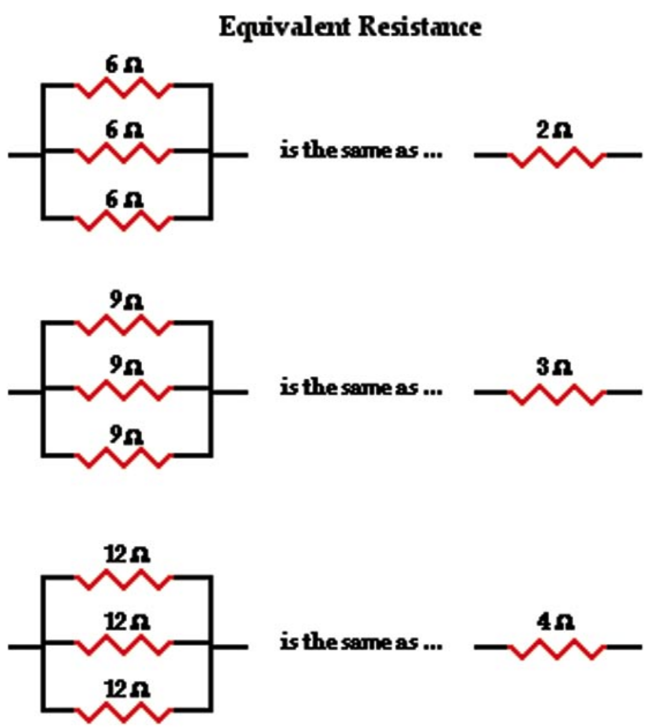
EQUIVALENT RESISTANCE

The actual amount of current always varies inversely with the amount of overall resistance. There is a clear relationship between the resistance of the individual resistors and the overall resistance of the collection of resistors. To explore this relationship, let's begin with the simplest case of two resistors placed in parallel branches, each having the same resistance value of 4 Ω. Since the circuit offers two equal pathways for charge flow, only one-half the charge will choose to pass through a given branch. While each individual branch offers 4 Ω of resistance to any charge that flows through it, only one-half of all the charge flowing through the circuit will encounter the 4 Ω resistance of that individual branch. Thus, as far as the battery which is pumping the charge is concerned, the presence of two 4-Ω resistors in parallel would be equivalent to having one 2-Ω resistor in the circuit. In the same manner, the presence of two 6-Ω resistors in parallel would be equivalent to having one 3-Ω resistor in the circuit. And the presence of two 12-Ω resistors in parallel would be equivalent to having one 6-Ω resistor in the circuit.

Equivalent Resistance



Now let's consider another simple case of having three resistors in parallel, each having the same resistance of 6 Ω. With three equal pathways for charge to flow through the external circuit, only one-third the charge will choose to pass through a given branch. Each individual branch offers 6 Ω of resistance to the charge that passes through it. However, the fact that only one-third of the charge passes through a particular branch means that the overall resistance of the circuit is 2 Ω. As far as the battery which is pumping the charge is concerned, the presence of three 6-Ω resistors in parallel would be equivalent to having one 2-Ω resistor in the circuit. In the same manner, the presence of three 9-Ω resistors in parallel would be equivalent to having one 3-Ω resistor in the circuit. And the presence of three 12-Ω resistors in parallel would be equivalent to having one 4-Ω resistor in the circuit.



This is the concept of equivalent resistance. The equivalent resistance of a circuit is the amount of resistance which a single resistor would need in order to equal the overall effect of the collection of resistors which are present in the circuit. For parallel circuits, the mathematical formula for computing the equivalent resistance (R_{eq}) is

$$1 / R_{eq} = 1 / R_1 + 1 / R_2 + 1 / R_3 + \ldots$$

where R_1, R_2, and R_3 are the resistance values of the individual resistors which are connected in parallel. The examples above could be considered simple cases in which all the pathways offer the same amount of resistance to an individual charge which passes through it. The simple cases above were done without the use of the equation.

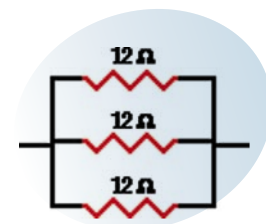
Yet the equation fits both the simple cases where branch resistors have the same resistance values and the more difficult cases where branch resistors have different resistance values. For instance, consider the application of the equation to the one simple and one difficult case shown here.

Case 1: Three 12 W resistors are placed in parallel

$$1/R_{eq} = 1/R_1 + 1/R_2 + 1/R_3$$
$$1/R_{eq} = 1/(12\ \Omega) + 1/(12\ \Omega) + 1/(12\ \Omega)$$

Using a calculator...

$$1/R_{eq} = 0.25\ \Omega^{-1}$$
$$R_{eq} = 1 / (0.25\ \Omega^{-1})$$
$$R_{eq} = 4.0\ \Omega$$

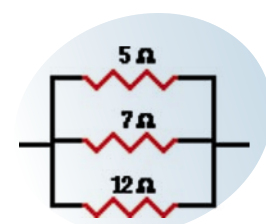


Case 2: A 5.0 Ω, 7.0 Ω, and 12 Ω resistor are placed in parallel

$$1/R_{eq} = 1/R_1 + 1/R_2 + 1/R_3$$
$$1/R_{eq} = 1/(5.0\ \Omega) + 1/(7\ \Omega) + 1/(12\ \Omega)$$

Using a calculator...

$$1/R_{eq} = 0.42619\ \Omega^{-1}$$
$$R_{eq} = 1 / (0.42619\ \Omega^{-1})$$
$$R_{eq} = 2.3\ \Omega$$



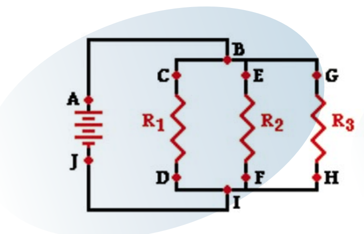
VOLTAGE DROPS FOR PARALLEL BRANCHES

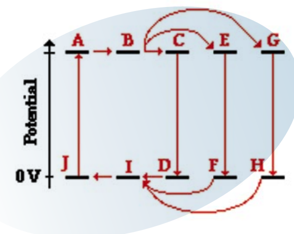
It has been emphasized that whatever voltage boost is acquired by a charge in the battery is lost by the charge as it passes through the resistors of the external circuit. The total voltage drop in the external circuit is equal to the gain in voltage as a charge passes through the internal circuit. In a parallel circuit, a charge does not pass through every resistor; rather, it passes through a single resistor. Thus, the entire voltage drop across that resistor must match the battery voltage. It matters not whether the charge passes through resistor 1, resistor 2, or resistor 3, the voltage drop across the resistor which it chooses to pass through must equal the voltage of the battery. Put in equation form, this principle would be expressed as

$$\Delta V_{battery} = \Delta V_1 = \Delta V_2 = \Delta V_3 = \ldots$$

If three resistors are placed in parallel branches and powered by a 12-volt battery, then the voltage drop across each one of the three resistors is 12 volts. A charge flowing through

the circuit would only encounter one of these three resistors and thus encounter a single voltage drop of 12 volts.
Electric potential diagrams were introduced in Section 1 of this unit and subsequently used to illustrate the consecutive voltage drops occurring in series circuits. An electric potential diagram is a conceptual tool for representing the electric potential difference between several points on an electric circuit. Consider the circuit diagram here and its corresponding electric potential diagram.



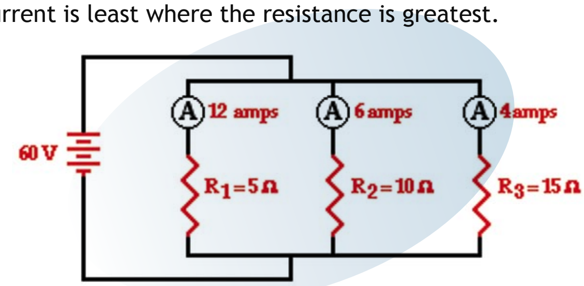


As shown in the electric potential diagram, positions A, B, C, E and G are all at a high electric potential. A single charge chooses only one of the three possible pathways; thus at position B, a single charge will move towards point C, E or G and then passes through the resistor that is in that branch. The charge does not lose its high potential until it passes through the resistor, either from C to D, E to F, or G to H. Once it passes through a resistor, the charge has returned to nearly 0 Volts and returns to the negative terminal of the battery to obtain its voltage boost. Unlike in series circuits, a charge in a parallel circuit encounters a single voltage drop during its path through the external circuit.

The current through a given branch can be predicted using the Ohm's law equation and the voltage drop across the resistor and the resistance of the resistor. Since the voltage drop is the same across each resistor, the factor which determines which resistor has the greatest current is the resistance. The resistor with the greatest resistance experiences the lowest current and the resistor with the least resistance experiences the greatest current. In this sense, it could be said that charge (like people) chooses the path of least resistance. In equation form, this could be stated as

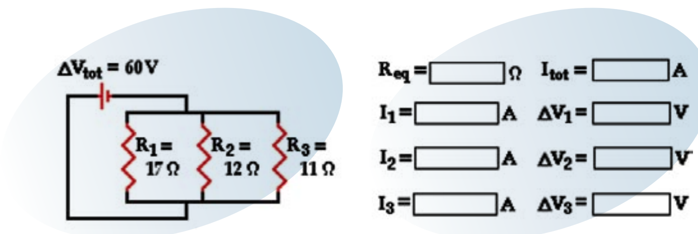
$$I_1 = \Delta V_1 / R_1 \qquad I_2 = \Delta V_2 / R_2 \qquad I_3 = \Delta V_3 / R_3$$

This principle is illustrated by the circuit shown here. The product of I•R is the same for each resistor (and equal to the battery voltage). Yet the current is different in each resistor. The current is greatest where the resistance is least and the current is least where the resistance is greatest.



MATHEMATICAL ANALYSIS OF PARALLEL CIRCUITS

The above principles and formulae can be used to analyze a parallel circuit and determine the values of the current at and electric potential difference across each of the resistors in a parallel circuit. Their use will be demonstrated by the mathematical analysis of the circuit shown below. The goal is to use the formulae to determine the equivalent resistance of the circuit (Req), the current through the battery (Itot), and the voltage drops and current for each of the three resistors.



The analysis begins by using the resistance values for the individual resistors in order to determine the equivalent resistance of the circuit.

$$1/R_{eq} = 1/R_1 + 1/R_2 + 1/R_3 = (1/17\ \Omega) + (1/12\ \Omega) + (1/11\ \Omega)$$
$$1/R_{eq} = 0.23306\ \Omega^{-1}$$
$$R_{eq} = 1 / (0.23306\ \Omega^{-1})$$
$$R_{eq} = 4.29\ \Omega$$
$$\text{(rounded from } 4.29063\ \Omega)$$

Now that the equivalent resistance is known, the current in the battery can be determined using the Ohm's law equation. In using the Ohm's law equation ($\Delta V = I \bullet R$) to determine the current in the battery, it is important to use the battery voltage for ΔV and the equivalent resistance for R. The calculation is shown here:

$$I_{tot} = \Delta V_{battery} / R_{eq} = (60\ V) / (4.29063\ \Omega)$$
$$I_{tot} = 14.0\ \text{amp}$$
$$\text{(rounded from } 13.98396\ \text{amp)}$$

The 60 V battery voltage represents the gain in electric potential by a charge as it passes through the battery. The charge loses this same amount of electric potential for any given pass through the external circuit. That is, the voltage drop across each one of the three resistors is the same as the voltage gained in the battery:

$$\Delta V_{battery} = \Delta V_1 = \Delta V_2 = \Delta V_3 = 60\ V$$

There are three values left to be determined - the current in each of the individual resistors. Ohm's law is used once more to determine the current values for each resistor - it is simply the voltage drop across each resistor (60 Volts) divided by the resistance of each resistor (given in the problem statement). The calculations are shown below.

$I_1 = \Delta V_1 / R_1$	$\Delta V_2 = \Delta V_2 / R_2$	$\Delta V_3 = \Delta V_3 / R_3$
$I_1 = (60V)/(17\Omega)$	$I_2 = (60V)/(1_3\Omega)$	$I_3 = (60V)/(11\Omega)$
$I_1 = 3.53$ amp	$I_2 = 5.00$ amp	$I_3 = 5.45$ amp

As a check of the accuracy of the mathematics performed, it is wise to see if the calculated values satisfy the principle that the sum of the current values for each individual resistor is equal to the total current in the circuit (or in the battery). In other words, is $I_{tot} = I_1 + I_2 + I_3$?

Is $I_{tot} = I_1 + I_2 + I_3$?
Is 14.0 amp = 3.53 amp + 5.00 amp + 5.45 amp?
Is 14.0 amp = 13.98 amp?

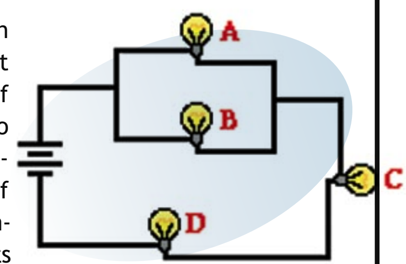
Yes!!

(The 0.02 amp difference is simply the result of having previously rounded the Itot value from 13.98.)

The mathematical analysis of this series circuit involved a blend of concepts and equations. As is often the case in physics, the divorcing of concepts from equations when embarking on the solution to a physics problem is a dangerous act. Here, one must consider the concepts that the current is everywhere the same and that the battery voltage is equivalent to the sum of the voltage drops across each resistor in order to complete the mathematical analysis. In the next part of this section, parallel circuits will be analyzed using Ohm's law and parallel circuit concepts. We will see that the approach of blending the concepts with the equations will be equally important to that analysis.

COMBINATION CIRCUITS

Previously, it was mentioned that there are two different ways to connect two or more electrical devices together in a circuit. They can be connected by means of series connections or by means of parallel connections. When all the devices in a circuit are connected by series connections, then the circuit is referred to as a series circuit. When all the devices in a circuit are connected by parallel connections, then the circuit is referred to as a parallel circuit. A third type of circuit involves the dual use of series and parallel connections in a circuit; such circuits are referred to as compound circuits or combination circuits. The circuit depicted here is an example of the use of both series and parallel connections within the same circuit. In this case, light bulbs A and B are connected by parallel connections and light bulbs C and D are connected by series connections. This is an example of a combination circuit.



When analyzing combination circuits, it is critically important to have a solid understanding of the concepts which pertain to both series circuits and parallel circuits. Since both types of connections are used in combination circuits, the concepts associated with both types of circuits apply to the respective parts of the circuit. The main concepts associated with series and parallel circuits are organized in the table below.

SERIES CIRCUITS

- The current is the same in every resistor; this current is equal to that in the battery.
- The sum of the voltage drops across the individual resistors is equal to the voltage rating of the battery.
- The overall resistance of the collection of resistors is equal to the sum of the individual resistance values,

$$R_{tot} = R_1 + R_2 + R_3 + \ldots$$

PARALLEL CIRCUITS

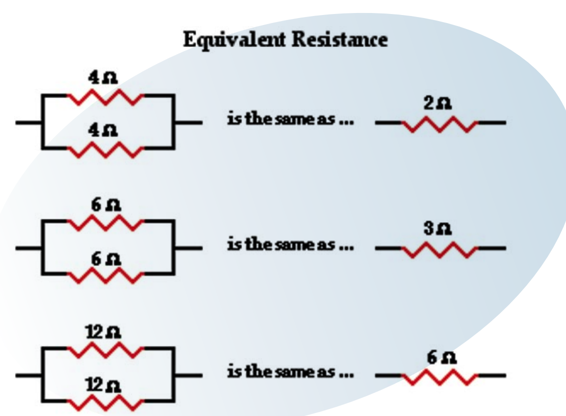
- The voltage drop is the same across each parallel branch.
- The sum of the current in each individual branch is equal to the current outside the branches.
- The equivalent or overall resistance of the collection of resistors is given by the equation

$$1/R_{eq} = 1/R_1 + 1/R_2 + 1/R_3 + \ldots$$

Each of these concepts has a mathematical expression. Combining the mathematical expressions of the above concepts with the Ohm's law equation ($\Delta V = I \cdot R$) allows one to conduct a complete analysis of a combination circuit.

Analysis of Combination Circuits

The basic strategy for the analysis of combination circuits involves using the meaning of equivalent resistance for parallel branches to transform the combination circuit into a series



circuit. Once transformed into a series circuit, the analysis can be conducted in the usual manner. Previously in Lesson 4, the method for determining the equivalent resistance of parallel branches was discussed. If the resistance of the branches are equal, then the total or equivalent resistance of those branches is equal to the resistance of one branch divided by the number of branches.

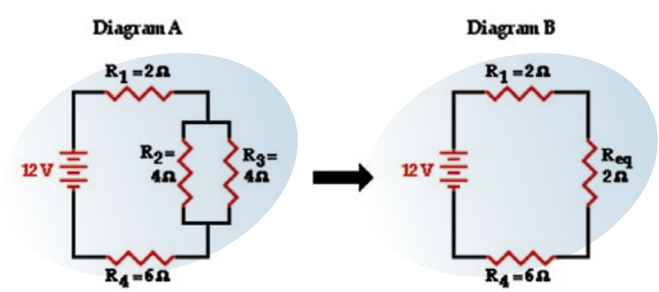
This method is consistent with the formula

$$1 / R_{eq} = 1 / R_1 + 1 / R_2 + 1 / R_3 + \ldots.$$

where R_1, R_2, and R_3 are the resistance values of the individual resistors which are connected in parallel. If the two or more resistors found in the parallel branches do not have equal resistance, then the above formula must be used. An example of this method was presented in a previous part of Section 4. By applying one's understanding of the equivalent resistance of parallel branches to a combination circuit, the combination circuit can be transformed into a series circuit. Then an understanding of the equivalent resistance of a series circuit can be used to determine the total resistance of the circuit. Consider the following diagrams: Diagram A represents a combination circuit with resistors R_2 and R_3 placed in parallel branches. Two 4-Ω resistors in parallel is equivalent to a resistance of 2 W. Thus, the two branches can be replaced by a single resistor with a resistance of 2 Ω. This is shown in Diagram B. Now that all resistors are in series, the formula for the total resistance of series resistors can be used to determine the total resistance of this circuit: The formula for series resistance is

$$R_{tot} = R_1 + R_2 + R_3 + \ldots$$

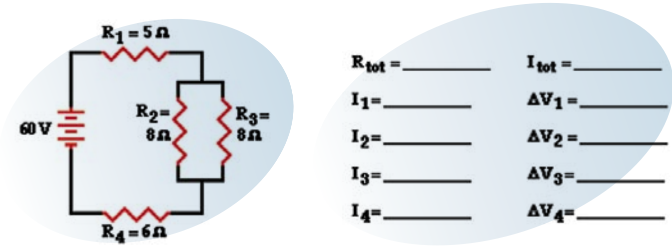
So in Diagram B, the total resistance of the circuit is 10 Ω.



Once the total resistance of the circuit is determined, the analysis continues using Ohm's law and voltage and resistance values to determine current values at various locations. The entire method is illustrated below with two examples.

EXAMPLE 1:

The first example is the easiest case - the resistors placed in parallel have the same resistance. The goal of the analysis is to determine the current in and the voltage drop across each resistor.



As discussed above, the first step is to simplify the circuit by replacing the two parallel resistors with a single resistor which has an equivalent resistance. Two 8 Ω resistors in series is equivalent to a single 4 Ω resistor. Thus, the two branch resistors (R_2 and R_3) can be replaced by a single resistor with a resistance of 4 W. This 4 W resistor is in series with R_1 and R_4. Thus, the total resistance is

$$R_{tot} = R_1 + 4\ \Omega + R_4 = 5\ \Omega + 4\ \Omega + 6\ \Omega$$
$$R_{tot} = 15\ \Omega$$

Now the Ohm's law equation ($\Delta V = I \bullet R$) can be used to determine the total current in the circuit. In doing so, the total resistance and the total voltage (or battery voltage) will have to be used.

$$I_{tot} = \Delta V_{tot} / R_{tot} = (60\ V) / (15\ \Omega)$$
$$I_{tot} = 4\ Amp$$

The 4 Amp current calculation represents the current at the battery location. Yet, resistors R_1 and R_4 are in series and the current in series-connected resistors is everywhere the same. Thus,

$$I_{tot} = I_1 = I_4 = 4\ Amp$$

For parallel branches, the sum of the current in each individual branch is equal to the current outside the branches. Thus, $I_2 + I_3$ must equal 4 Amp. There is an infinite possibilities of I_2 and I_3 values which satisfy this equation. Since the resistance values are equal, the current values in these two resistors is also equal. Therefore, the current in resistors 2 and 3 are both equal to 2 Amp.

$$I_1 = I_3 = 2\ Amp$$

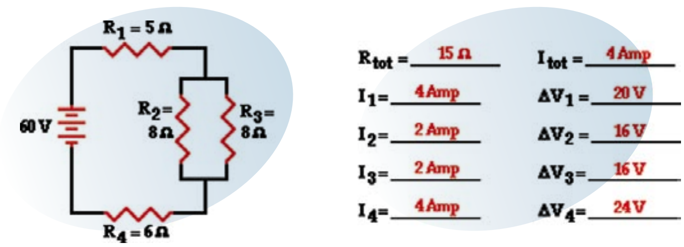
Now that the current at each individual resistor location is known, the Ohm's law equation ($\Delta V = I \bullet R$) can be used to determine the voltage drop across each resistor. These calculations are shown here.

$$\Delta V_1 = I_1 \bullet R_1 = (4\ Amp) \bullet (5\ \Omega)$$
$$\Delta V_1 = 20\ V$$

$\Delta V_2 = I_2 \bullet R_2 = (2\text{ Amp}) \bullet (8\ \Omega)$
$\Delta V_2 = 16\text{ V}$

$\Delta V_3 = I_3 \bullet R_3 = (2\text{ Amp}) \bullet (8\ \Omega)$
$\Delta V_3 = 16\text{ V}$

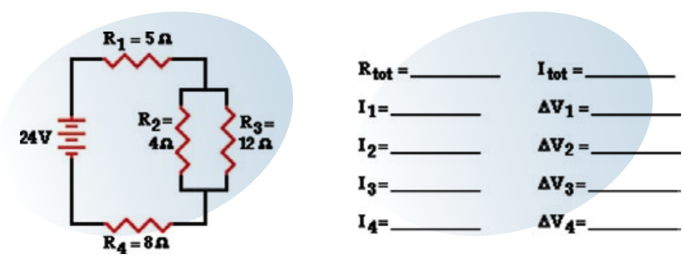
$\Delta V_4 = I_4 \bullet R_4 = (4\text{ Amp}) \bullet (6\ \Omega)$
$\Delta V_4 = 24\text{ V}$



The analysis is now complete and the results are summarized in this diagram.

EXAMPLE 2:

The second example is the more difficult case - the resistors placed in parallel have a different resistance value. The goal of the analysis is the same - to determine the current in and the voltage drop across each resistor.



As discussed above, the first step is to simplify the circuit by replacing the two parallel resistors with a single resistor with an equivalent resistance. The equivalent resistance of a 4 Ω and 12 Ω resistor placed in parallel can be determined using the usual formula for equivalent resistance of parallel branches:

$1 / R_{eq} = 1 / R_1 + 1 / R_2 + 1 / R_3 \ldots$
$1 / R_{eq} = 1 / (4\ \Omega) + 1 / (12\ \Omega)$
$1 / R_{eq} = 0.333\ \Omega\text{-}1$
$R_{eq} = 1 / (0.333\ \Omega\text{-}1)$
$R_{eq} = 3.00\ \Omega$

Based on this calculation, it can be said that the two branch resistors (R_2 and R_3) can be replaced by a single resistor with a resistance of 3 Ω. This 3 Ω resistor is in series with R_1 and R_4. Thus, the total resistance is

$R_{tot} = R_1 + 3\ \Omega + R_4 = 5\ \Omega + 3\ \Omega + 8\ \Omega$
$R_{tot} = 16\ \Omega$

Now the Ohm's law equation (DV = I • R) can be used to determine the total current in the circuit. In doing so, the total resistance and the total voltage (or battery voltage) will have to be used.

$I_{tot} = \Delta V_{tot} / R_{tot} = (24\text{ V}) / (16\ \Omega)$
$I_{tot} = 1.5\text{ Amp}$

The 1.5 Amp current calculation represents the current at the battery location. Yet, resistors R_1 and R_4 are in series and the current in series-connected resistors is everywhere the same. Thus,

$I_{tot} = I_1 = I_4 = 1.5\text{ Amp}$

For parallel branches, the sum of the current in each individual branch is equal to the current outside the branches. Thus, $I_2 + I_3$ must equal 1.5 Amp. There are an infinite possibilities of I_2 and I_3 values which satisfy this equation. In the previous example, the two resistors in parallel had the identical resistance; thus the current was distributed equally among the two branches. In this example, the unequal current in the two resistors complicates the analysis. The branch with the least resistance will have the greatest current. Determining the amount of current will demand that we use the Ohm's law equation. But to use it, the voltage drop across the branches must first be known. So, the direction which the solution takes in this example will be slightly different than that of the simpler case illustrated in the previous example.

To determine the voltage drop across the parallel branches, the voltage drop across the two series-connected resistors (R_1 and R_4) must first be determined. The Ohm's law equation ($\Delta V = I \bullet R$) can be used to determine the voltage drop across each resistor. These calculations are shown below.

$\Delta V_1 = I_1 \bullet R_1 = (1.5\text{ Amp}) \bullet (5\ \Omega)$
$\Delta V_1 = 7.5\text{ V}$
$\Delta V_4 = I_4 \bullet R_4 = (1.5\text{ Amp}) \bullet (8\ \Omega)$
$\Delta V_4 = 12\text{ V}$

This circuit is powered by a 24-volt source. Thus, the cumulative voltage drop of a charge traversing a loop about the circuit is 24 volts. There will be a 19.5 V drop (7.5 V + 12 V) resulting from passage through the two series-connected resistors (R_1 and R_4). The voltage drop across the branches must be 4.5 volts to make up the difference between the 24 volt total and the 19.5 volt drop across R_1 and R_4. Thus,

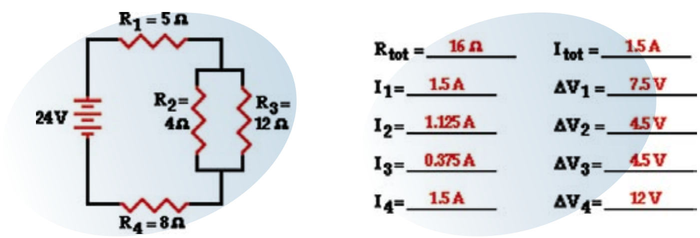
$\Delta V_2 = V_3 = 4.5\text{ V}$

Knowing the voltage drop across the parallel-connected resistors (R_1 and R_4) allows one to use the Ohm's law equation ($\Delta V = I \bullet R$) to determine the current in the two branches.

$$I_2 = \Delta V_2 / R_2 = (4.5\ V) / (4\ \Omega)$$
$$I_2 = 1.125\ A$$

$$I_3 = \Delta V_3 / R_3 = (4.5\ V) / (12\ \Omega)$$
$$I_3 = 0.375\ A$$

The analysis is now complete and the results are summarized in the diagram shown here.



DEVELOPING A STRATEGY

The two examples above illustrate an effective concept-centered strategy for analyzing combination circuits. The approach demanded a firm grasp of the series and parallel concepts discussed earlier. Such analyses are often conducted in order to solve a physics problem for a specified unknown. In such situations, the unknown typically varies from problem to problem. In one problem, the resistor values may be given and the current in all the branches is the unknown. In another problem, the current in the battery and a few resistor values may be stated and the unknown quantity becomes the resistance of one of the resistors. Different problem situations will obviously require slight alterations in the approaches. Nonetheless, every problem-solving approach will utilize the same principles utilized in approaching the two example problems shown earlier.

The following suggestions for approaching combination circuit problems are offered to the beginning student:

• If a schematic diagram is not provided, take the time to construct one. Use schematic symbols such as those shown in the example above.

• When approaching a problem involving a combination circuit, take the time to organize yourself, writing down known values and equating them with a symbol such as I_{tot}, I_1, R_3, ΔV_2, etc. The organization scheme used in the two examples above is an effective starting point.

• Know and use the appropriate formulae for the equivalent resistance of series-connected and parallel-connected resistors. Use of the wrong formulae will guarantee failure.

• Transform a combination circuit into a strictly series circuit by replacing (in your mind) the parallel section with a single resistor having a resistance value equal to the equivalent resistance of the parallel section.

• Use the Ohm's law equation ($\Delta V = I \bullet R$) often and appropriately. Most answers will be determined using this equation. When using it, it is important to substitute the appropriate values into the equation. For instance, if calculating I_2, it is important to substitute the DV_2 and the R_2 values into the equation.

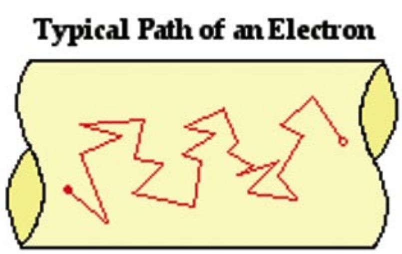
ELECTRICAL RESISTANCE

CIRCUIT CONNECTIONS

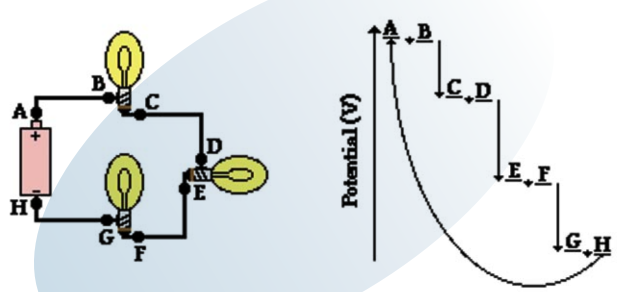
JOURNEY OF A TYPICAL ELECTRON

An electrochemical cell supplies energy to move a charge from its low energy, low potential terminal to the high energy, high potential terminal. In this sense, the cell supplies the energy to establish an electric potential difference across the two ends of the external circuit. Charge will then flow through the external circuit in the same manner that water will flow from an elevated position to a low position. It is the difference in potential that causes this flow.

In the wires of electric circuits, an electron is the actual charge carrier. An electron's path through the external circuit is far from being a straight path. An electron's journey through a circuit can be described as a zigzag path which results from countless collisions with the atoms of the conducting wire. Each collision results in the alteration of the path, thus leading to a zigzag type motion. While the electric potential difference across the two ends of a circuit encourages the flow of charge, it is the collisions of charge carriers with atoms of the wire that discourages the flow of charge. Different types of atoms offer a different degree of hindrance to the flow of the charge carriers which pass through it.



In all cases, the collisions of charge carriers in an electric circuit with the conducting elements of that circuit result in a loss of energy. While most the electrical energy possessed by a charge carrier is lost when it passes through an electrical device (often referred to as the load), even the wires of the circuit themselves act to remove energy from a charge. It is because of this energy loss in the load and in the wires themselves that the electric potential of a charge carrier is decreased as it traverses the external circuit. The electric energy supplied by the electrochemical cells becomes entirely used up in the external circuit.



A small amount of electric potential is lost in a wire. Most of the electric potential losses occur within the light bulbs. The total amount of electric potential loss in the external circuit is equal to the gain in electric potential which occurs within the battery.

In an electric circuit with several electrical devices, there may be multiple stepwise losses of electric potential as the charge traverses the circuit. There are several ways that multiple devices can be wired within a circuit; this is discussed elsewhere in this handbook. Regardless of the way in which the devices are wired, the total loss of electric potential of a single charge as it passes through the external circuit is equal to the gain in electric potential which it experiences in the battery. As depicted in the next diagram, a charge carrier traversing the external circuit from A to H passes through three different light bulbs. Each light bulb results in a loss of electric potential for the charge. This loss in electric potential corresponds to a loss of energy as the electrical energy is transformed by the light bulb into light energy and thermal energy. In addition to the changes in electric potential and electric energy which occur in the light bulbs, there is also a smaller amount of electric potential loss in the wires which connect the light bulbs. This small amount of loss in electric potential also corresponds to a small loss of energy as the electrical energy is transformed into thermal energy. The wires get hot - not as hot as the light bulb, but still measurably hot.

So the journey of an electron through an external circuit involves a long and slow zigzag path which is characterized by several successive losses in electric potential. Each loss of potential is referred to as a voltage drop. Accompanying this voltage drop is a voltage boost occurring within the internal circuit - for instance, within the electrochemical cell.

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.

Resistance is a hindrance to the flow of charge.

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 effects 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	1.59×10^{-8}
Copper	1.7×10^{-8}
Gold	2.4×10^{-8}
Aluminum	2.8×10^{-8}
Tungsten	5.6×10^{-8}
Iron	10×10^{-8}
Platinum	11×10^{-8}
Lead	22×10^{-8}
Nichrome	150×10^{-8}
Carbon	3.5×10^{5}
Polystyrene	10^{7} - 10^{11}
Polyethylene	10^{8} - 10^{9}
Glass	10^{10} - 10^{14}
Hard Rubber	10^{13}

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 the last five materials listed in the 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 - W. An electrical device having a resistance of 5 ohms would be represented as R = 5 W. 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.

A QUICK TEST...

1) Household circuits are often wired with two different widths of wires: 12-gauge and 14-gauge. The 12-gauge wire has a diameter of 1/12 inch while the 14-gauge wire has a diameter of 1/14 inch. Thus, 12-gauge wire has a wider cross section than 14-gauge wire. A 20-Amp circuit used for wall receptacles should be wired using 12-gauge wire and a 15-Amp circuit used for lighting and fan circuits should be wired using 14-gauge wire. Explain the physics behind such an electrical code.

Answer: A 12-gauge wire is wider than 14-gauge wire and thus has less resistance. The lesser resistance of 12-gauge wire means that it can allow charge to flow through it at a greater rate - that is, allow a larger current. Thus, 12-gauge wire is used in circuits which are protected by 20-Amp fuses and circuit breakers. On the other hand, the thinner 14-gauge wire can support less current owing to its larger resistance; it is used in circuits which are protected by 15-Amp fuses and circuit breakers.

2) Based on the information stated in the above question, explain the risk involved in using 14-gauge wire in a circuit that will be used to power an 16-ampere power saw.

Answer: A 12-gauge wire is wider than 14-gauge wire and thus has less resistance. The lesser resistance of 12-gauge wire means that it can allow charge to flow through it at a greater rate - that is, allow a larger current. Thus, 12-gauge wire can safely support a circuit that uses an appliance drawing up to 20 Amps of current. In fact, a 20-Amp circuit is protected by a fuse or circuit breaker that will flip off when the current reaches 20 Amps. If a 14-gauge wire is used on the same circuit, then the breaker would allow up to 20 Amps to flow through it. It could overheat and thus lead to the risk of fire. A 20-Amp circuit should never be wired using 14-gauge wire.

3) Determine the resistance of a 1-mile length of 12-gauge copper wire. Given: 1 mile = 1609 meters and diameter = 0.2117 cm.

Answer: 7.8 ohms. Use the equation

$$I = \frac{\Delta V}{R}$$

where L = 1609 m, A = P^I•R^2 (in $meters^2$), and = 1.7 x 10^{-8} ohm•meter. First find the cross-sectional area:
A = PI•R^2 = (PI) • [(0.002117 m) / 2)]^2 = 3.519 x 10-6 m^2
Now substitute into the above equation to determine the resistance.
R = (1.7 x 10-8 ohm • m) • (1609 m) / (3.519 x 10-6 m^2)
R = 7.8 Ω (7.7709 ohm)

4) Two wires - A and B - with circular cross-sections have identical lengths and are made of the same material. Yet, wire A has four times the resistance of wire B. How many times greater is the diameter of wire B than wire A?

Answer: D^B = 2 • D^A

If wire A has four times the resistance, then it must have the smaller cross-sectional area since resistance and cross-sectional area are inversely proportional. In fact, A must have one-fourth the cross-sectional area of B. Since the cross-sectional area of a circular cross-section is given by the expression PI•R^2, wire A must have one-half the radius of wire B and therefore one-half the diameter. Put another way, the diameter of wire B is two times greater than the diameter of wire A.

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. 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 • c_2. In the field of Newtonian Mechanics, there is F^{net} = m • a. In the field of Wave Mechanics, there is v = f • λ. And in the field of current electricity, there is

ΔV = I • R.

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

ΔV = I • R

In words, the electric potential difference between two points on a circuit (ΔV) 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). This equation will become the most common equation which we see in this section. Often referred to as the Ohm's law equation, this equation is a powerful predictor of the relationship between potential difference, current and resistance.

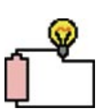
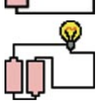
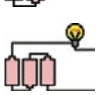
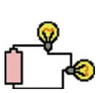
OHM'S LAW AS A PREDICTOR OF CURRENT

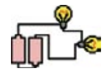
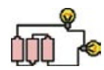
The Ohm's law equation can be rearranged and expressed as:

$$I = \frac{\Delta V}{R}$$

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 two-fold increase in the battery voltage would lead to a two-fold 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.

This table illustrates the relationship both qualitatively and quantitatively for several circuits with varying battery voltages and resistances.

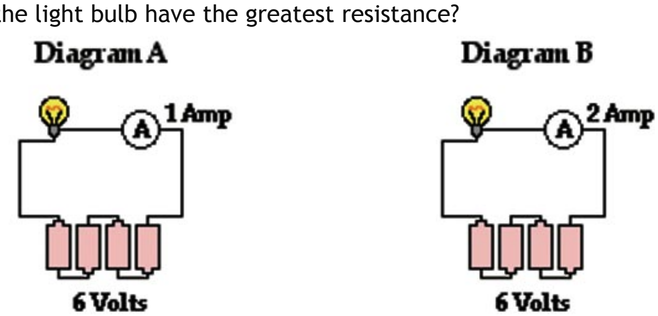
	CIRCUIT DIAGRAM	BATTERY VOLTAGE (DV)	TOTAL RESISTANCE (W)	CURRENT (AMPS)
1.		1.5 V	3 W	0.5 Amp
2.		3.0 V	3 W	1 Amp
3.		4.5 V	3 W	1.5 Amp
4.		1.5 V	6 W	0.25 Amp

	CIRCUIT DIAGRAM	BATTERY VOLTAGE (ΔV)	TOTAL RESISTANCE (Ω)	CURRENT (AMPS)
5.		3.0 V	3 Ω	0.5 Amp
6.		4.5 V	6 Ω	0.75 Amp
7.		4.5 V	3 Ω	0.50 Amp

Rows 1, 2 and 3 illustrate that the doubling and the tripling of the battery voltage leads to a doubling and a tripling of the current in the circuit. Comparing rows 1 and 4 or rows 2 and 5 illustrates that the doubling of the total resistance serves to halve the current in the circuit.

Because the current in a circuit is affected by the resistance, resistors are often used in the circuits of electrical appliances to affect the amount of current which is present in its various components. By increasing or decreasing the amount of resistance in a particular branch of the circuit, a manufacturer can increase or decrease the amount of current in that branch. Kitchen appliances such as electric mixers and light dimmer switches operate by altering the current at the load by increasing or decreasing the resistance of the circuit. Pushing the various buttons on an electric mixer can change the mode from mixing to beating by reducing the resistance and allowing more current to be present in the mixer. Similarly, turning a dial on a dimmer switch can increase the resistance of its built-in resistor and thus reduce the current.

The diagram shown here depicts a couple of circuits containing a voltage source (battery pack), a resistor (light bulb) and an ammeter (for measuring current). In which circuit does the light bulb have the greatest resistance?



Answer: Diagram A

Use the equation V = I • R to solve for the resistance.

Diagram A:

R = ΔV / I = (6 V) / (1 A) = 6 W

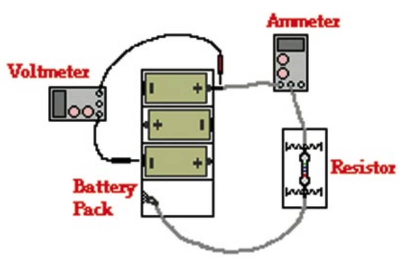
Diagram B:

R = ΔV / I = (6 V) / (2 A) = 3 W

The resistance is greatest in the circuit with the least current - Diagram A.

The Ohm's law equation is often explored in physics labs using a resistor, a battery pack, an ammeter, and a voltmeter. An ammeter is a device used to measure the current at a given location. A voltmeter is a device equipped with probes which can be touched to two locations on a circuit to determine the electric potential difference across those locations. By altering the number of cells in the battery pack, the electric potential difference across the external circuit can be varied. The voltmeter can be used to determine this potential difference and the ammeter can be used to determine the current associated with this ΔV. A battery can be added to the battery pack and the process can be repeated several times to yield a set of I-ΔV data. A plot of I versus ΔV will yield a line with a slope that is equivalent to the reciprocal of the resistance of the resistor. This can be compared to the manufacturer's stated value to determine the accuracy of the lab data and the validity of the Ohm's law equation.

Common Lab Apparatus for Exploring Ohm's Law



QUANTITIES, SYMBOLS, EQUATIONS AND UNITS!

The tendency to give attention to units is an essential trait of any good physics student. Many of the difficulties associated with solving problems may be traced back to the failure to give attention to units. As more and more electrical quantities and their respective metric units are introduced, it will become increasingly important to organize the information in your head. The table below lists several of the quantities which have been introduced thus far. The symbol, the equation and the associated metric units are also listed for each quantity. It would be wise to refer to this list often or even to make your own copy and add to it as the unit progresses. Some students find it useful to make a fifth column in which the definition of each quantity is stated.

Quantity	Symbol	Equation(s)	Standard Metric Unit	Other Units
Potential Difference (a.k.a. voltage)	ΔV	$\Delta V = \Delta P/Q$	Volt (V) $\Delta V = I \cdot R$	J/C
Current	I	$I = Q/t$	Amperes (A) $I = \Delta V/R$	Amp or C/s or V/Ω
Power	P	$P = \Delta PE/t$	Watt (W)	J/s
Resistance	R	$R = \rho \cdot L/A$	Ohm (Ω) $R = \Delta V/I$	V/A
Energy	E or ΔPE	$\Delta PE = \Delta V \cdot Q$	Joule (J) $\Delta PE = P \cdot t$	V • C or W • s

(Note the unit symbol C represents the unit Coulombs.)

POWER REVISITED

The previous section elaborated upon the dependence of current upon the electric potential difference and the resistance. The current in an electrical device is directly proportional to the electric potential difference impressed across the device and inversely proportional to the resistance of the device. If this is the case, then the rate at which that device transforms electrical energy to other forms is also dependent upon the current, the electric potential difference and the resistance. In this section, we will revisit the concept of power and develop new equations which express power in terms of current, electric potential difference and resistance.

NEW EQUATIONS FOR POWER

In Section 2, the concept of electrical power was introduced. Electrical power was defined as the rate at which electrical energy is supplied to a circuit or consumed by a load. The equation for calculating the power delivered to the circuit or consumed by a load was derived to be:

$$P = \Delta V \bullet I$$

(Equation 1)

The two quantities which power depends upon are both related to the resistance of the load by Ohm's law. The electric potential difference (ΔV) and the current (I) can be expressed in terms of their dependence upon resistance as shown in the following equations.

$$\Delta V = (I \bullet R) \qquad I = \Delta V / R$$

If the expressions for electric potential difference and current are substituted into the power equation, two new equations can be derived which relate the power to the current and the resistance and to the electric potential difference and the resistance. These derivations are shown here.

Equation 2:

$P = \Delta V \bullet I$

$P = (I \bullet R) \bullet I$

$P = I^2 \bullet R$

Equation 3:

$P = \Delta V \bullet I$

$P = \Delta V \bullet (\Delta V / R)$

$P = \Delta V^2 / R$

We now have three equations for electrical power, with two derived from the first using the Ohm's law equation. These equations are often used in problems involving the computation of power from known values of electric potential difference (ΔV), current (I), and resistance (R). **Equation 2** relates the rate at which an electrical device consumes energy to the current at the device and the resistance of the device. Note the double importance of the current in the equation as denoted by the square of current. **Equation 2** can be used to calculate the power provided that the resistance and the current are known. If either one is not known, then it will be necessary to either use one of the other two equations to calculate power or to use the Ohm's law equation to calculate the quantity needed in order to use **Equation 2**.

Equation 3 relates the rate at which an electrical device consumes energy to the voltage drop across the device and to the resistance of the device. Note the double importance of the voltage drop as denoted by the square of ΔV. **Equation 3** can be used to calculate the power provided that the resistance and the voltage drop are known. If either one is not known, then it will be important to either use one of the other two equations to calculate power or to use the Ohm's law equation to calculate the quantity needed in order to use **Equation 3**.

While these three equations provide one with convenient formulas for calculating unknown quantities in physics problems, one must be careful to not misuse them by ignoring conceptual principles regarding circuits. To illustrate, suppose that you were asked this question: If a 60-watt bulb in a household lamp was replaced with a 120-watt bulb, then how many times greater would the current be in that lamp circuit? Using equation 2, one might reason (incorrectly), that the doubling of the power means that the I2 quantity must be doubled.

Thus, current would have to increase by a factor of 1.41 (the square root of 2). This is an example of incorrect reasoning because it removes the mathematical formula from the context of electric circuits. The fundamental difference between a 60-Watt bulb and a 120-Watt bulb is not the current that is in the bulb, but rather the resistance of the bulb. It is the resistances which are different for these two bulbs; the difference in current is merely the consequence of this difference in resistance. If the bulbs are in a lamp socket which is plugged into a United States wall outlet, then one can be certain that the electric potential difference is around 120 Volts. The DV would be the same for each bulb. The 120-Watt bulb has the lower resistance; and using Ohm's law, one would expect it also has the higher current. In fact, the 120-Watt bulb would have a current of 1 Amp and a resistance of 120 W; the 60-Watt bulb would have a current of 0.5 Amp and a resistance of 240 W.

Calculations for 120-Watt Bulb

$P = \Delta V \bullet I$
$I = P / \Delta V$
$I = (120\ W) / (120\ V)$
$I = 1$ Amp

$V = \Delta I \bullet R$
$R = \Delta V / I$
$R = (120\ V) / (1\ Amp)$
$R = 120\ W$

Calculations for 60-Watt Bulb

$P = \Delta V \bullet I$
$I = P / \Delta V$
$I = (60\ W) / (120\ V)$
$I = 0.5$ Amp

$DV = I \bullet R$
$R = \Delta V / I$
$R = (120\ V) / (0.5\ Amp)$
$R = 240\ W$

Now using equation 2 properly, one can see why twice the power means that there would be twice the current since the resistance also changes with a bulb change. The calculation of current below yields the same result as shown above.

Calculations for 120-Watt Bulb

$P = I^2 \bullet R$
$I^2 = P / R$
$I^2 = (120\ W) / (120\ \Omega)$
$I^2 = 1\ W / \Omega$
$I = SQRT\ (1\ W / \Omega)$
$I = 1$ Amp

Calculations for 60-Watt Bulb

$P = I^2 \bullet R$
$I^2 = P / R$
$I^2 = (60\ W) / (240\ \Omega)$
$I^2 = 0.25\ W / \Omega$
$I = SQRT\ (0.25\ W / \Omega)$
$I = 0.5$ Amp

CURRENT ELECTRICITY

ELECTRIC POTENTIAL DIFFERENCE

ELECTRIC FIELD AND THE MOVEMENT OF CHARGE

Perhaps one of the most useful yet taken-for-granted accomplishments of the modern era is the development of electric circuits. The flow of charge through wires allows us to cook our food, light our homes, air-condition our work and living space, entertain us with movies and music and even allows us to drive to work or school safely. Here, we will explore the reasons why charge flows through wires of electric circuits and the variables that affect the rate at which it flows.

The means by which moving charge delivers electrical energy to appliances in order to operate them will be discussed in detail.

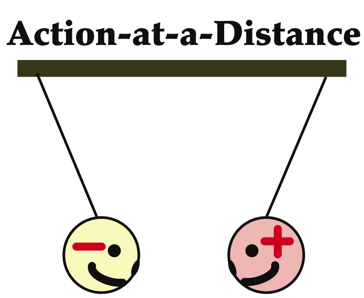
One of the fundamental principles that must be understood in order to grasp electric circuits pertains to the concept of how an electric field can influence charge within a circuit as it moves from one location to another. Electric force is a non-contact force. A charged balloon can have an attractive effect upon an oppositely charged balloon even when they are not in contact. The electric force acts over the distance separating the two objects. Electric force is an action-at-a-distance force.

Action-at-a-distance forces are sometimes referred to as field forces. The concept of a field force is utilized by scientists to explain this rather unusual force phenomenon that occurs in the absence of physical contact. The space surrounding a charged object is affected by the presence of the charge; an electric field is established in that space. A charged object creates an electric field - an alteration of the space or field in the region that surrounds it. Other charges in that field would feel the unusual alteration of the space. Whether a charged object enters that space or not, the electric field exists. Space is altered by the presence of a charged object; other objects in that space experience the strange and mysterious qualities of the space. As another charged object enters the space and moves deeper and deeper into the field, the effect of the field becomes more and more noticeable.

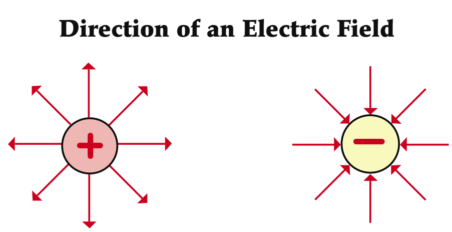
Electric field is a vector quantity whose direction is defined as the direction that a positive test charge would be pushed when placed in the field. Thus, the electric field direction about a positive source charge is always directed away from the positive source. And the electric field direction about a negative source charge is always directed toward the negative source.

ELECTRIC FIELD, WORK, AND POTENTIAL ENERGY

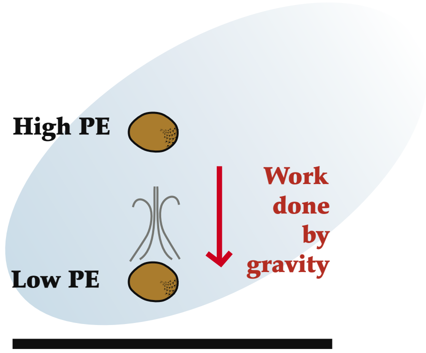
Electric fields are similar to gravitational fields - both involve action-at-a-distance forces. In the case of gravitational fields, the source of the field is a massive object and the action-at-a-distance forces are exerted upon other masses. The force of gravity is an internal or conservative force. When gravity does work upon an object to move it from a high location to a lower location, the object's total amount of mechanical energy is conserved. However, during the course of the falling motion, there was a loss of potential energy (and a gain of kinetic energy). When gravity does work upon an object to move it in the direction of the gravitational field, then the object loses potential energy. The potential energy originally stored within the object as a result of its vertical position is lost as the object

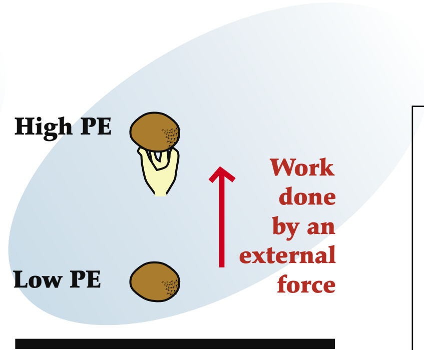


Opposites can attract- even when held some distance apart.



The electric field direction is always directed away from positive source charges and towards negative source charges.





moves under the influence of the gravitational field. On the other hand, energy would be required to move a massive object against its gravitational field. A stationary object would not naturally move against the field and gain potential energy. Energy in the form of work would have to be imparted to the object by an external force in order for it to gain this height and the corresponding potential energy.

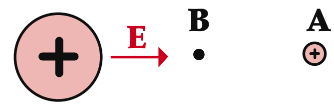
The important point to be made by this gravitational analogy is that work must be done by an external force to move an object against nature - from low potential energy to high potential energy. On the other hand, objects naturally move from high potential energy to low potential energy under the influence of the field force. It is simply natural for objects to move from high energy to low energy; but work is required to move an object from low energy to high energy.

In a similar manner, to move a charge in an electric field against its natural direction of motion would require work. The exertion of work by an external force would in turn add potential energy to the object. The natural direction of motion of an object is from high energy to low energy; but work must be done to move the object against nature. On the other hand, work would not be required to move an object from a high potential energy location to a low potential energy location. When this principle is logically extended to the movement of charge within an electric field, the relationship between work, energy and the direction that a charge moves becomes more obvious.

Consider the diagram shown here in which a positive source charge is creating an electric field and a positive test charge being moved against and with the field. In Diagram A, the positive test charge is being moved against the field from location A to location B. Moving the charge in this direction would be like going against nature. Thus, work would be required to move the object from location A to location B and the positive test charge would be gaining potential energy in the process. This would be analogous to moving a mass in the uphill direction; work would be required to cause such an increase in gravitational potential energy. In Diagram B, the positive test charge is being moved with the field from location B to location A. This motion would be natural and not require work from an external force. The positive test charge would be losing energy in moving from location B to location A. This would be analogous to a mass falling downward; it would occur naturally and be accompanied by a loss of gravitational potential energy. One can conclude from this discussion that the high energy location for a positive test charge is a location nearest the positive source charge; and the low energy location is furthest away.

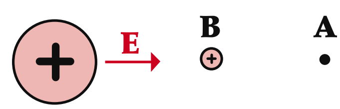
The above discussion per

Diagram A



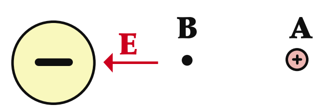
Moving the + test charge from location A to location B will require work and increase the potential energy of the charge.

Diagram B



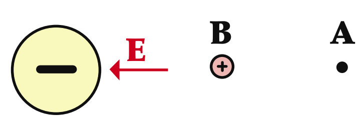
The + test charge will naturally move in the direction of the E field; work is not required. The potential energy of the charge will decrease.

Diagram C



The + test charge will naturally move in the direction of the E field; work is not required. The potential energy of the charge will decrease.

Diagram D



Moving the + test charge from location B to location A will require work and increase the potential energy of the charge.

tained to moving a positive test charge within the electric field created by a positive source charge. Now we will consider the motion of the same positive test charge within the electric field created by a negative source charge. The same principle regarding work and potential energy will be used to identify the locations of high and low energy.

In Diagram C, the positive test charge is moving from location A to location B in the direction of the electric field. This movement would be natural - like a mass falling towards Earth. Work would not be required to cause such a motion and it would be accompanied by a loss of potential energy. In Diagram D, the positive test charge is moving from location B to location A against the electric field. Work would be required to cause this motion; it would be analogous to raising a mass within Earth's gravitational field. Since energy is imparted to the test charge in the form of work, the positive test charge would be gaining potential energy as the result of the motion. One can conclude from this discussion that the low energy location for a positive test charge is a location nearest a negative source charge and the high energy location is a location furthest away from a negative source charge.

As we begin to discuss circuits, we will apply these principles regarding work and potential energy to the movement of charge about a circuit. Just as we reasoned here, moving a positive test charge against the electric field will require work and result in a gain in potential energy. On the other hand, a positive test charge will naturally move in the direction of the field without the need for work being done on it; this movement will result in the loss of potential energy. Before making this application to electric circuits, we need to first explore the meaning of the concept electric potential.

ELECTRIC POTENTIAL DIFFERENCE

ELECTRIC POTENTIAL

As stated earlier, it was reasoned that the movement of a positive test charge within an electric field is accompanied by changes in potential energy. A gravitational analogy was relied upon to explain the reasoning behind the relationship between location and potential energy. Moving a positive test charge against the direction of an electric field is like moving a mass upward within Earth's gravitational field. Both movements would be like going against nature and would require work by an external force.

This work would in turn increase the potential energy of the object. On the other hand, the movement of a positive test charge in the direction of an electric field would be like a mass falling downward within Earth's gravitational field. Both movements would be like going with nature and would occur without the need of work by an external force. This motion would result in the loss of potential energy.

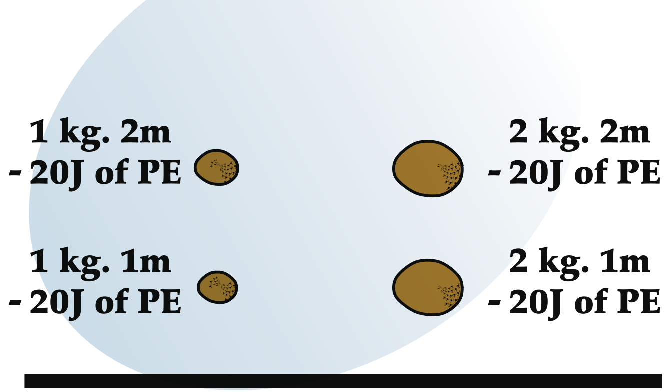
Potential energy is the stored energy of position of an object and it is related to the location of the object within a field. We will introduce the concept of electric potential and relate this concept to the potential energy of a positive test charge at various locations within an electric field.

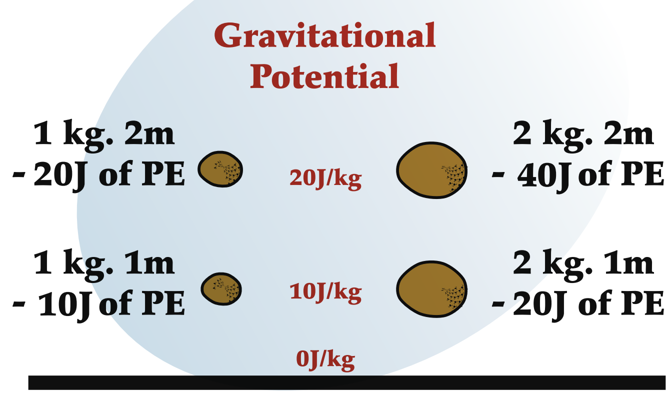
THE GRAVITATIONAL ANALOGY REVISITED

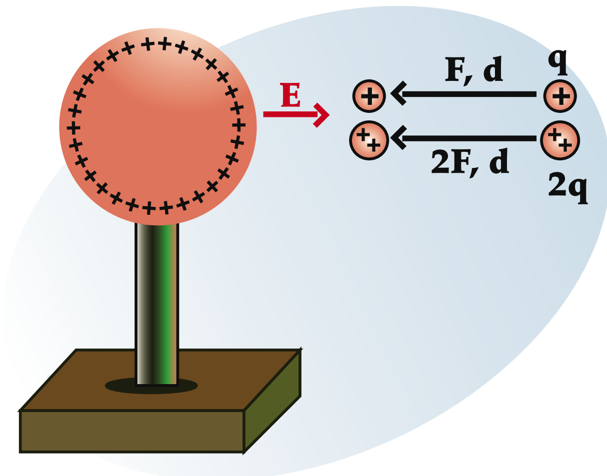
A gravitational field exists about the Earth that exerts gravitational influences upon all masses located in the space surrounding it. Moving an object upward against the gravitational field increases its gravitational potential energy. An object moving downward within the gravitational field would lose gravitational potential energy. Gravitational potential energy is defined as the energy stored in an object due to its vertical position above the Earth.

The amount of gravitational potential energy stored in an object depended upon the amount of mass the object possessed and the amount of height to which it was raised. Gravitational potential energy depended upon object mass and object height. An object with twice the mass would have twice the potential energy and an object with twice the height would have twice the potential energy. It is common to refer to high positions as high potential energy locations.

A glance at the diagram here reveals the fallacy of such a statement. Observe that the 1 kg mass held at a height of 2 meters has the same potential energy as a 2 kg mass held at a height of 1 meter. Potential energy depends upon more than just location; it also depends upon mass. In this sense, gravitational potential energy depends upon at least two types of quantities:



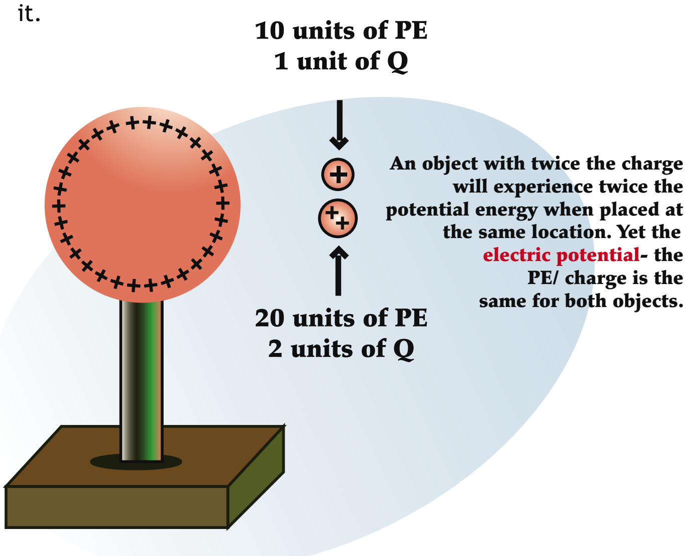




1) Mass - a property of the object experiencing the gravitational field; and

2) Height - the location within the gravitational field.

So it is improper to refer to high positions within Earth's gravitational field as high potential energy positions. But is there a quantity that could be used to rate such heights as having great potential of providing large quantities of potential energy to masses which are located there? Yes! While not discussed during the unit on gravitational potential energy, it would have been possible to introduce a quantity known as gravitational potential - the potential energy per kilogram. Gravitational potential would be a quantity which could be used to rate various locations about the surface of the Earth in terms of how much potential energy each kilogram of mass would possess when placed there. The quantity of gravitational potential is defined as the PE/mass. Since both the numerator and the denominator of PE/mass are proportional to the object's mass, the expression becomes "mass-independent". Gravitational potential is a location dependent quantity that is independent of the mass of the object experiencing the field. Gravitational potential describes the affects of a gravitational field upon objects that are placed at various locations within it.



If gravitational potential is a means of rating various locations within a gravitational field in terms of the amount of potential energy per unit of mass, then the concept of electric potential must have a similar meaning. Consider the electric field created by a positively charged Van de Graaff generator. The direction of the electric field is in the direction that a positive test charge would be pushed; in this case, the direction is outward away from the Van de Graaff sphere. Work would be required to move a positive test charge towards the sphere against the electric field. The amount of force involved in doing the work is dependent upon the amount of charge being moved (according to Coulomb's law of electric force). The greater the charge on the test charge, the greater the repulsive force and the more work which would have to be done on it to move it the same distance.

If two objects of different charge - with one being twice the charge of the other - are moved the same distance into the electric field, then the object with twice the charge would require twice the force and thus twice the amount of work. This work would change the potential energy by an amount which is equal to the amount of work done. Thus, the electric potential energy is dependent upon the amount of charge on the object experiencing the field and upon the location within the field. Just like gravitational potential energy, electric potential energy is dependent upon at least two types of quantities:

1) Electric charge - a property of the object experiencing the electrical field, and

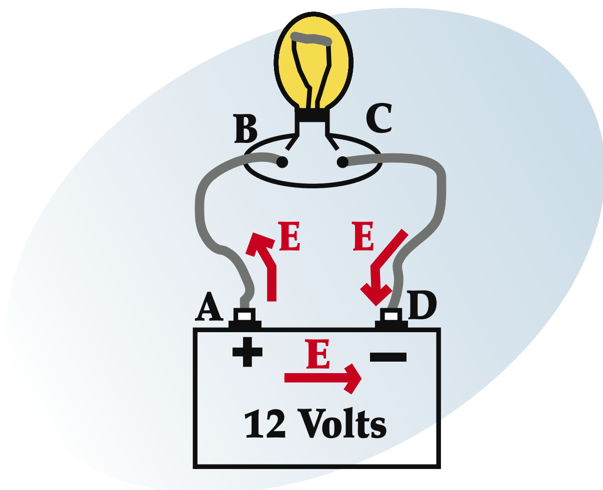
2) Distance from source - the location within the electric field

While electric potential energy has a dependency upon the charge of the object experiencing the electric field, electric potential is purely location dependent. Electric potential is the potential energy per charge.

$$\text{Electric Potential} = \frac{PE}{Q}$$

The concept of electric potential is used to express the effect of an electric field of a source in terms of the location within the electric field. A test charge with twice the quantity of charge would possess twice the potential energy at a given location; yet its electric potential at that location would be the same as any other test charge. A positive test charge would be at a high electric potential when held close to a positive source charge and at a lower electric potential when held further away. In this sense, electric potential becomes simply a property of the location within an electric field. Suppose that the electric potential at a given location is 12 Joules per coulomb, then that is the electric potential of a 1 coulomb or a 2 coulomb charged object. Stating that the electric potential at a given location is 12 Joules per coulomb, would mean that a 2 coulomb object would possess 24 Joules of potential energy at that location and a 0.5 coulomb object would experience 6 Joules of potential energy at the location.

A Simple Electric Circuit



ELECTRIC POTENTIAL IN CIRCUITS

As we begin to discuss electric circuits, we will notice that a battery powered electric circuit has locations of high and low potential.

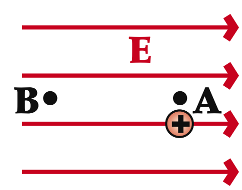
Charge moving through the wires of the circuit will encounter changes in electric potential as it traverses the circuit. Within the electrochemical cells of the battery, there is an electric field established between the two terminals, directed from the positive terminal towards the negative terminal. As such, the movement of a positive test charge through the cells from the negative terminal to the positive terminal would require work, thus increasing the potential energy of every Coulomb of charge that moves along this path. This corresponds to a movement of positive charge against the electric field. It is for this reason that the positive terminal is described as the high potential terminal. Similar reasoning would lead one to conclude that the movement of positive charge through the wires from the positive terminal to the negative terminal would occur naturally. Such a movement of a positive test charge would be in the direction of the electric field and would not require work. The charge would lose potential energy as it moves through the external circuit from the positive terminal to the negative terminal. The negative terminal is described as the low potential terminal. This assignment of high and low potential to the terminals of an electrochemical cell presumes the traditional convention that electric fields are based on the direction of movement of positive test charges.

In a certain sense, an electric circuit is nothing more than an energy conversion system. In the electrochemical cells of a battery-powered electric circuit, the chemical energy is used to do work on a positive test charge to move it from the low potential terminal to the high potential terminal. Chemical energy is transformed into electric potential energy within the internal circuit (i.e., the battery). Once at the high potential terminal, a positive test charge will then move through the external circuit and do work upon the light bulb or the motor or the heater coils, transforming its electric potential energy into useful forms for which the circuit was designed. The positive test charge returns to the negative terminal at a low energy and low potential, ready to repeat the cycle (or should we say circuit) all over again.

ELECTRIC POTENTIAL DIFFERENCE

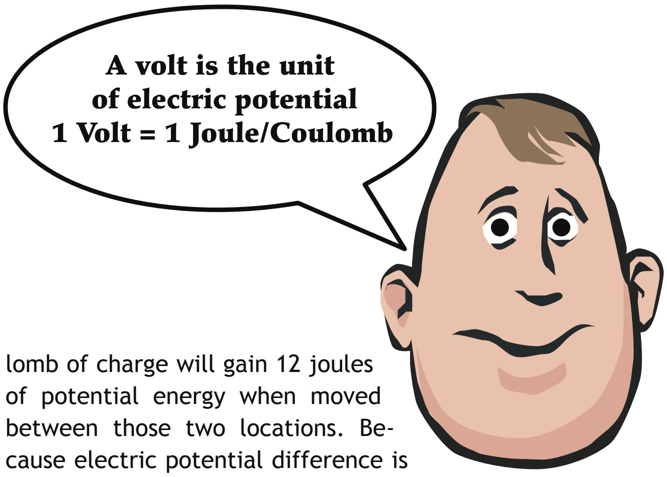
Electric potential is a location dependent quantity which expresses the amount of potential energy per unit of charge at a specified location. When a Coulomb of charge (or any given amount of charge) possesses a relatively large quantity of potential energy at a given location, then that location is said to be a location of high electric potential. And similarly, if a Coulomb of charge (or any given amount of charge) possesses a relatively small quantity of potential energy at a given location, then that location is said to be a location of low electric potential. As we begin to apply our concepts of potential energy and electric potential to circuits, we will begin to refer to the difference in electric potential between two points. This part will be devoted to an understanding of electric potential difference and its application to the movement of charge in electric circuits.

Consider the task of moving a positive test charge within a uniform electric field from location A to location B as shown in this diagram. In moving the charge against the electric field from location A to location B, work will have to be done on the charge by an external force. The work done on the charge changes its potential energy to a higher value; and the amount of work that is done is equal to the change in the potential energy. As a result of this change in potential energy, there is also a difference in electric potential between locations A and B. This difference in electric potential is represented by the symbol V and is formally referred to as the electric potential difference. By definition, the electric potential difference is the difference in electric potential (V) between the final and the initial location when work is done upon a charge to change its potential energy. In equation form, the electric potential difference is



$$AV = V_B - V_A = \frac{\text{Work}}{\text{Charge}} = \frac{\text{APE}}{\text{Charge}}$$

The standard metric unit on electric potential difference is the volt, abbreviated V and named in honor of Alessandra Volta. One Volt is equivalent to one Joule per Coulomb. If the electric potential difference between two locations is 1 volt, then one Coulomb of charge will gain 1 joule of potential energy when moved between those two locations. If the electric potential difference between two locations is 3 volts, then one coulomb of charge will gain 3 joules of potential energy when moved between those two locations. And finally, if the electric potential difference between two locations is 12 volts, then one cou

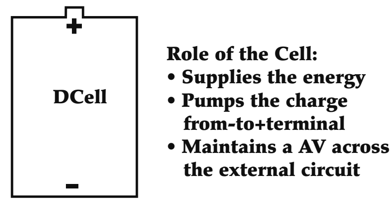


lomb of charge will gain 12 joules of potential energy when moved between those two locations. Because electric potential difference is expressed in units of volts, it is sometimes referred to as the voltage.

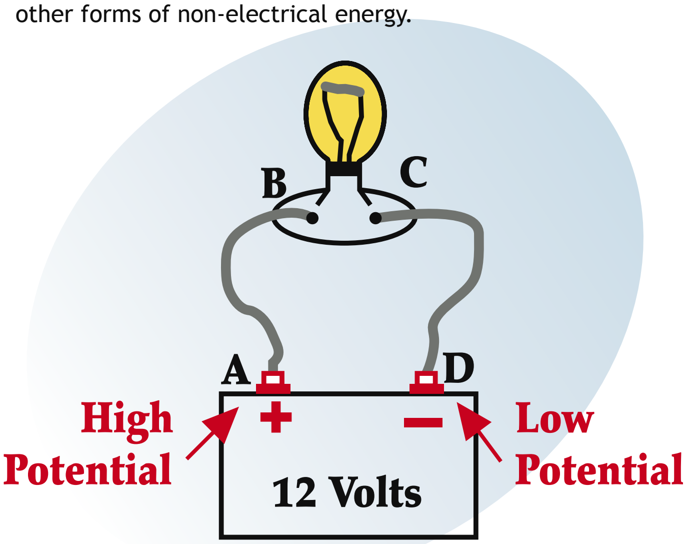
ELECTRIC POTENTIAL DIFFERENCE AND SIMPLE CIRCUITS

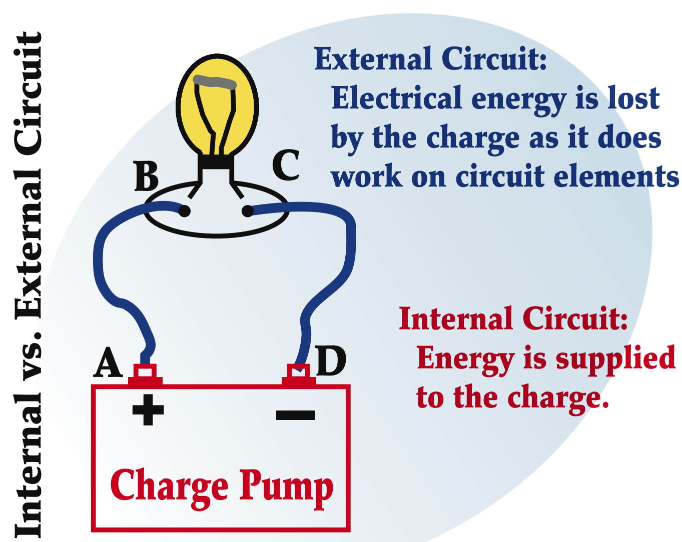
Electric circuits, as we shall see, are all about the movement of charge between varying locations and the corresponding loss and gain of energy which accompanies this movement. As mentioned earlier, the concept of electric potential was applied to a simple battery-powered electric circuit. In that discussion, it was explained that work must be done on a positive test charge to move it through the cells from the negative terminal to the positive terminal. This work would increase the potential energy of the charge and thus increase its electric potential. As the positive test charge moves through the external circuit from the positive terminal to the negative terminal, it decreases its electric potential energy and thus is at low potential by the time it returns to the negative terminal. If a 12 volt battery is used in the circuit, then every coulomb of charge is gaining 12 joules of potential energy as it moves through the battery. And similarly, every coulomb of charge loses 12 joules of electric potential energy as it passes through the external circuit. The loss of this electric potential energy in the external circuit results in a gain in light energy, thermal energy and other forms of non-electrical energy.

With a clear understanding of electric potential difference, the role of an electrochemical cell or collection of cells (i.e., a battery) in a simple circuit can be correctly understood. The cells simply supply the energy to do work upon the charge to move it from the negative terminal to the positive terminal. By providing energy to the charge, the cell is capable of maintaining an electric potential difference across the two ends of the external circuit. Once the charge has reached the high potential terminal, it will naturally flow through the wires to the low potential terminal. The movement of charge through an electric circuit is analogous to the movement of water at a water park or the movement of roller coaster cars at an amusement park. In each analogy, work must be done on the water or the roller coaster cars to move it from a location of low gravitational potential to a location of high gravitational potential. Once the water or the roller coaster cars reach high gravitational potential, they naturally move downward back to the low potential location. For a water ride or a roller coaster ride, the task of lifting the water or coaster cars to high potential requires energy. The energy is supplied by a motor-driven water pump or a motor-driven chain. In a battery-powered electric circuit, the cells serve the role of the charge pump to supply energy to the charge to lift it from the low potential position through the cell to the high potential position.



It is often convenient to speak of an electric circuit such as the simple circuit discussed here as having two parts - an internal circuit and an external circuit. The internal circuit is the part of the circuit where energy is being supplied to the charge. For the simple battery-powered circuit that we have been referring to, the portion of the circuit containing the elec-



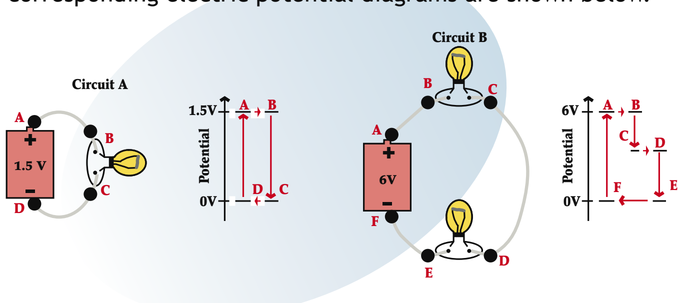


trochemical cells is the internal circuit. The external circuit is the part of the circuit where charge is moving outside the cells through the wires on its path from the high potential terminal to the low potential terminal. The movement of charge through the internal circuit requires energy since it is an uphill movement in a direction that is against the electric field. The movement of charge through the external circuit is natural since it is a movement in the direction of the electric field. When at the positive terminal of an electrochemical cell, a positive test charge is at a high electric pressure in the same manner that water at a water park is at a high water pressure after being pumped to the top of a water slide. Being under high electric pressure, a positive test charge spontaneously and naturally moves through the external circuit to the low pressure, low potential location.

As a positive test charge moves through the external circuit, it encounters a variety of types of circuit elements. Each circuit element serves as an energy-transforming device. Light bulbs, motors, and heating elements (such as in toasters and hair dryers) are examples of energy-transforming devices. In each of these devices, the electrical potential energy of the charge is transformed into other useful (and non-useful) forms. For instance, in a light bulb, the electric potential energy of the charge is transformed into light energy (a useful form) and thermal energy (a non-useful form). The moving charge is doing work upon the light bulb to produce two different forms of energy. By doing so, the moving charge is losing its electric potential energy. Upon leaving the circuit element, the charge is less energized. The location just prior to entering the light bulb (or any circuit element) is a high electric potential location; and the location just after leaving the light bulb (or any circuit element) is a low electric potential location. Referring to the diagram shown here, locations A and B are high potential locations and locations C and D are low potential locations. The loss in electric potential while passing through a circuit element is often referred to as a voltage drop. By the time that the positive test charge has returned to the negative terminal, it is at 0 volts and is ready to be re-energized and pumped back up to the high voltage, positive terminal.

ELECTRIC POTENTIAL DIAGRAMS

An electric potential diagram is a convenient tool for representing the electric potential differences between various locations in an electric circuit. Two simple circuits and their corresponding electric potential diagrams are shown below.



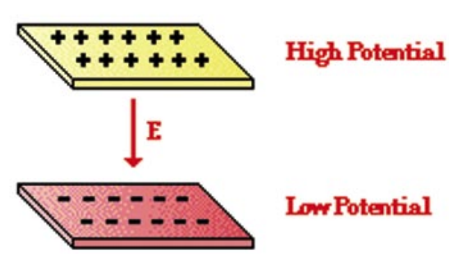
In Circuit A, there is a 1.5 volt D-cell and a single light bulb. In Circuit B, there is a 6-volt battery (four 1.5 volt D-cells) and two light bulbs. In each case, the negative terminal of the battery is the 0 volt location. The positive terminal of the battery has an electric potential which is equal to the voltage rating of the battery. The battery energizes the charge to pump it from the low voltage terminal to the high voltage terminal. By so doing, the battery establishes an electric potential difference across the two ends of the external circuit. Being under electric pressure, the charge will now move through the external circuit. As its electric potential energy is transformed into light energy and heat energy at the light bulb locations, the charge decreases its electric potential. The total voltage drop across the external circuit equals the battery voltage as the charge moves from the positive terminal back to 0 volts at the negative terminal. In the case of Circuit B, there are two voltage drops in the external circuit, one for each light bulb. While the amount of voltage drop in an individual bulb depends upon various factors (to be discussed later), the cumulative amount of drop must equal the 6 volts gained when moving through the battery.

ELECTRIC CURRENT
Section 2

WHAT IS AN ELECTRIC CIRCUIT?

In Section 1, the concept of electric potential difference was discussed. Electric potential is the amount of electric potential energy per unit of charge that would be possessed by a charged object if placed within an electric field at a given location. The concept of potential is a location-dependent quantity - it expresses the quantity of potential energy on a per charge basis such that it is independent on the amount of charge actually present on the object possessing the electric potential. Electric potential difference is simply the difference in electric potential between two different locations within an electric field.

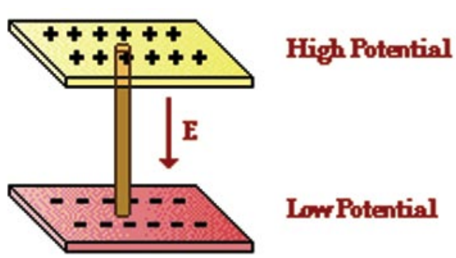
To illustrate the concept of electric potential difference and the nature of an electric circuit, consider the following situation. Suppose that there are two metal plates oriented parallel to each other and each being charged with an opposite type of charge - one being positive and the other being negative. This arrangement of charged plates would create an electric field in the region between the plates which is directed away from the positive plate and towards the negative plate. A positive test charge placed between the plates would move away from the positive plate and towards the negative plate. This movement of a positive test charge from the positive plate



to the negative plate would occur without the need of energy input in the form of work; it would occur naturally and thus lower the potential energy of the charge. The positive plate would be the high potential location and the negative plate would be the low potential location. There would be a difference in electric potential between the two locations.

Now suppose that the two oppositely charged plates are connected by a metal wire. What would happen? The wire serves as a sort of charge pipe through which charge can flow. Over the course of time, one could think of positive charges moving from the positive plate through the charge pipe (wire) to the negative plate. That is, positive charge would naturally move in the direction of the electric field which had been created by the arrangement of the two oppositely charged plates. As a positive charge leaves the upper plate, the plate would become less positively charged as illustrated in the animation at the right. As a positive charge reaches the negative plate, that plate would become less negatively charged. Over the course of time, the amount of positive and negative charge on the two plates would slowly diminish. Since the electric field depends upon the amount of charge present on the object creating the electric field, the electric field created by the two plates would gradually diminish in strength over the course of time. Eventually, the electric field between the plates would become so small that there would be no observable movement of charge between the two plates. The plates would ultimately lose their charge and reach the same electric potential. In the absence of an electric potential difference, there will be no charge flow.

The illustration comes close to demonstrating the meaning of an electric circuit. However, to be a true circuit, charges must continually flow through a complete loop, returning to their original position and cycling through again. If there was a means of moving positive charge from the negative plate back up onto the positive plate, then the movement of positive charge downward through the charge pipe (i.e., the wire) would occur continuously. In such a case, a circuit or loop would be established.



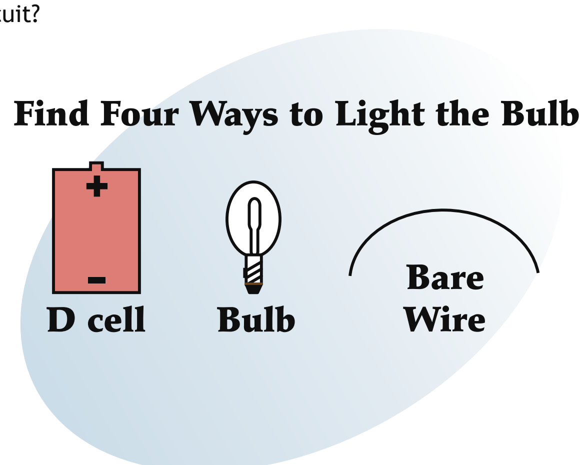
A common lab activity that illustrates the necessity of a complete loop utilizes a battery pack (a collection of D cells), a light bulb, and some connecting wires. The activity involves observing the effect of connecting and disconnecting a wire in a simple arrangement of the battery pack, light bulbs and wires. When all connections are made to the battery pack, the light bulb lights. In fact, the lighting of the bulb occurs immediately after the final connection is made. There is no perceivable time delay between when the last connection is made and when the light bulb is perceived to light up.

The fact that the light bulb lights and remains lit is evidence that charge is flowing through the light bulb filament and that an electric circuit has been established. A circuit is simply a closed loop through which charges can continuously move. To demonstrate that charges are not only moving through the light bulb filament but also through the wires connecting the battery pack and the light bulb, a variation on the above activity is made. A compass is placed beneath the wire at any location such that its needle is placed in alignment with the wire. Once the final connection is made to the battery pack, the light bulb lights and the compass needle deflects. The needle serves as a detector of moving charges within the wire. When it deflects, charges are moving through the wire. And if the wire is disconnected at the battery pack, the light bulb is no longer lit and the compass needle returns to its original orientation. When the light bulb lights, charge is moving through the electrochemical cells of the battery, the wires and the light bulb filaments; the compass needle detects the movement of this charge. It can be said that there is a current - a flow of charge within the circuit.

The electric circuit demonstrated by the combination of battery, light bulb and wires consists of two distinct parts: the internal circuit and the external circuit. The part of the circuit containing electrochemical cells of the battery is the internal circuit. The part of the circuit where charge is moving outside the battery pack through the wires and the light bulb is the external circuit. In Lesson 2, we will focus on the movement of charge through the external circuit. Later we will explore the requirements which must be met in order to have charge flowing through the external circuit.

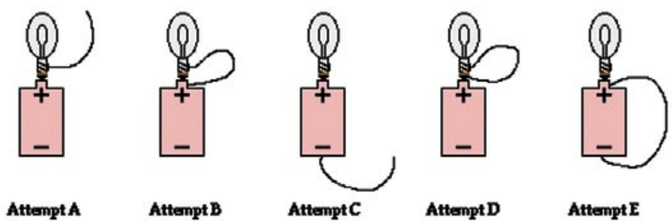
REQUIREMENTS OF A CIRCUIT

Suppose that you were given a small light bulb, an electrochemical cell and a bare copper wire and were asked to find the four different arrangements of the three items that would result in the formation of an electric circuit that would light the bulb. What four arrangements would result in the successful lighting of the bulb? And more importantly, what does each of the four arrangements have in common that would lead us into an understanding of the two requirements of an electric circuit?

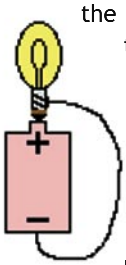


The activity itself is a worthwhile activity and if not performed before, one ought to try it before reading further. Like many lab activities, there is power in the actual engagement in the activity that cannot be replaced by simply reading about it. When this activity is performed in the physics classroom, there are numerous observations which can be made by watching a class full of students eager to find the four arrangements. The following arrangements are often tried and do not result in the lighting of the bulb.

Unsuccessful Attempts at Lighting the Light Bulb



After a few minutes of trying, several healthy chuckles, and an occasional exclamation of how hot the wire is getting, a couple of students become successful at lighting the bulb. Unlike the attempts shown here, the first successful attempt is characterized by the production of a complete conducting loop from the positive terminal to the negative terminal, with both the battery and the light bulb being part of the loop. As shown in the next diagram, the base of the light bulb connects to the positive terminal of the cell and the wire extends from the ribbed sides of the light bulb down to the negative terminal of the cell.



A complete conducting loop is made with the light bulb being part of the loop. A circuit exists and charge flows along the complete conducting path, lighting the bulb in the process. Compare the arrangement of the cell, bulb and wire at the right to the unsuccessful arrangements shown earlier. In attempt A, the wire does not loop back to the negative terminal of the cell. In attempt B, the wire does form a loop but not back to the negative terminal of the cell. In attempt C, there is no complete loop at all. Attempt D resembles attempt B in that there is a loop but not from the positive terminal to the negative terminal. And in attempt E, there is a loop and it does go from positive terminal to negative terminal; this is a circuit but the light bulb is not included as part of it. CAUTION: Attempt E will cause your fingers to get hot as you hold the bare wire and charge begins to flow at a high rate between the positive and negative terminals.

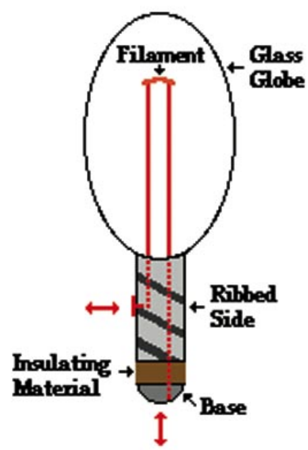
LIGHT BULB ANATOMY

Once one group of students successfully lights the bulb, many other lab groups quickly follow suit. But then the question emerges as to what other ways that the cell, bulb and bare wire can be arranged in such a manner as to light the bulb. Often a short light bulb anatomy lesson prompts the lab groups into a quick discovery of one or more of the remaining arrangements.

A light bulb is a relatively simple device consisting of a filament resting upon or somehow attached to two wires. The wires and the filament are conducting materials which allow charge to flow through them. One wire is connected to the ribbed sides of the light bulbs. The other wire is connected to the bottom base of the light bulb. The ribbed edge and the bottom base are separated by an insulating material which prevents the direct flow of charge between the bottom base and the ribbed edge. The only pathway by which charge can make it from the ribbed edge to the bottom base or vice versa is the pathway that includes the wires and the filament. Charge can either enter the ribbed edge, make the pathway through the filament and exit out the bottom base; or it can enter the bottom base, make the pathway through the filament and exit out the ribbed edge. As such, there are two possible entry points and two corresponding exit points.

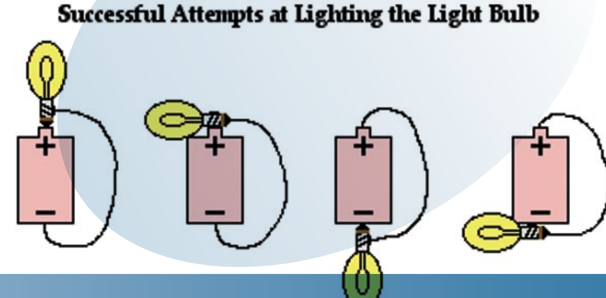
The successful means of lighting the bulb as shown above involved placing the bottom base of the bulb on the positive terminal and connecting the ribbed edge to the negative terminal using a wire. Any charge which enters the light bulb at the bottom base exits the bulb at the location where the wire makes contact with the ribbed edge. Yet the bottom base does not have to be the part of the bulb that touches the positive terminal. The bulb will light just as easily if the ribbed edge is placed on top of the positive terminal and the bottom base is connected to the negative terminal using a wire. The final two arrangements which lead to a lit light bulb involve placing the bulb at the negative terminal of the cell, either by making contact to it with the ribbed edge or with the bottom base. A wire must then connect the other part of the bulb to the positive terminal of the cell.

Light Bulb Anatomy



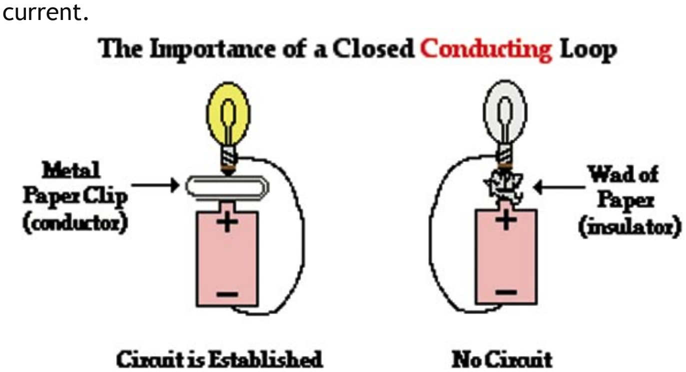
The conducting path for charge is indicated by the red lines.

Successful Attempts at Lighting the Light Bulb

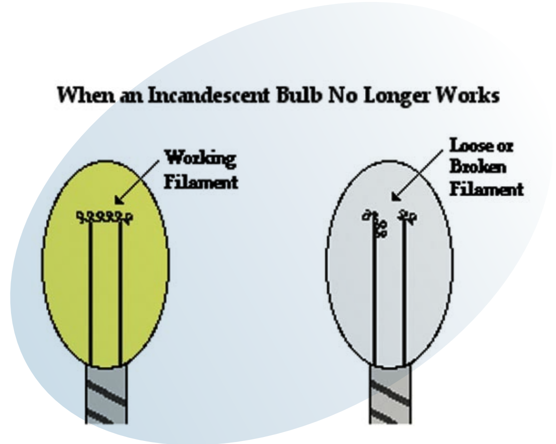


THE REQUIREMENT OF A CLOSED CONDUCTING PATH

There are two requirements which must be met to establish an electric circuit. The first is clearly demonstrated by the above activity. There must be a closed conducting path which extends from the positive terminal to the negative terminal. It is not enough that there is simply a closed conducting loop; the loop itself must extend from the positive terminal to the negative terminal of the electrochemical cell. An electric circuit is like a water circuit at a water park. The flow of charge through wires is similar to the flow of water through the pipes and along the slides at a water park. If a pipe gets plugged or broken such that water cannot make the complete path through the circuit, then the flow of water will soon cease. In an electric circuit, all connections must be made and made by conducting materials capable of carrying charge. As the cell, bulb and wire experiment continues, some students explore the capability of various materials to carry a charge by inserting them in their circuit. Metallic materials are conductors and can be inserted into the circuit to successfully light the bulb. On the other hand, paper and plastic materials are typically insulators and their insertion within the circuit will hinder the flow of charge to such a degree that the current ceases and the bulb no longer lights. There must be a closed conducting loop from the positive to the negative terminal in order to establish a circuit and to have a current.



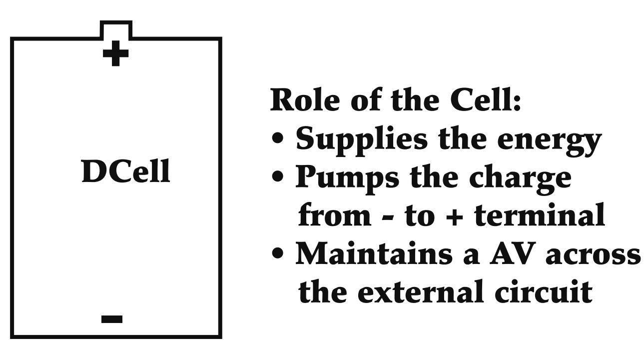
With an understanding of this first requirement of an electric circuit, it becomes clear what is happening when an incandescent light bulb in a table lamp or floor lamp no longer works. Over time, a light bulb filament becomes weak and brittle and can often break or simply become loose. When this occurs, the circuit is opened and a closed conducting loop no longer exists. Without a closed conducting loop, there can be no circuit, no charge flow and no lit bulb. Next time you find a broken bulb in a lamp, safely remove it and inspect the filament. Often times, shaking the removed bulb will cause a rattle; the filament has likely fallen off the supporting posts which it normally rests upon to the bottom of the glass globe. When shook, you will hear the rattle of the filament hitting the glass globe.



THE REQUIREMENT OF AN ENERGY SUPPLY

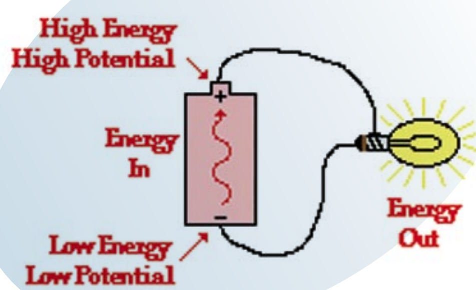
The second requirement of an electric circuit that is common in each of the successful attempts demonstrated above is that there must be an electric potential difference across the two ends of the circuit. This is most commonly established by the use of an electrochemical cell, a pack of cells (i.e., a battery) or some other energy source. It is essential that there is some source of energy capable of increasing the electric potential energy of a charge as it moves from the low energy terminal to the high-energy terminal.

As discussed in Section 1, it takes energy to move a positive test charge against the electric field. As applied to electric circuits, the movement of a positive test charge through the cell from the low energy terminal to the high-energy terminal is a movement against the electric field. This movement of charge demands that work be done on it in order to lift it up to the higher energy terminal. An electrochemical cell serves the useful role of supplying the energy to do work on the charge in order to pump it or move it through the cell from the negative to the positive terminal. By doing so, the cell establishes an electric potential difference across the two ends of the electric circuit. (The concept of an electric potential difference and its application to electric circuits was discussed in detail in Section 1.)



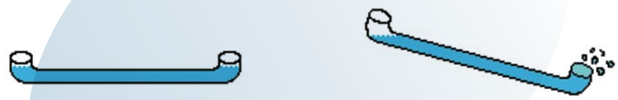
In household circuits, the energy is supplied by a local utility company which is responsible for making sure that the hot and the neutral plates within the circuit panel box of your home always have an electric potential difference of about 110 Volts to 120 Volts (in the United States). In typical lab activities, an electrochemical cell or group of cells (i.e., a battery) is used to establish an electric potential difference across the two ends of the external circuit of about 1.5 Volts (a single cell) or 4.5 Volts (three cells in a pack). Analogies are often made between an electric circuit and the water circuit at a water park or a roller coaster ride at an amusement park. In all three cases, there is something which is moving through a complete loop - that is, through a circuit.

And in all three cases, it is essential that the circuit include a section where energy is put into the water, the coaster car or the charge in order to move it uphill against its natural direction of motion from a low potential energy to a high potential energy. A water park ride has a water pump that pumps the water from ground level to the top of the slide. A roller coaster ride has a motor-driven chain that carries the train of coaster cars from ground level to the top of the first drop. And an electric circuit has an electrochemical cell, battery (group of cells) or some other energy supply that moves the charge from ground level (the negative terminal) to the positive terminal. By constantly supplying the energy to move the charge from the low energy, low potential terminal to the high energy, high potential terminal, a continuous flow of charge can be maintained.



By establishing this difference in electric potential, charge is able to flow downhill through the external circuit. This motion of the charge is natural and does not require energy. Like the movement of water at a water park or a roller coaster car at an amusement park, the downhill motion is natural and occurs without the need for energy from an external source. It is the difference in potential - whether gravitational potential or electric potential - which causes the water, the coaster car and the charge to move. This potential difference requires the input of energy from an external source. In the case of an electric circuit, one of the two requirements to establish an electric circuit is an energy source.

A Difference in Potential Causes a Fluid to Flow



Water won't flow if the two ends of the pipe are at the same potential.

If the two ends of the pipe are at different potentials, than water will flow.

In conclusion, there are two requirements which must be met in order to establish an electric circuit. The requirements are:

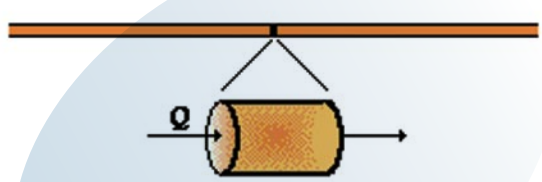
1. There must be an energy supply capable doing work on charge to move it from a low energy location to a high energy location and thus establish an electric potential difference across the two ends of the external circuit.

2. There must be a closed conducting loop in the external circuit which stretches from the high potential, positive terminal to the low potential, negative terminal.

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 this diagram, 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:

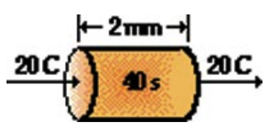
$$\text{Current} = I = \frac{Q}{t}$$

Note that the equation above uses the symbol I to represent the quantity current.

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.

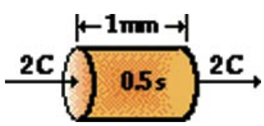
1 ampere = 1 coulomb / 1 second

To test your understanding, determine the current for the following two situations. Note that some extraneous information is given in each situation.



I = ______ Ampere

Answer: I = Q / t = (20 C) / (40 s) = 0.50 Ampere

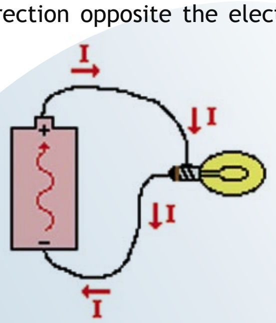


I = ______ Ampere

Answer: I = Q / t = (2 C) / (0.5 s) = 4.0 Ampere

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.

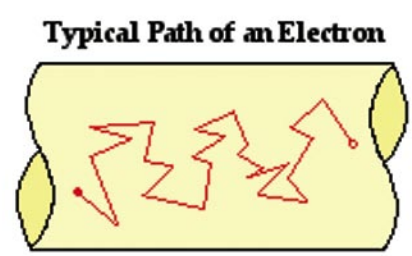


Electric current in the external circuit is directed from the positive to the negative terminal.

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 worldwide and one that a student of physics can easily become accustomed.

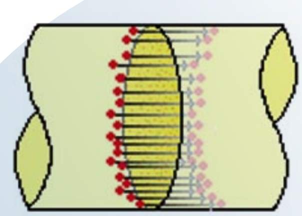
CURRENT VERSUS DRIFT SPEED

Current has to do with the number of coulombs of charge that 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.

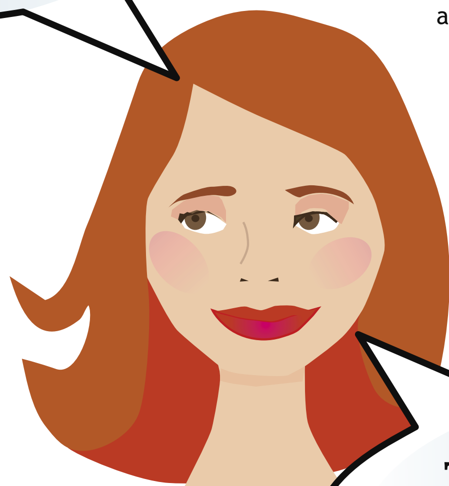


The path of a typical electron through a wire could be described as a rather chaotic, zigzag path characterized by collisions with fixed atoms. Each collision results in a change in direction of the electron. Yet because of collisions with atoms in the solid network of the metal conductor, there are 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 effect 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!

One might then ask: How can there be 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



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



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 racetrack. 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 come on immediately after the switch 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 on, the circuit is closed and there is an electric potential difference 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 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 that 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 notice able 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.

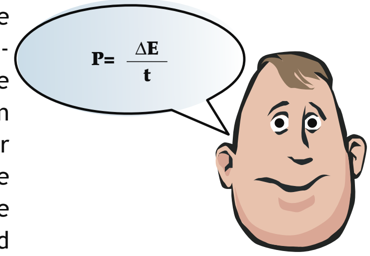
PUTTING CHARGES TO WORK

Electric circuits are designed to serve a useful function. The mere movement of charge from terminal to terminal is of little use if the electrical energy possessed by the charge is not transformed into another useful form. To equip a circuit with a battery and a wire leading from positive to negative terminal without an electrical device (light bulb, beeper, motor, etc.) would lead to a high rate of charge flow. Such a circuit is referred to as a short circuit. With charge flowing rapidly between terminals, the rate at which energy would be consumed would be high. Such a circuit would heat the wires to a high temperature and drain the battery of its energy rather quickly. When a circuit is equipped with a light bulb, beeper, or motor, the electrical energy supplied to the charge by the battery is transformed into other forms in the electrical device. A light bulb, beeper and motor are generally referred to as a load. In a light bulb, electrical energy is transformed into useful light energy (and some non-useful thermal energy). In a beeper, electrical energy is transformed into sound energy. And in a motor, electrical energy is transformed into mechanical energy.

An electrical circuit is simply an energy transformation tool. Energy is provided to the circuit by an electrochemical cell, battery, generator or other electrical energy source. And energy is delivered by the circuit to the load at the location of the load. The rate at which this energy transformation occurs is of great importance to those who design electrical circuits for useful functions. Power is the rate at which mechanical work is done. Here, we will discuss power in electrical terms; while the context is different, the essential meaning of the concept of power will remain the same. Power is the rate at which electrical energy is supplied to a circuit or consumed by a load. The electrical energy is supplied to the load by an energy source such as an electrochemical cell. Recall from Section 1 that a cell does work upon a charge to move it from the low energy to the high energy terminal. The work done on the charge is equivalent to the electrical potential energy change of the charge. Thus, electrical power, like mechanical power, is the rate at which work is done. Like current, power is a rate quantity. It's mathematical formula is expressed on a per time basis.

$$\text{Power} = \frac{\text{Work Done on Charge}}{\text{Time}} = \frac{\text{Energy Consumed by Load}}{\text{Time}}$$

Whether the focus is the energy gained by the charge at the energy source or the energy lost by the charge at the load, electrical power refers to the rate at which the charge changes its energy. In an electrochemical cell (or other energy source), the change is a positive change (i.e., a gain in energy) and at the load, the change is a negative change (i.e., a loss in energy). Thus, power is often referred to as the rate of energy change and its equation is expressed as the energy change per time.



Like mechanical power, the unit of electrical power is the watt, abbreviated W. (Quite obviously, it is important that the symbol W as the unit of power not be confused with the symbol W for the quantity of work done upon a charge by the energy source.) A watt of power is equivalent to the delivery of 1 joule of energy every second. In other words:

1 watt = 1 joule / second

When it is observed that a light bulb is rated at 60 watts, then there are 60 joules of energy delivered to the light bulb every second. A 120-watt light bulbs draws 120 joules of energy every second. The ratio of the energy delivered or expended by the device to time is equal to the wattage of the device.

THE KILOWATT-HOUR

Electrical utility companies who provide energy for homes provide a monthly bill charging those homes for the electrical energy which they used. A typical bill can be very complicated with a number of line items indicating charges for various aspects of the utility service. But somewhere on the bill will be a charge for the number of kilowatt-hours of electricity which were consumed. Exactly what is a kilowatt-hour? Is it a unit of power? Time? Energy or some other quantity? And when we pay for the electricity which we use, what exactly is it that we are paying for?

A careful inspection of the unit kilowatt-hour reveals the answers to these questions. A kilowatt is a unit of power and an hour is a unit of time. So a kilowatt-hour is a unit of Power-time. If Power = DEnergy / time, then Power-time = DEnergy. So a unit of power-time is a unit of energy. The kilowatt-hour is a unit of energy. When an electrical utility company charges a household for the electricity which they used, they are charging them for electrical energy. A utility company in the United States is responsible for assuring that the electric potential difference across the two main wires of the house is 110 to 120 volts. And maintaining this difference in potential requires energy.

It is a common misconception that the utility company provides electricity in the form of charge carriers or electrons. The fact is that the mobile electrons which are in the wires of our homes would be there whether there was a utility company or not. The electrons come with the atoms that make up the wires of our household circuits. The utility company simply provides the energy which causes the motion of the charge carriers within the household circuits. And when they charge us for a few hundred kilowatt-hours of electricity, they are providing us with an energy bill.

CALCULATING POWER

The rate at which energy is delivered to a light bulb by a circuit is related to the electric potential difference established across the ends of the circuit (i.e., the voltage rating of the energy source) and the current flowing through the circuit. The relationship between power, current and electric potential difference can be derived by combining the mathematical definitions of power, electric potential difference and current. Power is the rate at which energy is added to or removed from a circuit by a battery or a load. Current is the rate at which charge moves past a point on a circuit. And the electric potential difference across the two ends of a circuit is the potential energy difference per charge between those two points. In equation form, these definitions can be stated as:

$$P = \frac{\Delta E}{t}$$

Equation 1

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

Equation 2

$$\Delta V = \frac{\Delta PE}{Q}$$

Equation 3

Equation 3 can be rearranged to show that the energy change across the two ends of a circuit is the product of the electric potential difference and the charge - DV • Q. Substituting this expression for energy change into Equation 1 will yield the following equation:

$$P = \frac{\Delta V \bullet Q}{t}$$

In the equation above, there is a Q in the numerator and a t in the denominator. This is simply the current; and as such, the equation can be rewritten as:

$$P = \Delta V \bullet I$$

The electrical power is simply the product of the electric potential difference and the current. To determine the power of a battery or other energy source (i.e., the rate at which it delivers energy to the circuit), one simply takes the electric potential difference which it establishes across the external circuit and multiplies it by the current in the circuit. To determine the power of an electrical device or a load, one simply takes the electric potential difference across the device (sometimes referred to as the voltage drop) and multiplies it by the current in the device.

COMMON MISCONCEPTIONS REGARDING ELECTRIC CIRCUITS

So far, an effort has been made to present a model of how and why electric charge flows within an electric circuit. Terms have been defined and rules and principles presented and discussed. The goal has been to help students of physics to construct an accurate mental model of the world of current electricity. This goal is often impeded by the presence of preconceived ideas regarding the nature of charge flow and the role of a battery in a circuit. In many instances, these preconceived notions about charge flow and batteries are incorrect ideas and are completely inconsistent with the model presented here. Like all misconceptions in physics, they must be directly confronted in order to successfully build an accurate mental model of the physical world.

To begin the exploration of these misconceptions, test yourself against the following five true-false statements.

True or False?

a. When an electrochemical cell no longer works, it is out of charge and must be recharged before it can be used again.

b. An electrochemical cell can be a source of charge in a circuit. The charge which flows through the circuit originates in the cell.

c. Charge becomes used up as it flows through a circuit. The amount of charge which exits a light bulb is less than the amount which enters the light bulb.

d. Charge flows through circuits at very high speeds. This explains why the light bulb turns on immediately after the wall switch is flipped.

e. The local electrical utility company supplies millions and millions of electrons to our homes everyday.

(Each of these statements is false)

HOW IS ELECTRICITY GENERATED? CHAPTER 3

Introduction

Renewable Energy Sources

Nonrenewable Sources

Nuclear Energy Sources

Battery Power

Introduction

It's easy to take our seemingly plentiful supply of electricity for granted. We can flick on our lights or get a cold drink from our refrigerators just about anytime we want. Since we seem to have so much electricity, we might conclude that the energy sources we use to generate this electricity are also found in abundant quantities; but this is only partially true. Renewable energy sources will always be available, but others, the non-renewables, are being used up.

RENEWABLE AND NONRENEWABLE ENERGY SOURCES

Renewable energy sources are those that are naturally regenerated, or renewed, within a useful amount of time: wood and other substances produced by living things (biomass), natural heat from the earth's interior (geothermal), moving or falling water (hydropower), the wind, the sun, and the ocean. We can use these resources today, and nature will still provide them tomorrow.

Non-renewable energy sources are those that can be depleted. Nature does not renew these in a useful amount of time. These include fossil fuels (coal, oil, natural gas) and nuclear fuels. These resources are being used up faster than nature could ever replace them.

RENEWABLE? CLEAN? GREEN?

We sometimes read or hear the terms "clean energy," "green energy," "sustainable energy," and "alternative energy," along with the term "renewable energy." Some people use these terms interchangeably, which can be confusing.

Clean or green energy usually refers to energy that is environmentally friendly. When we generate electricity with these resources, very few pollutants, if any, enter our air or water.

Sustainable energy usually refers to a process, system, or technology that does not deplete resources or cause environmental damage.

Sustainable energy practices preserve meaningful natural resource choices for future generations.

When people use the term alternative energy, they are usually speaking of alternatives to the conventional energy sources: fossil fuels, "large" hydropower, and nuclear. Alternative energy can definitely include renewables. Most often, though, the term alternative is applied to certain transportation fuels — any fuels other than gasoline and diesel — such as ethanol, biodiesel, and hydrogen.

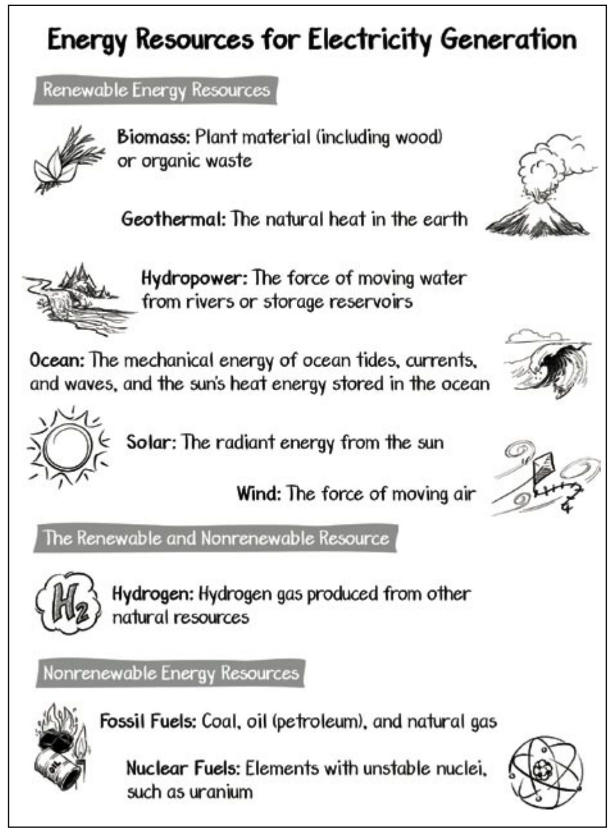
ENERGY AWARENESS, ENERGY CHOICES

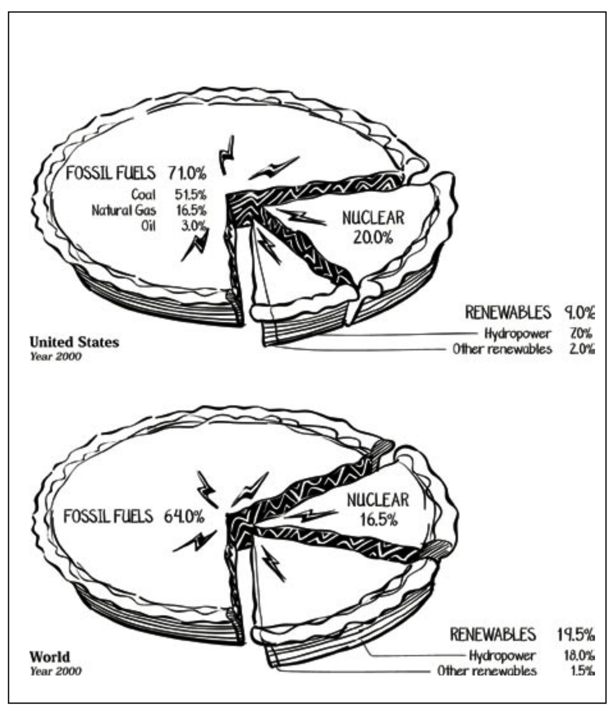
Electricity has contributed greatly to our comfort and to our society's development, but we are using up valuable and irreplaceable energy resources. Since the beginning of the Industrial Revolution our use of energy sources, particularly fossil fuels, has increased with each passing year. In the last 30 years alone, their use has tripled.

We are indeed fortunate to have other energy options. In the pages that follow you will find a comprehensive explanation of the energy resources and technologies we use to make electricity.

RESOURCES BEING USED TO GENERATE ELECTRICITY

These pie charts show the percentages of electricity produced from different energy resources in the United States* and around the world.





RENEWABLE ENERGY SOURCES

BIOMASS

Biomass was one of the first energy resources ever used by humans. It includes anything that is or was once alive.
Ever since the discovery of ways to create fire, humans have been burning wood and other organic material to create heat and light.

In the United States, biomass, mostly from trees, was the premier energy source until the 1830s. It was displaced by fossil fuels (mainly coal) when the Industrial Revolution took hold. Recently, however, the use of biomass, in a widening range of forms, has begun to increase.

Today it is an important energy source for many processes, including the generation of electricity.

THE BIOMASS RESOURCE

Most living things receive and store energy from the sun. This energy is released when the organic material is digested, burned, or decomposed.

This released energy can be used to produce electricity. Today, many kinds of biomass are used as energy resources.

SOLID BIOMASS

Solid biomass is anything organic that has not yet broken down into a gas or a liquid. There are many kinds of solid biomass. Chipped wood, whole trees, energy crops, and agricultural wastes are examples.

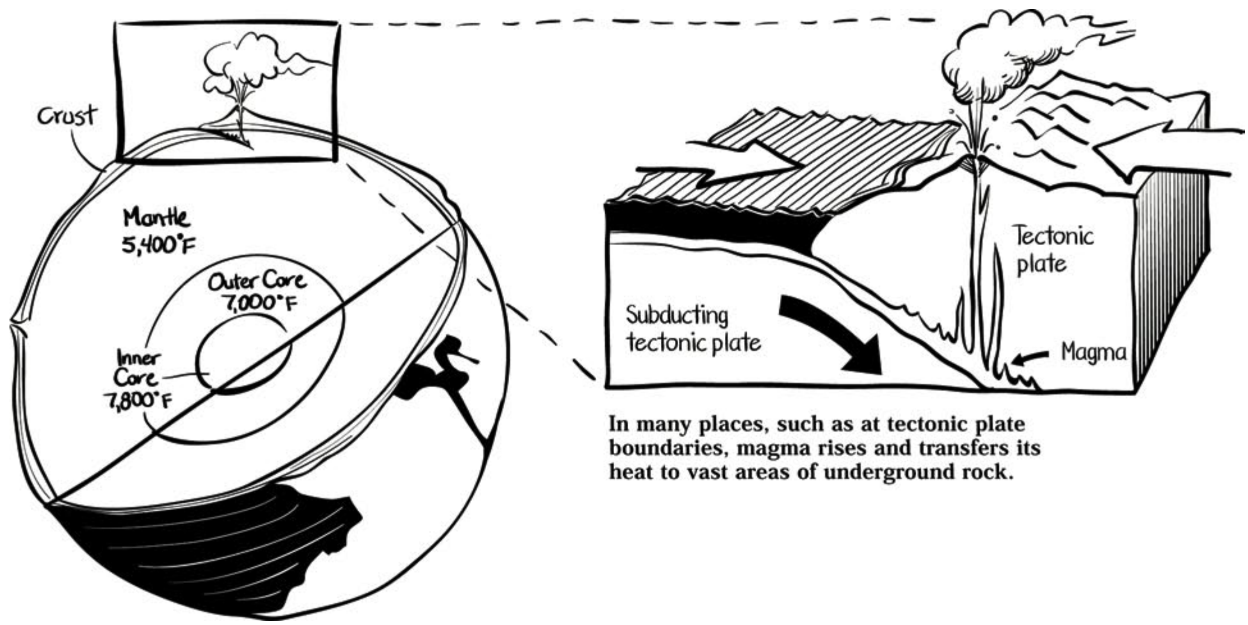
Other solid biomass sources are trimmings from forests and orchards; wastes from building construction, food processing, and paper industries; animal manure; and plain old garbage.

At home and at work people produce tons of waste each year, much of which is organic. Many of us produce a lot of this "green" waste just from cutting our lawns and trimming our trees and bushes.

Until recently, all garbage (including organic waste) was dumped into landfills or burned without any pollution controls. Today, many biomass power plants (complete with pollution controls) use solid biomass to produce electricity. Instead of going to landfills much of our green waste is now trucked directly to biomass plants. A plant in Michigan uses 300,000 tons per year of wood waste from local timber industries (and puts wastewater to use in its cooling towers). A plant in Wisconsin uses 250,000 tons of wood wastes, shredded railroad ties, and even scrap tires.

MUNCHING MICROBES

Picture a landfill teeming with rotting, long-buried waste. Microbes gobble this decaying quagmire of leftover stuff that originally came from living things. As the microbes munch, they burp methane gas. Methane gas is normally released into the atmosphere and is a potent greenhouse gas. However, at a landfill near Eugene, Oregon (as at many others around the United States), the gas is collected and burned for heat to generate electricity. This biomass power plant has been in operation since 1992 and continues to send electrical power to several thousand homes.



In many places, such as at tectonic plate boundaries, magma rises and transfers its heat to vast areas of underground rock.

BIOFUELS AND BIOGAS

We can produce both liquid and gas fuels from solid biomass. This is not a new idea. The production of biomass gas, called gasification, is based on a method developed in the early 1800s to produce gas from coal for town streetlights in both England and the United States. And since the 1940s, in over a million homes in India, people have cooked with biomass gas made in their own small gasifiers.

Today, gasifiers use high-tech processes to produce a gas from solid biomass by heating it under very controlled conditions. This gas can then be converted to a liquid. Gasification facilities can be large or small, serving power plants that range from just a few kilowatts to 50 MW or more.

GEOTHERMAL

People have always been fascinated with volcanoes and their fiery displays of nature's power. Many ancient societies once thought volcanoes were home to temperamental gods or goddesses. Today we know that volcanoes result from the immense heat energy — geothermal energy — found in Earth's interior. This heat also causes hot springs, steam vents (fumaroles), and geysers.

Over the ages, humans have benefited from Earth's geothermal energy by using the hot water that naturally rises up to the earth's surface. We have soaked in hot springs for healing and relaxation and have even used them as instant cooking pots. Hot springs have also been an important part of cultural life, especially in Japan and Europe.

Today we drill wells deep underground to bring hot water and steam to the surface. We use the geothermal water to heat buildings, to speed the growth of plants and fish, and to dry lumber, fruits and vegetables. We use the really hot water and steam to generate electricity.

THE GEOTHERMAL RESOURCE

Geo means earth and thermal means heat. So geothermal energy is the heat energy of the earth.

The Inner Earth: Hot, Hot, Hot!

Billions of years ago Earth was a fiery ball of liquid and gas. As the planet cooled, an outer rocky crust formed over the hot interior. This relatively thin crust "floats" on top of a massive layer of very hot rock called the mantle. Some of the mantle rock is actually melted, or molten, forming magma.

Heat from the mantle and the magma continuously transfers up into the crust. (Heat is also being generated in the crust itself by the natural decay, or breakdown, of radioactive elements found in all rock.)

The crust is broken into enormous slabs — tectonic plates — that are actually moving very slowly (about the rate your fingernails grow) over the mantle, separating from, crushing into, or sliding (subducting) under one another. The edges of these huge plates are often restless with volcanic and earthquake activity. At these plate boundaries, and in other places where the crust is thinned or fractured, magma is closer to the surface than it is elsewhere. Sometimes the magma emerges above ground — where we know it as lava. But most of it stays below ground where, over time, it creates large regions of hot rock.

HYDROPOWER

Flowing water is one of nature's most powerful forces. Humans began harnessing this energy force several thousand years ago. By the first century BC, waterwheels were working in many parts of the world, including Greece. (In fact, the term hydro comes from an ancient Greek word for water.) For centuries waterwheels in many countries provided the energy to grind grain and saw lumber. By the 1700s, more than 10,000 waterwheels were hard at work in colonial New England alone.

During the Industrial Revolution, waterwheels were also used to run textile mills and other factories. By the late 1800s water turbines were driving a new device – the generator – to produce electricity.

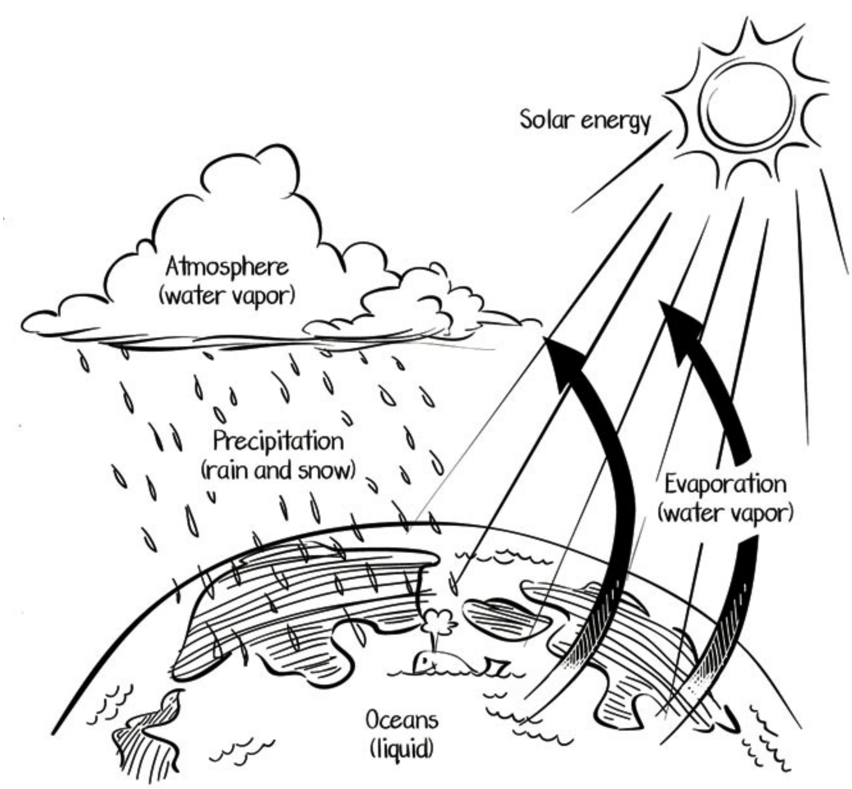
Before the end of that century the world's first commercial water-driven electrical station opened at Niagara Falls, New York, and the era of hydroelectric power was born.

THE HYDROPOWER RESOURCE

The hydropower resource is the force of flowing water, provided to us naturally by the earth's water cycle and by gravity. The force of the flow of a medium-size river is equal to several million horsepower.

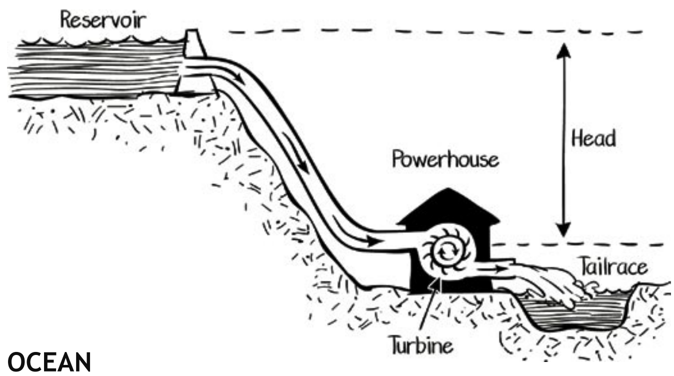
(One million horsepower, if converted to electricity, would equal the power of 746 MW.) You can imagine how easily this much force can be put to work driving waterwheels or water turbines.

Energy from the sun (solar energy) causes evaporation of water from the land and from the oceans, rivers, and lakes. This puts water vapor into the atmosphere where it can condense to form clouds, which then return the water to the earth as rain, snow, and ice. Water runoff is pulled down by gravity to form streams and rivers, which flow to lakes and to the sea. This cycle of evaporation and precipitation is continuous.



THE STEEPER THE BETTER

The amount of force that water can impart depends on two factors: the head, the vertical distance the water falls; and the flow, the volume (amount or mass) of the water. The greater the head and the flow, the more water energy is available. So hydropower systems work best with a steep drop (high head) and a large flow. One gallon (3.8 liters) of water falling 100 feet (30 meters) per second can generate about 1 kW of electric power. No wonder waterfall areas, with their naturally steep drops, were chosen as the sites for the world's first hydroelectric power plants.



OCEAN

Since earliest times, the ocean has been a vast resource for travel, food, pearls, minerals, oil, and much more. Some say that the ocean is the last remaining frontier on earth. Much of the deep seafloor, with its many marvels, remains to be explored. And there's the lure of undiscovered shipwrecks and the riches they might contain. However, there is yet another ocean frontier that some think is much more valuable than buried treasure. This is the ocean's energy frontier, one that we are just beginning to understand and put to work.

THE OCEAN RESOURCE

Oceans have tremendous energy in the movement of their currents and waves. And the oceans store a vast amount of heat from the sun.

With today's technology both of these ocean energy resources can be put to work generating electricity.

MARINE CURRENTS

There are two kinds of marine currents: two-way (tidal) currents, and one-way currents.

Two-way currents are the ocean tides, caused by gravitational pull of the moon and sun. Each heavenly body pulls on the part of the ocean nearest to it, causing bulges in water height. As the earth rotates, those bulges move in relation to the world's coastlines, pulling water onto and away from the shore. So the turning of the earth causes a moving pattern in the ocean: at every coast in turn, the level rises and falls, resulting in two high tides and two low tides daily.

One-way currents are like massive "rivers" of ocean water flowing within the ocean for hundreds — sometimes thousands — of miles.

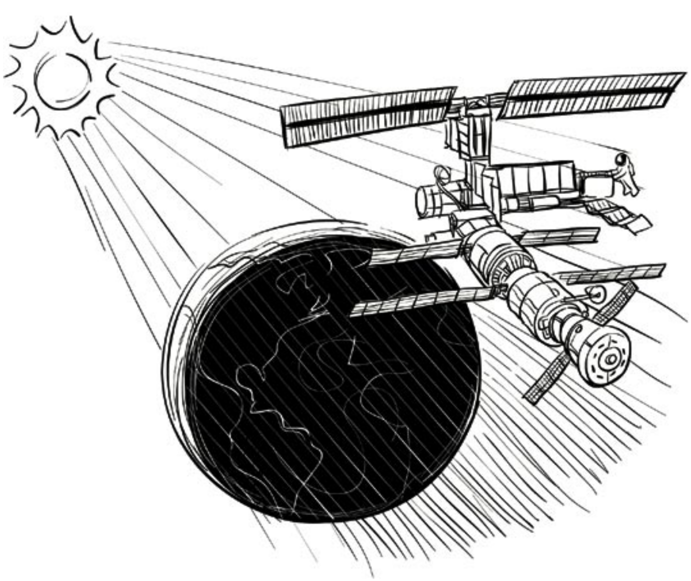
SOLAR

With solar energy, the sky's the limit. Our sun is the world's most widely used energy resource. Plants began capturing the sun's energy millions of years ago, and members of the animal kingdom have always basked in its warmth.

Human dwellings have long included openings that let in the sun's light and heat. Glass windows were used as early as 79 AD, as revealed in the archeological ruins of Pompeii and Herculaneum (Roman cities completely preserved under layers of ash from a volcanic eruption). Now, our use of windows to admit the sun's radiation is such a common practice that we don't even think about it. And today, with technology ranging from tiny solar cells to huge power plants shimmering with rows of curved mirrors, we use solar energy to make electricity.

THE SOLAR RESOURCE

We all know that our sun gives off radiating waves of heat and light energy. Without these, our planet would not have life. The sun's waves move rapidly as tiny bundles of energy called photons. These photons travel vast distances from the sun through the vacuum of space and bathe our planet with solar energy every day.



SHEDDING LIGHT ON THE SOLAR SPECTRUM

All the sun's radiant energy waves form the electromagnetic, or solar, spectrum. Forty-five percent of the radiation of the solar spectrum that reaches the earth's surface is visible light. Almost all the rest we do not see (although we can detect and measure it), yet it all delivers energy. For example, ultraviolet radiation, though we can't see it, can tan or burn our skin. And we're all familiar with the sun's infrared, or thermal (heat), radiation. Infrared radiation is what keeps the earth (and us) warm.

Some parts of the earth receive more solar radiation than others.

In general, the areas at or near the equator receive the most. For example, the tropics get about two and a half times more infrared radiation than the poles. However, any area that receives a steady supply of solar radiation, whether a little or a lot, can make use of the energy pouring in from our sun.

We use just a fraction of our enormous solar resource. More energy from sunlight strikes Earth in one hour than all the energy consumed on the planet in a year.

GENERATING ELECTRICITY FROM SOLAR RESOURCES

Here, we discuss solar energy only as a source of electricity.

PHOTOVOLTAICS (PV)

In the 1950s, American engineers sought a method to power U.S. space satellites. They found it in a process called photovoltaics (PV). We still use photovoltaics to energize orbiting satellites, space stations, and the Hubble telescope. Back on the earth, PV is widely used for everything from roadside call boxes to large power plants.

WIND

The power of the wind has been helping humans do work for centuries. As early as 5000 BC boats propelled by wind sailed along the Nile River. Windmills may have been used in China by 200 BC, and by 900 AD large windmills were grinding grain on the plains of Persia. The windmill spread to England as early as 1100 AD and was a common sight throughout medieval Europe. In the 1800s the American West was settled with the help of thousands of water-pumping windmills.

The first wind turbines for generating electricity were designed in Europe around 1910. These soon appeared in the United States, bringing electricity to rural homes and farms. Beginning in the late 1930s, the widespread installation of power lines made these small wind turbines obsolete. However, this was not the wind turbine's last appearance "down on the farm." Today, the wind turbine is once again a familiar sight — on open plains, along mountain passes, even off of windy coastlines. Far advanced from their creaky windmill cousins, today's wind turbines are sleek and powerful contributors to today's electricity scene.

THE WIND RESOURCE

Wind patterns vary greatly from one place to the next. For example, one area in the middle of Ohio is consistently calm, while the winds off nearby Lake Erie can almost knock a person over.

Regional wind patterns are greatly affected by terrain and by air currents in the upper atmosphere. For example, upper-level winds (the jet stream) are a primary factor in the weather systems that bluster through the American Great Plains. The flat terrain in this area, offering no obstruction to the wind, also helps make this one of the windiest regions in the United States.

Experts who study wind patterns have developed a scale of 1 to 7 to classify wind power (wind speed, wind height, and other factors).

Class 1 has the least power; Class 7, the highest. Wind turbines operate best in winds from Classes 3 through 7. There are many places in the U.S. where wind resources are Class 3 or above, including large parts of the Great Plains, the windy passes of the large mountain ranges, sections of both coasts, and portions of Alaska and Hawaii. Some wind experts believe that U.S. wind resources, if developed, could match total current U.S. electricity generation.

GENERATING ELECTRICITY FROM WIND RESOURCES

The basic machinery that converts wind power to electricity is called a wind turbine. The force of the wind spins blades attached to a hub that turns as the blades turn. Together, the blades and hub are called the rotor. The turning rotor spins a generator, producing electricity.

There is also a controller that starts and stops the rotation of the turbine blades. The generator, controller, and other equipment are found inside a covered housing (nacelle) directly behind the turbine blades.

Outside, an anemometer measures wind speed and feeds this information to the controller.

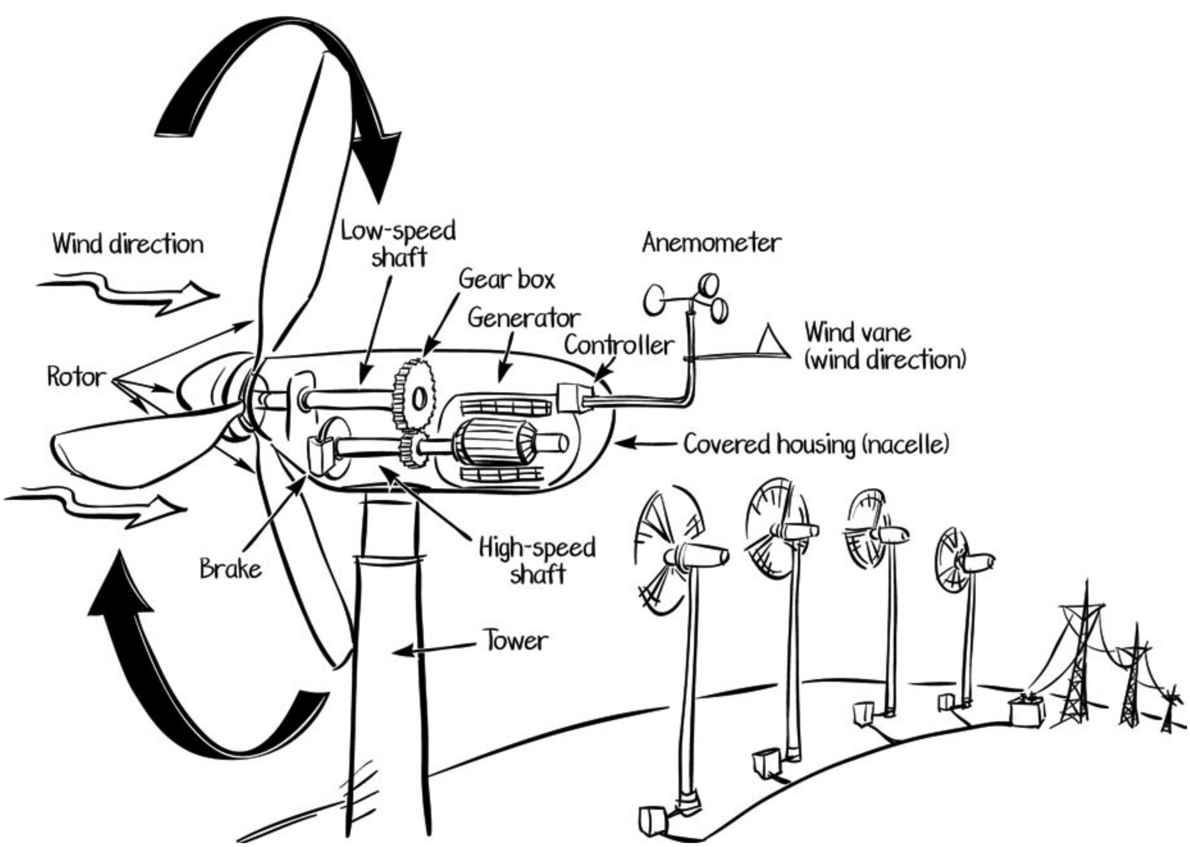
Wind turbines begin to turn with wind speeds of between 10 and 15 miles per hour (15 and 23 kilometers per hour). They automatically shut off at 55-60 mph (100 km/h), since anything above this speed is too hard on the machinery. Some wind turbine models run at a fixed speed no matter how fast the wind is blowing. Newer models are "variable speed." Their turning speed changes as wind speeds change, making them more efficient and allowing them to withstand gusty gales.

THE RENEWABLE AND NON-RENEWABLE RESOURCE

HYDROGEN

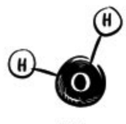
Hydrogen is one of the most abundant elements on Earth. Yet it wasn't until the 1700s that scientists first proved its existence, and it was later still that they recognized its value. Finally, by the mid-1800s, people were using hydrogen in "town gas," providing light and heat in cities across the United States and Europe. More recently, it has become useful in the production of ammonia, fertilizers, glass, refined metals, vitamins, cosmetics, cleaners, and much more.

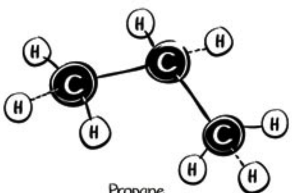
Hydrogen has launched many U.S. rockets into outer space. And hydrogen fuel cells, first used successfully in the 1960s, have been the main power source aboard all of NASA's space shuttles. Over the last 30 years, researchers have also been looking at ways to use hydrogen as a fuel for everyday life.



Hydrogen: Renewable or Nonrenewable?

Hydrogen can be renewable or nonrenewable, depending on how it is produced. If it comes from a renewable resource (such as water) and is produced using electricity from renewable energy, it is renewable. Otherwise, the hydrogen is considered nonrenewable. Most hydrogen produced today is nonrenewable.





THE HYDROGEN RESOURCE

On Earth, hydrogen is the third most common element, yet most of us aren't very familiar with it. This is because hydrogen doesn't occur naturally by itself. Instead, it is always found in combination with other elements.

Water, as we know, is a compound made of the elements hydrogen and oxygen — hence the formula H2O. Hydrogen joins with carbon to make fossil fuels such as natural gas, coal, and petroleum.

It is found in the molecules of all living things.

HYDROGEN UNBOUND

In order to use hydrogen we must separate it from the compounds in which it is bound. Once freed, it is a colorless, combustible gas that will release a great deal of energy. Scientists have developed different ways to produce hydrogen. One important method is electrolysis. Other techniques use chemical or biological processes.

PRODUCING RENEWABLE HYDROGEN BY ELECTROLYSIS.

Electrolysis was first closely studied in the 1830s by English scientist Michael Faraday. In this process, electricity is passed through water. The electrical charge causes the hydrogen and oxygen in the water molecule to split apart and turn into gases.

A chemical called an electrolyte is often added to the water to help conduct electrons through it.

Water used in electrolysis is, of course, a renewable resource, but for the resulting hydrogen to be considered renewable, the electricity for this process must also have come from a renewable source. Any renewable method of generating electricity could be used.

NONRENEWABLE ENERGY SOURCES

FOSSIL FUELS

Fossil fuels — coal, oil, and natural gas —have been highly prized energy sources for centuries. Mining for coal may have first occurred in China as far back as 200 BC. By 200 AD the Romans made wide use of the coal resources they found in the British Isles. In the 1100s, oil wells were being drilled in Europe and along the west coast of the Caspian Sea. It was the Industrial Revolution, however, that launched the widespread use of fossil fuels to power factories and transportation systems. Electricity was first produced using coal in the 1880s. Since that time, fossil fuels have been the dominant source of energy for electrical production, transportation, and industry in the United States and around the world.

THE FOSSIL FUEL RESOURCE

All fossil fuels are formed from plants and animals that lived millions of years ago — long before the days of the dinosaurs (hence, the phrase "fossil" fuels). When these plants and animals died, their remains decomposed and were eventually buried under tons of soil and rock. Subjected to heat and pressure over time, this organic matter eventually formed coal (a solid), oil (a liquid), and natural gas (a vapor). These three different fossil fuel types resulted from variations in the underground conditions.

Fossil fuels are nonrenewable resources. That is because today's fossil fuel resources formed so very long ago, when much of the land was covered with swamps and the climate was very warm.

These conditions were perfect for many living things, including huge ferns, trees, and other plants. The swamps and seas were teeming with algae and other small organisms. These lush conditions are not nearly as widespread today. Small amounts of fossil fuels may still be forming, but not in significant quantities. And, they will not form in a useful amount of time.

Living things are carbon-based, so all fossil fuels are made of molecules that contain carbon. They also contain hydrogen, giving rise to the name "hydrocarbons." Hydrocarbons burn easily. They are a reliable source of heat energy and are convenient to transport.

When fossil fuels are burned, carbon combines with oxygen, resulting in emissions of carbon dioxide gas. Fossil fuels contain other substances in addition to hydrocarbons. Sulfur, nitrogen, mercury and other impurities are found in varying amounts in each fossil fuel. When burned, these recombine with other materials and form air pollutants.

COAL

Coal is a solid hydrocarbon that we excavate from underground, just as we mine for minerals. One age-old method is to mine coal from tunnels dug deep underground. The other, and more recent, method is called surface- or strip-mining. Here, deposits within about 200 feet of the surface are exposed by removing the overlaying rock and soil. Once topside, coal is easy to transport, usually in large containers aboard ships or on trains.

There are abundant supplies of coal in the United States, with coal deposits in states across the continent. The top coal-producing states are West Virginia, Kentucky and Pennsylvania. Globally, Australia, India, and South Africa produce the most coal.

OIL

Oil, also known as petroleum or crude oil, is a thick black liquid hydrocarbon found in reservoirs hundreds to thousands of feet below the surface. We extract it by drilling wells deep into the underground rock and then inserting pipes. Natural pressure can bring the oil shooting to the surface when wells are new; but, in most cases, pumps are needed to bring the oil to the surface. These oil field pumping units are common sights on land and at sea (on offshore platforms) in oil-producing areas.

Once captured, crude oil is taken to refineries and processed into various products. These include gasoline, diesel, aviation fuel, home heating oil, asphalt, and oil burned for electrical power. Oil products are sent from refineries through pipelines directly to consumers, or are delivered in large tanks aboard trains, trucks, or tanker ships.

NUCLEAR

The atomic age was born in 1939 when physicists burst apart the nucleus of a uranium atom, releasing a tremendous amount of energy as heat and light. They called this reaction nuclear fission (fission means "to split").

Nuclear fission's first job was to make atomic bombs during World War II (in the 1940s). However, we soon learned how to control the energy from nuclear fission so we could use it to produce electricity.

Today, nuclear energy is used widely for electricity generation. It is also used to power nuclear submarines and aircraft carriers.

THE NUCLEAR RESOURCE

Nuclear energy is the energy trapped inside atoms, those tiny particles from which all matter is made.

THE ENERGY OF ATOMS AND MOLECULES

In nature, atoms are bonded together into molecules, which in turn are bonded into various types of matter. It takes a great deal of energy to hold these molecules together.

Every atom is made up of even tinier "subatomic" particles, including the protons and neutrons in the atom's nucleus (central part). The energy that holds these subatomic nuclear particles together is significantly greater than the energy that holds molecules together.

Making nuclear energy can be roughly compared to burning wood.

When we burn wood, we produce energy by breaking the electron bonds between molecules. If we stand beside a blazing bonfire we feel the energy as heat and see the energy as light. Similarly, when we produce a nuclear reaction we break the bonds between protons and neutrons within the nucleus of each atom, releasing enormous amounts of energy — considerably more than our bonfire.

URANIUM NUCLEUS IS "EASY" TO SPLIT

Most of the elements found on Earth have stable nuclei. This means they don't split apart easily. But some elements, such as uranium, have unstable nuclei, which causes these elements to give off small particles (to "radiate"). One type of uranium, Uranium 235 (U-235) is especially unstable.

URANIUM: FUEL FOR NUCLEAR POWER

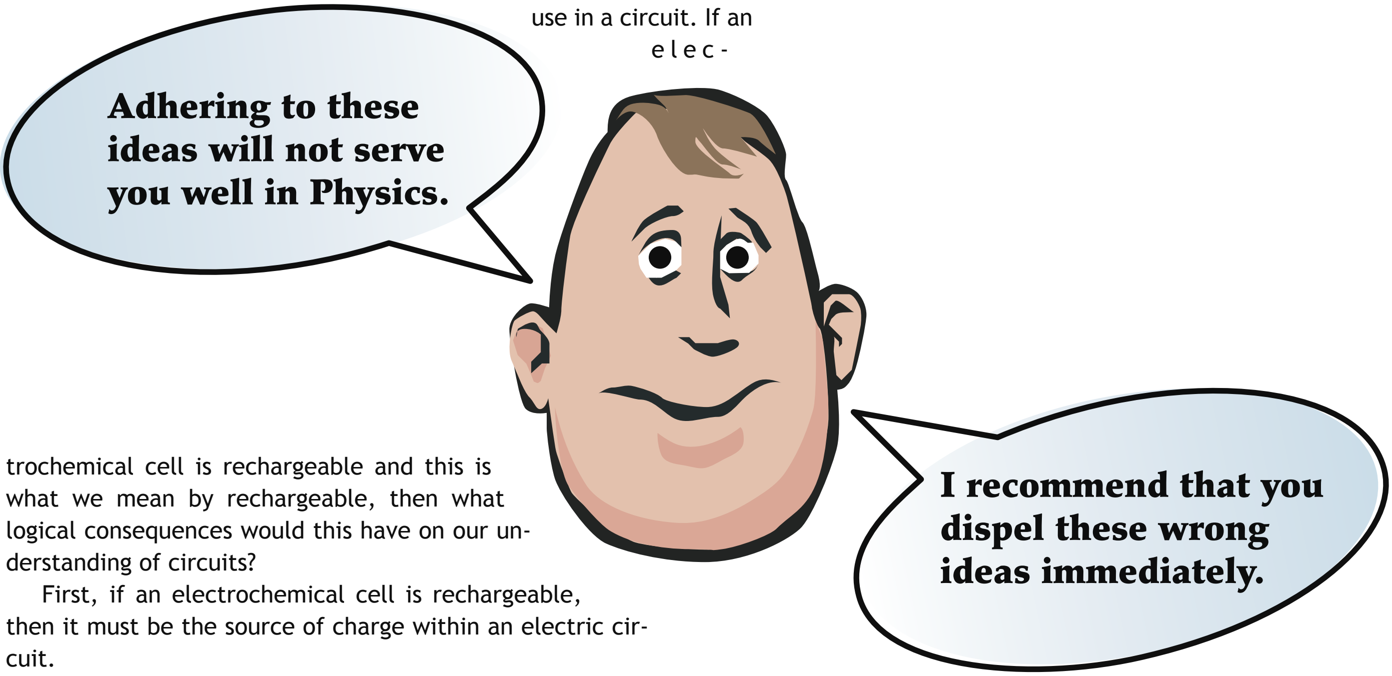
Uranium is very hard and very dense. That is, it has a lot of mass per given quantity. Whereas one gallon of milk weighs about 8 pounds, one gallon of uranium weighs 150 pounds.

Uranium is found in many parts of the world, including the United States. We dig uranium-bearing rock (ore) from the ground just as we mine other minerals. There is a limited supply — though scarcity is less of an issue than it is for fossil fuels, since uranium is used in much smaller quantities. Uranium is, nevertheless, a nonrenewable resource.

BATTERY POWER

BATTERIES ARE NOT RECHARGEABLE

Batteries are not rechargeable. This statement ought to get some people's attention. The belief that an electrochemical cell is rechargeable may be the starting point of a logically developed collection of misconceptions which are completely inconsistent with the model of circuits presented in this unit. Let's suppose for a moment that an electrochemical cell is rechargeable; and let's suppose that when we say they are rechargeable, we mean that we can place the cell in a small machine and replace or replenish the charge which it has lost through use in a circuit. If an electrochemical cell is rechargeable and this is what we mean by rechargeable, then what logical consequences would this have on our understanding of circuits?



First, if an electrochemical cell is rechargeable, then it must be the source of charge within an electric circuit.

Obviously, if a cell must have its charge replenished or resupplied, then it must do so because its role is to supply the charge needed to operate an electric circuit. It would be reasonable to believe that the charge which flows through a circuit to operate a flashlight bulb must originate in the flashlight battery compartment. And perhaps it would be reasonable to believe that the charge which flows out of the cells and into the bulb becomes consumed or used up in such a manner that it does not flow out of the bulb in as much quantity as it flows into the bulb. The amount of charge exiting the bulb is less than that which enters the bulb. After all, one may think, electricity is used up by a circuit; perhaps what is being used up is the charge which is supplied by the electrochemical cells. And when the flashlight bulb no longer works, the cells inside must have lost all its charge and must be placed in this little recharging machine and be recharged.

The above paragraph represents a perfectly logical extension (though entirely inaccurate) of the belief that batteries are rechargeable. If you really do believe that an electrochemical cell is rechargeable, then you likely answered True to the first three statements of the True-False quiz. But the collection of misconceptions usually does not end with the above paragraph. The reasoning continues. If one believes that an electrochemical cell is the source of charge in a flashlight circuit, then one should also believe that charge must move through the wires of a circuit at a very fast speed. After all, one can clearly observe that the bulb lights immediately after the switch on the flashlight is turned to ON. There is no noticeable time delay between when the switch is flipped and when the light bulb lights. Thus, it is reasonable to believe that if charge is being supplied by the cells in the battery compartment, then it must travel through the 2 cm of wire from the battery to the light bulb in less than a millisecond.

Whatever time it does take, it cannot be much since a time delay is never observed. The reasoning may continue as follows: a home is not powered by a battery, but rather by an electrical utility company. Instead of using electrochemical cells as the source of charge in a home, the electricity is supplied by the utility company. One could then easily imagine that the utility company must supply a countless number of electrons to homes each day in order to operate all the appliances which are used. These electrons travel at nearly the speed of light from the fuse box or electrical panel to the appliance when an appliance is turned on. This reasoning would explain why a light bulb lights immediately after the light switch is flipped to the ON position.

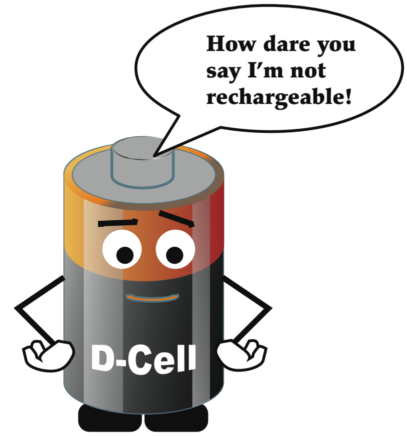
GETTING THE RIGHT MENTAL MODEL

Again, the above two paragraphs represent a logical extension of the belief that an electrochemical cell is the source of charge in a circuit and that they must have their charged resupplied or replenished when they no longer work. This logic would lead a student of physics to answer True to all five statements of the True-False quiz. The problem with the reasoning above is that it leads to completely wrong conclusions. While the reasoning may be logical, the conclusions which it leads to are completely false due to its entirely incorrect initial premise - that batteries are rechargeable. It is important to realize that the mental model developed by such reasoning patterns is completely inconsistent with the model already presented. Consider the following highlights discussed already in this unit and compare them to the conclusions drawn in the above paragraphs.

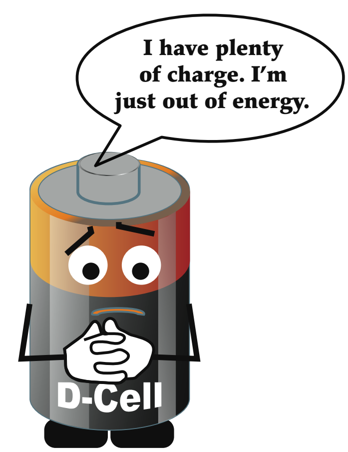
- An electrochemical cell supplies the energy needed to move a charge from a low potential location to a high potential location.
- The charge that flows through a circuit originates in the wires of the circuit. The charge carriers in wires are simply the electrons possessed by the atoms which make up the wires.
- Charge moves abnormally slowly - on average, about 1 meter in an hour - through a circuit. Yet as soon as a switched is turned to ON, charge located everywhere within the circuit begins to move.
- The rate at which charge flows is everywhere the same within an electric circuit. The rate at which charge flows into a light bulb is the same as the rate at which charge flows out of a light bulb.
- An electrical appliance such as a light bulb transforms the electrical energy of moving charge into other forms of energy such as light energy and thermal energy. Thus, the amount of electrical energy possessed by a charge as it exits an appliance is less than it possessed when it entered the appliance.

If an electrochemical cell is not rechargeable, then why do stores sell rechargeable cells for a higher cost? What kind of rip-off is that? The fact is that electrochemical cells that are referred to as rechargeable can be bought in stores. And these batteries can be placed in small machines that are called rechargers. And the process of doing so can extend the life of the battery. So as far as the consumer is concerned, it really isn't a rip-off at all. But literally speaking, batteries should never be referred to as rechargeable.

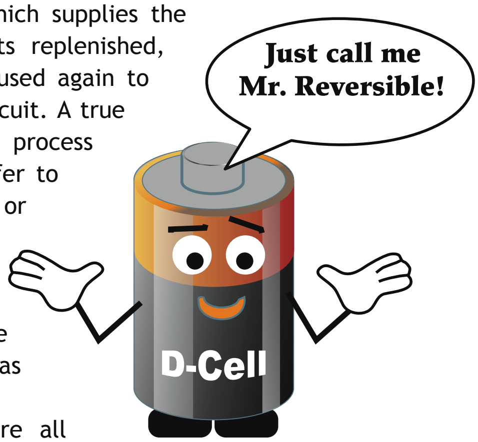
Electric circuits are all about energy, not charge. When a battery no longer works, it is out of energy. A battery (or single cell) operates by packing a collection of reactive chemicals inside. These chemicals undergo an oxidation-reduction reaction that produces energy. This energy-producing reaction is capable of pumping the charge through the battery from low energy terminal to high-energy terminal and establishing the electric potential difference across the external circuit. And when a battery no longer works, it is because the chemicals have been consumed to the point that the ability of the battery to move the charge between terminals has been severely diminished. When a battery no longer works, it is because the conversion of reactants to products have occurred to the extent that the energy-producing reaction is no longer able to do its job of pumping charge.



Some batteries are said to be rechargeable because this problem of the consumption of chemical reactants can be easily fixed. Such so-called rechargeable batteries rely upon a reversible reaction. The reaction can be run in the reverse direction, turning the chemical products back into chemical reactants within the cell. Since the usual reaction that powers the circuit is an exothermic reaction (a fancy chemistry name for energy-producing), the reverse reaction is an endothermic reaction which requires energy in order to work. By placing the cell



into a so-called recharger, the energy of a household electrical circuit can be used to drive the reaction in the reverse direction and transform the chemical products back into chemical reactants. This reverse process requires energy; it is the recharger which supplies the energy. With reactants replenished, the cell can now be used again to power the electric circuit. A true understanding of this process would lead one to refer to such cells as reversible or re-energizable; and the machines that are used to reverse the reaction would be properly referred to as re-energizers.



Electric circuits are all about energy, not charge. The charge is simply the medium that moves the energy from location to location. The batteries or other energy source does work upon the charge to supply it with energy and place it at a high electric potential. Charge at high electric potential will spontaneously begin its very slow migration towards the low potential terminal of the cell. Charge everywhere within the circuit moves together, like soldiers marching in step. As an individual charge moves through circuit elements such as light bulbs, its electrical energy is transformed into other forms of energy such as light energy and thermal energy. With many, many charges moving through the light bulb at the same time, there is a significant transformation of electrical energy to light energy to cause the light bulb filament to noticeably glow. Upon passage through a light bulb filament, an individual charge is less energized and at a lower electric potential. The charge completes its slow migration back to the low potential terminal where the electrochemical cell does work upon the charge again to move it back up to high electric potential. Once at high potential, the charge can begin its loop again through the external circuit.

WHERE DOES ELECTRICITY COME FROM? CHAPTER 4

Who Discovered Electricity?

Who Invented Electricity?

Who Discovered Electricity?

Before electricity became available over 100 years ago, houses were lit with kerosene lamps, food was cooled in iceboxes, and rooms were warmed by wood-burning or coal-burning stoves.

Many scientists and inventors have worked to decipher the principles of electricity since the 1600s. Some notable accomplishments were made by Benjamin Franklin, Thomas Edison, and Nikola Tesla.

Benjamin Franklin demonstrated that lightning is electricity. Thomas Edison invented the first long-lasting incandescent light bulb.

Prior to 1879, direct current (DC) electricity had been used in arc lights for outdoor lighting. In the late 1800s, Nikola Tesla pioneered the generation, transmission, and use of alternating current (AC) electricity, which can be transmitted over much greater distances than direct current. Tesla's inventions used electricity to bring indoor lighting to our homes and to power industrial machines.

Despite its great importance in our daily lives, few of us probably stop to think what life would be like without electricity. Like air and water, we tend to take electricity for granted. But we use electricity to do many jobs for us every day — from lighting, heating, and cooling our homes to powering our televisions and computers.

AROUND 600 BC

- Thales, a Greek, found that when amber was rubbed with silk, it became electrically charged and attracted objects. He had originally discovered static electricity.

1600

- William Gilbert (England) first coined the term electricity from elektron, the Greek word for amber. Gilbert wrote about the electrification of many substances. He was also the first person to use the terms electric force, magnetic pole, and electric attraction.
- Otto von Guericke (Germany) described and demonstrated a vacuum, and then invented a machine that produced static electricity.
- Robert Boyle (Ireland) discovered that electric force could be transmitted through a vacuum and observed attraction and repulsion.

1675

- Stephen Gray (England) distinguished between conductors and nonconductors of electrical charges.

1745-46

- Georg Von Kleist (Germany) developed the first electric capacitator, a device for storing electricity.
- Pieter van Musschenbroek (the Netherlands) independently developed an electric capacitator that would be called the Leyden jar after the University of Leyden where he worked.

1752

- Ben Franklin (United States) tied a key to a kite string during a thunderstorm, and proved that static electricity and lightning were the same thing.

1800

- Alessandro Volta (Italy) invented the first electric battery. The term volt is named in his honor.

1808

- Sir Humphry Davy (England) invented the first effective lamp. The arc lamp was a piece of carbon that glowed when connected by wires to a battery.

1820

- Separate experiments by Hans Christian Oersted (Denmark), Andre-Marie Ampere (France), and Francois Arago (France) confirmed the relationship between electricity and magnetism.

WHO INVENTED ELECTRICITY?

1821

• Michael Faraday (England) discovered the principle of electro-magnetic rotation that would later be the key to developing the electric motor.

1826

• Georg Ohm (Germany) defined the relationship between power, voltage, current and resistance in Ohms Law.

1831

• Using his invention the induction ring, Michael Faraday (England) proved that electricity can be induced (made) by changes in an electromagnetic field. Faraday's experiments about how electric current works led to the understanding of electrical transformers and motors.

• Joseph Henry (United States) separately discovered the principle of electromagnetic induction but did not publish his work. He also described an electric motor.

1832

• Using Faraday's principles, Hippolyte Pixii (France) built the first dynamo, an electric generator capable of delivering power for industry. Pixii's dynamo used a crank to rotate a magnet around a piece of iron wrapped with wire.

1835

• Joseph Henry (United States) invented the electrical relay, which could send electrical currents long distances.

1837

• Thomas Davenport (United States) invented the electric motor, an invention that is used in most electrical appliances today.

1839

• Sir William Robert Grove (Scotland) developed the first fuel cell, a device that produces electrical energy by combining hydrogen and oxygen.

1841

• James Prescott Joule (England) showed that energy is conserved in electrical circuits involving current flow, thermal heating, and chemical transformations. A unit of thermal energy, the Joule, was named after him.

1844

• Samuel Morse (United States) invented the electric telegraph, a machine that could send messages long distances across wires.

1860s

• The mathematical theory of electromagnetic fields was published. J.C. Maxwell (Scotland) created a new era of physics when he unified magnetism, electricity, and light. Maxwell's four laws of electrodynamics (Maxwell's Equations) eventually led to electric power, radios, and television.

1876

• Charles Brush (United States) invented the open coil dynamo (or generator) that could produce a steady current of electricity.

1878

• Joseph Swan (England) invented the first incandescent light bulb (also called an electric lamp). His light bulb burned out quickly.

• Charles Brush (United States) developed an arc lamp that could be powered by a generator.

• Thomas Edison (United States) founded the Edison Electric Light Co. in New York City. He bought a number of patents related to electric lighting and began experiments to develop a practical, long-lasting light bulb.

1879

• After many experiments, Thomas Edison (United States) invented an incandescent light bulb that could be used for about 40 hours without burning out. By 1880, his bulbs could be used for 1,200 hours.

• Electric lights (Brush arc lamps) were first used for public street lighting in Cleveland, Ohio.

• California Electric Light Company, Inc. in San Francisco was the first electric company to sell electricity to customers. The company used two small Brush generators to power 21 Brush arc light lamps.

1881

• The electric streetcar was invented by E.W. v. Siemens.

1882

• Thomas Edison (United States) opened the Pearl Street power station in New York City. The power station was one of the world's first central electric power plants and could power 5,000 lights. It used a direct current (DC) power system, unlike the power systems that we use today which use alternating current (AC).

• The first hydroelectric station opened in Wisconsin.

• Edward Johnson first put electric lights on a Christmas tree.

1883

• Nikola Tesla (U.S. immigrant from Austrian Empire) invented the Tesla coil, a transformer that changed electricity from low voltage to high voltage, making it easier to transport over long distances.

1884

• Nikola Tesla invented the electric alternator for producing alternating current (AC). Until this time, electricity had been generated using direct current (DC) from batteries.

• Sir Charles Algernon Parsons (England) invented a steam turbine generator, capable of generating huge amounts of electricity.

1886

• William Stanley, Jr. (United States) developed the induction coil transformer and an alternating current electric system.

1888

• Nikola Tesla demonstrated the first polyphase alternating current (AC) electrical system. His AC system included all units needed for electricity production and use: generator, transformers, transmission system, motor (used in appliances) and lights. George Westinghouse, the head of Westinghouse Electric Company, bought the patent rights to the AC system.

• Charles Brush was the first to use a large windmill to generate electricity. He used the windmill to charge batteries in the cellar of his home in Cleveland, Ohio.

1893

• The Westinghouse Electric Company used an alternating current (AC) system to light the Chicago World's Fair.

• A 22-mile AC power line was opened, sending electricity from Folsom Powerhouse in California to Sacramento.

(If you want to learn more about the history of electricity, you may want to purchase our History of Electricity handbook)

BASIC HOME WIRING CHAPTER 5

Roughing In a Residence

Electrical Code

220 & 240 Circuits

2 Wire & 3 Wire

ROUGHING IN A RESIDENCE

What are the basic residential wiring circuits? Can you put the hall plug on the same breaker as the dining room? How many switches have to be in the stairwell? What size wire do you use for a dryer? How many amps can 12-2-WG take?

All of these questions are answered somewhere in the 700 (more or less) pages of the National Electric Code. Luckily many of the most common residential wiring questions are answered right here in just a few pages. This is not intended to replace the NEC or the necessity to become familiar with the NEC.

ARE YOU QUALIFIED?

This article is not intended to be a complete guide on the subject of residential wiring, but only an aid to those who already have some knowledge on the subject. This is not intended as a guide to wire an entire house.

Disclaimer: Incompetent or improper wiring work can result in loss of life limb and property. Wiring which is not properly inspected may void your homeowners insurance. In some areas it is not legal for anyone other than a licensed electrician to do wiring work at all. This book does not cite code. Furthermore, the code changes on a regular basis and is subject to local jurisdictions. If you are going to do electrical wiring, you should become educated about the code as it applies in your area.

SERVICE EQUIPMENT

The Service equipment (main panel, entrance conductors, meter base, and associated hardware) must be adequate to safely supply the required load. If you haven't already done so, you can use a Load Calculator to determine the size that you will need.

The main service equipment panel shall be mounted either outside or inside the dwelling at the point of entrance of the service conductors to the building. All service equipment and electrical panels shall have a clear area 30" wide and 36" deep in front. This clear area must extend from floor to ceiling with no intrusions from other equipment, cabinets, counters, appliances, pipes, etc. Panels are NOT allowed in clothes closets or bathrooms.

According to Article 250 of the NEC, the neutral in the main panel must be bonded to the service enclosure and the grounding electrode system. Also in the main service equipment, the neutral and equipment grounding conductors are bonded together; in sub-panels, the neutral is isolated from ground - this is to maintain a single point ground system and avoid a condition known as a ground loop.

BRANCH CIRCUITS GUIDELINES

• Do NOT mix different wire sizes on the same branch circuit.

• Type NM cable must be stapled within 12" of metal boxes, 8" of plastic boxes and every 4 1/2 feet thereafter. Proper connectors must be used where NM cable enters metal cabinets, boxes or panel boards.

• When Type NM cable is installed parallel to framing members, or in bored holes, it shall be located at least 1 1/4" from the nearest edge of the framing member, where nails or screws may penetrate the cables. If this distance cannot be maintained, the cable shall be protected by a steel plate or sleeve at least 1/16" thick. Section 300.4 (A), NEC

• Cable or raceway-type wiring methods installed in a groove, to be covered by wallboard, siding, paneling, carpeting, or similar finish, shall be protected by 1/16-inch steel plate, sleeve, or equivalent, or must be recessed in the groove 1 1/4-inch for the full length of the groove in which the cable or raceway is installed. Exception: Raceways as covered in articles 342, 344, 352, and 358. Section 300.4 (E), NEC

ELECTRICAL CODE

REQUIRED RECEPTACLES - CODE SUMMARY

• For most areas of a house, receptacles must be no more than 12 feet apart and no more than 6 feet from a door or entryway – i.e., every point on almost all walls should be no farther than 6 horizontal feet from a receptacle. The wall spaces formed by fixed room dividers, such as freestanding counters, or railings, are included in the six-foot measurement.

• Receptacles installed in the floor within 18” of the wall may be used in place of wall-mounted receptacles. Receptacles installed in the floor must use a box-receptacle combination designed specifically for that purpose.

• Every hallway over 10 feet long must have at least one receptacle - other than this, hallways are exempt from the 6 foot rule.

• No outlets may be installed over an electric baseboard heater.

• Plugs which are located behind a stationary appliance such as a refrigerator or washing machine do not count when considering plug spacing.

• Any wall space that is 2 feet or more in width must have a receptacle.

• Every basement and garage must have at least one receptacle, and all must be GFI protected. At least one receptacle must be installed in each unfinished portion of a basement. This receptacle is in addition to any receptacles that may be installed for laundry or other specific purposes.

• One 20-amp branch circuit must be provided for the laundry. This circuit is limited to receptacles within the laundry room. No other outlets are permitted on this circuit.

• There must be at least two GFI plug on the outside of the house located near the front and back doors, and all exterior plugs must be GFI protected. Note: Outdoor outlets installed in wet locations shall have an enclosure that is weatherproof whether or not it is in use.

• An accessible 15 or 20 amp plug must be within 25 feet of all HVAC equipment.

• As a general rule you may have up to 10 receptacles on a single circuit, but this is a gray area which is subject to the discretion of the codes official.

• Dining room plugs must be on a separate circuit.

• At least one 20-amp circuit for bathroom receptacles must be supplied. Each bathroom must have its own GFI plug circuit with a plug near the wash basin, and no lights or other plugs or appliances on these circuits. Where a 20-ampere circuit supplies a single bathroom, outlets for other equipment within the same bathroom shall be permitted to be supplied in accordance with 210.23(A). This circuit shall NOT be used to supply a major fixture such as a whirlpool or hot tub!

• At least one 15 or 20 amp, 120 volt GFCI protected receptacle must be installed at an indoor spa or hot tub location - not closer than five feet from the inside wall of the unit and not more than ten feet away from it. Light fixtures, outlets and ceiling fans over spas and hot tubs shall be a minimum of 7’6” above the maximum water level. Note - pump motors and other spa related electrical equipment must remain accessible for service after all finishes are in place. Accessible does not include cutting holes in walls, or removing tile - plan ahead, and use common sense.

• Outdoors spa or hot tubs have the same requirements as a swimming pool. Check in section 680 of the NEC for those requirements.

• Note that all bedrooms outlets must be protected by an arc-fault circuit interrupter listed to provide protection of the entire branch circuit. This includes wiring to the smoke detector outlets. 210.12, NEC

KITCHEN RECEPTACLES - CODE SUMMARY

• In the kitchen and eating areas every counter space wider than 12 inches must have a GFI protected plug, in general all kitchen counter top plugs should be GFI protected. Countertop receptacles shall be installed so that no point along the wall is more than 24” measured horizontally from a receptacle outlet in that space. Peninsular bars and islands 12" or wider shall have at least one receptacle. Exception: Tennessee Code in dwelling unit's section states, "The installation of receptacles for island counter spaces and peninsular counter spaces below the countertop shall be optional.

• At least two 20-ampere branch circuits are required to feed receptacle outlets for small appliance loads, including refrigeration equipment in the kitchen, pantry, breakfast room, and dining room. These circuits, whether two or more are used, shall NOT supply anything other than receptacles in these areas. Lighting outlets and built-in appliances such as garbage disposals, hood fans, dishwashers, and trash compactors are NOT permitted on these circuits.

• Kitchen counter top receptacles must be supplied by at least two small appliance branch circuits.

• Kitchen appliance and convenience receptacles must be on 20 amp breakers, and wired with 12 gauge wire.

REQUIRED GROUND FAULT PROTECTION

A ground fault circuit interrupter must protect ALL receptacles listed below:

• Bathroom receptacles.

• Outdoor receptacles.

• Garage receptacles, except those not readily accessible such as ceiling mounted receptacles, or single receptacles in dedicated spaces for appliances.

• Kitchen receptacles that serve counter top surfaces.

• Counter top receptacles within 6 feet of a wet bar sink.

• All receptacles in an unfinished basement.

• Sump pumps.

• Crawl spaces at or below grade.

• Spas, Hydro massage, Hot tubs and associated electrical components.

• Pretty much any location where water and electricity might mix.

APPLIANCE BRANCH CIRCUITS - CODE SUMMARY

• The following Appliances must be on a separate 20-amp circuit: Dishwasher, Garbage disposal, Washing machine.

• As a general rule all 240-volt appliances must be on their own circuit.

• Hot tubs, garden tubs, Jacuzzis and the like must be GFI protected and wired as required for the particular model and local codes.

• The service areas of all appliances must be accessible after the final finish is complete.

REQUIRED LIGHT FIXTURES - CODE SUMMARY

• General Lighting Branch Circuits shall be computed on a three watts per square foot basis. You may wire up to 600 square feet of living area on a 15 ampere branch circuit or up to 800 square feet on a 20-ampere circuit. These branch circuits may supply lighting outlets in all areas of the dwelling and convenience receptacles, other than Small Appliances, Laundry, Bathroom, or HVAC - as outlined above.

• Every room, hallway, stair way, attached garage, and outdoor entrance must have at least one light fixture controlled by a wall switch. However, in most rooms other than kitchens and bathrooms, the wall switch may control one or more plugs into which lamps may be plugged instead of a ceiling or wall mounted fixture.

• There must be at least one wall switch controlled light in a utility room, attic, basement or under floor space used for storage or which contains equipment such as heat and air, water heaters, sump pumps, etc. which may ever require service. The switch must be located at the entry point to these areas.

• Hallways and stairs with more than six steps require the lights to be controlled by a switch at each end.

• In closets, fluorescent fixtures must have at least 6 inches of clearance away from shelves or storables. In a typical two foot deep (approx.) closet, the fixture will be mounted on the wall just over the door.

• In summary, put a light in every room or large closet, outside of every exterior door, and under the floor and in the attic if there is electrical equipment in these spaces or if they are suitable for storage.

• Switch the room lights at every door entering the room, switch a hall or stairway at both ends, and switch exterior lights at the doors which they service.

• As a rule of thumb you can put up to 10 average light fixtures on a single circuit, unless this will add up to excessive wattage for the circuit (note, a ceiling fan and light kit qualify as one fixture).

• Notable exceptions would be floodlights, which are high wattage fixtures. Four double bulb floodlights would pretty well fill up a circuit by themselves.

• The actual rule for this is to not exceed 80% of the calculated wattage capacity of the circuit.

• Wattage capacity of the circuit equals the amp rating of the breaker times the voltage (120), so for a typical 15 amp light circuit add up all of the maximum wattage's and make sure that they are less than 80% of 15x120 (1440 watts max).

Keep in mind that the inspectors may be looking for no more than 10 fixtures (more or less according to local variances) per circuit, your calculations notwithstanding.

SMOKE DETECTORS - CODE SUMMARY

• There must be a 120-volt battery back up smoke detector on the ceiling, or on the wall close to the ceiling in the area outside of every bedroom, and inside of each bedroom. All smoke detectors must be tied together so that if one goes off they all do. Smoke detectors must be protected by an arc fault breaker.

When you are roughing in for smoke detectors daisy-chain them with 14-3 WG and the extra (red) wire will interconnect the system.

• Note that all bedrooms outlets must be protected by an arc-fault circuit interrupter listed to provide protection of the entire branch circuit. This includes wiring to the smoke detector outlets. 210.12, NEC

GROUND CONDUCTOR MAKE UP

All equipment grounding conductors must be connected together with solderless pressure connectors such as wire nuts or crimp sleeves, leaving sufficient extra conductor for attachment to the metal box and/or device. When crimp type connectors are used, they must be crimped using the tool recommended by the manufacturer. Please note that ALL metal junction and outlet boxes must be grounded by attaching the equipment grounding conductor out of the NM cable to the metal box using an approved screw or grounding clip. When circuit conductors are made up, six inches of free conductor must be left for use in make-up and for the attachment of devices.

ELECTRIC HEAT

Electric heat may be installed on 15, 20, or 30 amp branch circuits. Listed below is the maximum wattage that may be installed on each size branch circuit. (All circuits are calculated at 240 v)

- 15A - 2,880 watts maximum
- 20A - 3,840 watts maximum
- 30A - 5,760 watts maximum

For example, if you are installing baseboard heaters which are rated 250 watts a linear foot, you could install 15 feet on a 20 amp, 240 volt circuit. 250W x 15 = 3,750 watts.

JOB PROCEDURES

Lay out the locations of all plugs, switches and fixtures.

(Electrician, job Supervisor) Lay out all wall boxes on the floor directly under the location where they will go. (Electrician) Install wall boxes using a spacer stick.

(Helper) Drill holes for wire runs. Drill one hole in the top plate over every single wall box, two holes over every double box, three over every triple box, etc. even if you don't think you will need them all. It's much faster to drill all of your holes at one time instead of one at a time, as you need them. Install ceiling boxes.

(Electrician) Install headers for fixture that don't install on a box, such as fluorescent lights, surface mount equipment plugs, thermostats, etc.

(Helper) Pull the wires to each circuit one circuit at a time starting with the home runs, then the power wires to every location that gets unswitched power, when you have unswitched power to everywhere that gets it, then pull the wires for switches and switched power to multiple lights. While pulling wires strip the cable from at least 6 inches of the ends and install them in the boxes and staple them within 8 inches (of wire) at the boxes, don't tighten box clamps or install intermediate staples at this time. Pull all of the wires in a single circuit before moving on to the next circuit. Following this procedure will make the work efficient, and will help to prevent mistakes. Try to avoid distractions while pulling wires and making up boxes.

If you have a helper, the helper should drill holes, pull home runs, and single fixture circuits like the washing machine, and 240 equipment. If the helper pulls other wires to stay busy, they should be very closely supervised. Don't forget the doorbell, and smoke detectors.

(Electrician) After all wires have been pulled and installed in boxes: Install intermediate staples.

(Helper) Make up grounds in single gang wall boxes. (Helper, with supervision) Make up fixture and switch boxes.

(Electrician) Install electrical panel and install wires into it including the cold water line ground.

If you have time, you may choose to strip the cables and connect the neutrals and grounds inside the panel at this time, but this is not required for a rough in inspection. Usually you do not want to install breakers at this time because of the likelihood that they will be stolen. This completes the rough in procedure.

INSPECTIONS

Several inspections (a.k.a. permits) are required for most residential construction projects:

- Temporary Service Inspection (if a temporary service will be used).
- Rough in inspection.
- Final inspection.
- HVAC system electrical inspection.
- In addition to these, any electrical work done by a subcontractor other than the electrician will have to be inspected (usually both rough in an finals) for example - well pumps, or external wood fired furnaces.
- In some cases you may be able to get a service release between rough in and final inspections so that you can more easily run HVAC and other high current services during construction. If so you will usually have to get an inspection

Wire Size and type	Is Suitable for this purpose
14-3 wg	15 amps max, Switch circuits
14-2 wg	15 amps max, Standard 120 volt 15 amp general purpose branch circuits. With all of the electronics equipment that families have (and are likely to have in the future) in the interest of doing a good job it is worth considering to just not use any wire smaller than 12 gauge so that 20 amp breakers can safely be used on all circuits - Even if the local codes would allow 14 gauge wire. Using one less wire size on the job also helps to decrease waste.
12-3 wg	20 amps max, switch circuits and (rarely) 240 volt 20 amp equipment
12-2 wg	20 amps max, branch circuits, kitchen receptacles, and other 120 volt 20 amp small appliance circuits
10-2 wg	30 amps max, Water heaters, AC units, and (rarely) other straight 240 volt 30 amp appliances
10-3 wg	30 amps, Electric clothes dryer, and other 220/110 volt 30 amp combo appliances
8-3 wg	50 amps max, Oven or cook top, and other 220/110 volt 50 amp combo appliances
6-3 wg	65 amps max, Range or oven/cook top combo, other 220/110 volt 60 amp combo appliances

for the service release.

If any inspection is failed then the codes official will usually leave a brief (and often cryptic) note outlining the reasons for the failure, and an additional inspection permit will have to be purchased.

Note that all subcontractors who do wiring work must pull their own permits using their own contractor's license. It is not permitted to have work that was done by other subcontractors inspected under any license other than their own. If you are a homeowner who is wiring your own house under a licensing exemption, you are not allowed to pull permits for subcontractors.

ROUGH IN INSPECTION

At the time you call for your rough in inspection, you should have all wires pulled, stapled properly, installed in ditches, and splices made up and ready to accept devices and fixtures. DO NOT cover any wires with insulation/wall coverings, install any devices/fixtures, or cover any wiring that is to be buried.
Note: Temporary address numbers should be installed prior to the rough in or temporary service inspections.

FINAL INSPECTION

All permits must be on site. The electrical installation should be complete at the time of request. All devices and fixtures installed, service equipment complete, and labeled properly. All wiring shall be free from short circuits, ground faults and open circuits. All light fixtures are required to be grounded along with light switches that are within five feet of a grounded object.

Note: Permanent address numbers should be installed prior to the Final inspection.

TIPS AND ADVICE

• In my experience electrical inspectors are helpful and friendly, but very busy. They usually don't mind answering a quick question or two, but they don't have time to teach everyone how to be an electrician. Try to explore other sources of information before using their valuable time. Other sources of information include the counter help at your local electrical contractor supply house, books, other electricians, the internet, and of course the NEC manual.

• If it is at all possible, try to be on your job site at the time of all inspections. You are much more likely to pass your inspection if you are there. It will also be much easier to comprehend what the inspector wants you to do in person, and on occasion they will let you take care of minor infractions on the spot thus avoiding a costly delay for another inspection. However, don't follow them around or otherwise annoy the inspector as that is not usually productive.

• Ceiling mounted paddle fans weighing 35 pounds or less may be supported by outlet boxes identified for such use. Fans weighing more than 35 pounds must be supported independently of the box (422.18), NEC.

• Central heating equipment shall be supplied by an individual branch circuit.

• Disconnects are required in sight of the following equipment:

- Electric water heaters
- Well pump controllers
- HVAC equipment
- Spas and hot tubs
- Hydro massage bathtubs
- Appliances

Disconnects can include the main breaker panel, a sub panel, a cord that can be unplugged, dedicated switches, other disconnect devices. When in doubt refer to the code, or your local inspector.

BOXES AND CONDUCTOR FILL CAPACITY

The code requires that all outlet and junction boxes have sufficient space for the use they are put to, and there are charts and formulas for determining those capacities. However, whenever possible you just use the large volume boxes. The bigger boxes will cost a few cents more, but they will save time and effort when you are trying to fit your connections neatly inside them. But just in case you must pinch every penny: Based on the following chart each #12 conductor that enters a box needs 2.25 cubic inches with the exception of the grounding conductor which requires one 2.25 cubic inch for all of the grounds. Also, each strap containing one or more devices is counted as the equivalent of two conductors.

VOLUME REQUIRED PER CONDUCTOR

- #14 - 2 cubic inches
- #12 - 2.25 cubic inches
- #10 - 2.5 cubic inches
- #8 - 3 cubic inches
- #6 - 5 cubic inches

Just add up all of the values for each conductor, and compare it to the fill capacity stamped on the junction box.

220 & 240 CIRCUITS

To understand how a 240 volt (also known as 220 volt) household circuit works you should first know a little bit about how a regular 120/110 volt circuit works. If you are at all familiar with residential electrical wiring then you probably already know that in most cases appliances, and fixtures connect to three wires:

1) A black wire, which is often known as the "hot" wire, carries the current in to the fixture.

2) A white wire called the neutral completes the electrical circuit.

3) A bare copper wire called the ground, the sole function of which is to enhance user safety.

When the circuit is in use current is "pushed" through the fixture by way of the "hot" wire and then to ground by way of the neutral, and unless something goes wrong the bare ground wire doesn't do anything except to remain ever vigilant in case of a problem.

Since house current is alternating current the actual direction that the electrons flow reverses direction 60 times per second (60 cycles). Put another way, the hot wire has a negative charge alternating with an equal positive charge, and the polarity of the hot wire reverses 60 times per second.

Now for the quick explanation of 240/220 volt house current — appliances which use straight 240 current (such as electric water heaters, or rotary phase converters) also have three wires:

1) A black wire that is often known as the "hot" wire, which carries the current in to the fixture.

2) Another "hot" wire which may be blue, red or white (if it is white the code actually requires it to painted or otherwise marked one of the other colors, but often it is not) which also carries current in to the fixture.

3) A bare copper wire called the ground, the sole function of which is to enhance user safety.

That's it, no neutral. Now, if you are paying attention, then you are probably wondering, "If there isn't a neutral wire then how is the circuit completed?" The answer is that when one hot wire is negative, then the other is positive, so the two hot wires complete the circuit together because they are "out of phase". This is why 240 volt circuits connect to double pole breakers that are essentially two single pole breakers tied together. In the main panel, every other breaker is out of phase with the adjoining breakers. So, in essence, 240 volt wiring is powered by two 120 volt hot wires that are 180 degrees out of phase.

We have previously mentioned "straight" 240 volt appliances, but there is another class of 240 volt equipment; some appliances (such as clothes dryers and ranges) use 240 volt current to power their main function (drying clothes or cooking food) but use 120 volt current to power accessories such as the clock on your stove or the light inside the oven, or the digital readout on your dryer controls. That is why some 240 volt circuits have four wires:

1) A black wire that is often known as the "hot" wire, which carries the current in to the fixture.

2) Another "hot" wire which is red, which also carries current in to the fixture.

3) A white wire called the neutral, which completes the electrical circuit for the 120 volt accessories only.

4) A bare copper wire called the ground, the sole function of which is to enhance user safety.

At one time, the code allowed for one insulated wire to function as both ground and neutral in 120/240 volt combo circuits, but now all such circuits must use the 4 wire scheme. This is why your new dryer (or electric range) might have 4 prongs on its plug and your old dryer receptacle only has 3 holes. In which case article 250.140 of the 2005 NEC (National Electric Code) allows for the "pigtail" (the cord and plug assembly) to be changed to match the old 3 wire receptacle as long as certain conditions are met. The National Electric Code allows that, but your local code might not, so check first, or even better yet make a deal with the appliance dealer to do it for you.

THE BASICS OF INSTALLING 220 CIRCUITS

BASIC 220 VOLT CIRCUITS

220 volt circuits (a.k.a. 230 volt, or 240 volt) are used to supply power to appliances which draw high currents such as clothes dryers, ranges, ovens, cooktops, heaters, air conditioners, rotary phase converters, and water heaters.

PARTS OF A 220 CIRCUIT

No matter what appliance you are wiring for, any 220 circuit has three elements:

1) The breaker panel connections.
2) The supply wire.
3) The terminal connection, which can be either a special receptacle or a direct connection to an appliance.

DISCONNECTS

For any appliances rated over 300 Volt-Amps (which includes almost everything 220) there must be either a means of disconnect at the appliance or a breaker lock permanently installed in the panel so that a service man can ensure his own safety. (NEC article 422.31) "Means of disconnect" can include a pigtail which can be unplugged from a receptacle, a disconnect device (often used for HVAC equipment) or a unit mounted switch which has a clearly labeled off position. Appliances which are in a direct line of sight of and in the same room as the breaker panel are exempt from this requirement.

Any time that you are working with aluminum wire, you must coat all connections with conductive grease such as Ideal brand Noalox. Failure to do so will result in a connection failure due to corrosion, and a hazardous condition which could result in fire or electrical shock.

BREAKER PANEL CONNECTIONS

Important safety note: Main panels cannot usually be de-energized by turning off breakers. Only qualified personnel should work on main electrical panels. A simple mistake can result in death or injury.

All 220 circuits connect to the breaker panel through a double pole breaker (or equivalent fuse). Double pole breakers often look like a pair of single pole breakers that are stuck together - because that is exactly what they are. 220 equipment will actually function if it is connected by way of two single pole breakers, but it wouldn't be safe or up to code, because in the event of a fault one breaker might trip causing the appliance to stop working, but it would still be energized by the other breaker. So double pole breakers are designed to trip both sides simultaneously. The amp ratings of breakers should never exceed the amp rating of either the wire, appliance, receptacle, or disconnect used in the circuit.

POWER CONNECTIONS

The 2 line voltage wires which are feeding the 220 circuit connect to the double pole breaker in the panel. Both of these wires should be either black or red for their entire exposed length inside of the breaker panel. These wires can be colored with paint, tape, or perm marker to comply with this code.

GROUND AND NEUTRAL CONNECTIONS

All modern 220 circuits will also have a ground wire which is identified by either green insulation or by being bare metal with no insulation. The ground wire connects to the ground bar. Some 220 circuits will also have a white insulated neutral wire which connects to the neutral bar, or to the combined neutral/ground bar.

WIRE FOR 220 CIRCUITS

The wire requirements for 220 volt circuits are pretty much the same as for any other circuit - it must be of the proper type for the place that it is being used, it must have sufficient volt-amp capacity, and it must have the correct number of conductors. Proper color-coding would also be nice, but isn't a big deal because the exposed lengths of the conductors (in the main panel and in the terminal device) can be colored with paint, tape, or permanent marker. If you are wiring for a dryer, range, or any other 220-110 combo appliance you must use a four conductor wire with an insulated neutral and a separate ground such as X-3-WG. If you are wiring for straight 220 equipment such as a water heater then you can use a three-conductor wire such as X-2-WG. The amp rating of the wire should never be less than that of the circuit breaker that is used. (You can find a handy wire application/amp rating chart shown earlier.)

Note: You can no longer install 3 wire range or dryer circuits - you must install 4 wire systems for ranges and dryers. If you already have a 3 wire range or dryer then don't worry, your old appliance can be made compatible with a 4 wire system by installing a 4 wire pigtail on it. Then when you buy a new appliance it will plug right in to your new 4-wire system.

TERMINAL CONNECTIONS

Connecting the terminal connections on a 220 system aren't all that different than installing any other appliance, fixture or receptacle except that the wire and connection hardware is usually bigger (and a little bit harder to work with) and there is an extra "hot" wire. Because of the bigger stiffer wire it is also more important to cut the conductors to the correct length as you won't be able to stuff extra wire into a box like you can with most fixtures.

Why do some 220 circuits have a neutral wire and others don't? Because some appliances contain 110 volt internal circuits (such as timers and electronic displays) which require a neutral connection to comply with current codes. When these 4 wire appliances are connected to old 3 wire systems via a 3 wire pigtail they use the ground conductor for the neutral. Other "straight" 220 appliances such as water heaters have no need for a neutral because the current both feeds and returns by way of the two hot wires as the current polarity alternates. Ideally, in any circuit the ground wire serves only as a safety feature and never carries any current under normal circumstances.

2 WIRE & 3 WIRE

HOW TO UPGRADE A TWO WIRE OUTLET TO A SAFE 3 WIRE OUTLET FOR LESS THAN TEN DOLLARS

Replacing a 2 prong outlet with a 3 prong GFCI outlet greatly improves the safety of an ungrounded electrical system, and it only takes 15-30 minutes - it will probably take almost as long to read this article as it will to do the job.

Subjects in this article are covered by the National Electric Code - NEC 2005 section 406.3(D)(b),(c)

Have you ever had to use an adaptor in order to plug an appliance or tool into an old 2 wire non-polarized outlet? Or even worse, have you ever used a tool that was missing the grounding prong because someone had hacked it off in order to use a two wire outlet? Or worse yet, has someone installed regular three wire outlets into your 2 wire system, thus allowing grounded appliances to be plugged in while giving a false sense of security? All of these situations are potentially life threatening, and should be corrected.

Many houses which were built before 1941 still have two wire electrical systems, which can't safely accommodate many modern appliances. If your home is in this category, then there is a safe, economical way for you to upgrade your outlets to a three wire system, by installing Ground Fault Circuit Interrupter outlets (commonly called GFI or GFCI receptacles).

The third wire of a three wire system is designed primarily to protect people from being shocked. It accomplishes this by providing a path for the current which is caused by a "Ground Fault" (also known as a "short") to go to "ground". If the current is at all substantial, this will cause the breaker to trip (or the fuse to blow), preventing the faulty equipment from being used, and thus protecting the user from being shocked. Nothing is completely fool proof though, and one of the shortcomings of a regular grounded system is that there could be a ground fault without sufficient current to trip the breaker, but would still allow a person to be shocked under certain circumstances, especially if the person is a better path to ground than the system ground (if you were standing in water for example).

A GFI device actually provides better protection than a grounded 3 wire system does, but in a different way. The GFCI electronically detects even a very small ground fault and very quickly interrupts the current to the device. This provides protection even if you are standing in water, that is if everything is working correctly, but don't tempt fate by unnecessarily gambling on technology. Never use electricity when you are standing on wet ground.

Warning: Some appliances, such as microwave ovens can hold a high voltage charge on internal parts (like a capacitor) which could conceivably energize the appliance frame, so you should not rely on a GFCI connected to a two wire system to safely power a microwave oven. You should have an actual grounded receptacle installed by a qualified person instead.

Note: Even though a GFIC receptacle will be able to accommodate grounded 3 wire plugs, and will usually protect people from shocks due to ground faults it still won't actually be grounded if installed on a two wire system. Because of this fact certain devices won't work correctly if plugged into such an outlet - especially surge suppressors which work by directing excess current to ground. So, don't plug delicate electronics into a GFIC outlet that is connected to a 2 wire systems. Surge suppressors and delicate electronics need an actual ground!

Replacing a two wire outlet with a three wire GFI receptacle is a safe, easy do it yourself upgrade that will make your home safer and more convenient.

Disclaimer: If you choose to do wiring work of any kind then you and you alone are responsible for learning what the code requires, and applying the code to your work. If you are going to do electrical wiring, you should educate yourself about the code.

HOW TO DO IT
WHAT YOU WILL NEED:

1) GFCI receptacle and cover.
2) #2 Phillips screw driver
3) Medium slot screwdriver
4) Wire stripper
5) Lineman's pliers

YOU MIGHT ALSO NEED ELECTRICAL TAPE

A very small slot screw driver
2 red wire nuts
Short pieces (3-4 inches) of black and white copper house wire
Circuit Tester

PROCEDURE:

Before you start - In most jurisdictions a codes inspection will not be required for a simple remove and replace procedure like this, but you should check with your local code authority (call your electric service provider) and get an inspection if it is required. It is possible that in some jurisdictions it is not legal for anyone except a licensed electrician to perform something like this. It is also possible (even likely) that in the event that your home were to burn down because of defective work that you have done yourself, and not had inspected, that your homeowners insurance could be void. Find out before you proceed!

1) Turn off the electricity to the receptacle that you are replacing - DO NOT rely on the labels in the electrical panel. The easiest and most fool proof way to be sure that the power is off is to plug a radio or other noisy appliance into the receptacle in question and observe that it has gone off when you trip the breaker.

2) Remove the old cover and plug - try not to damage the wires while disconnecting them.

a) If the free amount of wire is more than 6 inches then you can simply cut the wires close to the receptacle.

b) If the wires are not longer than 6 inches then you should try to disconnect them without cutting them.

c) If the wires are connected to the receptacle with simple screw connections then the removal process is pretty obvious.

d) Some receptacles use a connection (now against most codes) where the wires just push into a hole on the receptacle and a barb keeps them from coming out. You can free the wires in this case by pushing a very small screwdriver into the small slot next to the wire hole, and thus depressing the barb and releasing the wire.

e) Yet another possibility is a setup similar to d) but instead of a barb the wires are retained (and released) by screws on the sides of the receptacle. Just loosen those screws and the wires come out.

3) Inspect the wires for damage; if you find damaged insulation, you can repair that by wrapping it in approved electrical tape. Note that all black vinyl tape is not necessarily approved for this purpose. If the conductors are damaged or are too short to work with, you might have to replace the cables, which would be outside of the scope of this article.

4) If you have only one black and one white wire, then they are the "Line" Voltage wires. Skip to step 6.

5) If you have two black and two white wires then you will have to use a circuit tester to determine which are the "Line" and which are the "Load" wires. Once you have determined which is which and labeled the wires, proceed to step 6.

6) Strip about 1/2" of each wire taking care not to cut into or nick the conductor. Connect the black line voltage wire to the brass screw on the GFCI plug which is labeled "line"; connect the white wire to the silver/white screw that is also labeled "line". Connect the load wires (if any) to the screws labeled "Load". It may be possible for some GFCI receptacles to function (although not correctly) even if wired up backward (a condition known as Reversed Polarity) so take care that the black wire is connected to the brass screw and the white wire is connected to the white/silver screw. Note: One GFCI receptacle can protect other receptacles in the same circuit, and this is what you are accomplishing if you have connected the "load" wires as described. You may also replace the protected outlets with plain 3 prong outlets, but you must label all of them including the GFCI outlet "GFCI Protected" and "No Equipment Ground".

7) Many GFCI receptacles have connections like those in e) above, in which case you simply insert the stripped portion of wire into the appropriate hole and tighten the side screws. Others require that you form a hook on the end of the wire and tighten it under a screw, in which case take care that the hook goes around the screw in a clockwise direction, otherwise the screw might come loose during installation or use, causing an Arc Fault (a.k.a. a loose connection). Make sure that all connections are tight by checking screws one last time with your screwdriver, and giving the wire a little tug. The number one cause of house fires is loose connections, so don't cut any corners here, and you might consider installing Arc Fault Breakers just to be safe. However, if you over tighten anything and you feel or hear something break, then throw the broken plug away, and get a new one.

8) After checking all connections, push the receptacle fully into position in the box before tightening the screws that hold it in.

9) Install the cover plate.

10) Turn on the electricity.

11) Push the "Test" button on the GFCI plug - if the "Reset" button pops out, then all is well. Otherwise, you have done something wrong. The most likely thing being that you connected the line voltage (a.k.a. "hot") wires to the "load" instead of the "line" terminals. Any such problems must be corrected immediately.

12) Label all protected outlets including the GFCI outlet "GFCI Protected" and "No Equipment Ground". Be aware that when the GFCI is tripped, then all protected outlets will be disabled.

13) Be safe - make sure that you have smoke detectors and fire extinguishers, and an emergency plan for your family in case of fire.

ELECTRICITY FOR STUDENTS CHAPTER 6

Overview & Review

A Quick Test

Overview & Review

Essentially, there are two kinds of Electricity: Static Electricity and Current Electricity. Both depend on electrons, the tiny charged particles that orbit the nucleus of an atom.

Static Electricity has been known about since earliest times, though it was not properly understood until the discovery of subatomic particles a little over a hundred years ago.

Static Electricity on a large scale causes lightning and on a much smaller scale can give you an annoying shock when you step out of a car. You can generate it simply by combing your hair with a nylon comb. The electrical charge transferred to the comb will cause it to attract the hair, or, if you like, to pick up little scraps of paper.

Though interesting, static electricity is of limited practical use. Instead we'll concentrate on current electricity - which is a flow of electrons through a conductor (usually a copper cable).

WHAT IS ENERGY?

In Physics, Energy is defined as the ability to do Work. (Everyday examples of Work are: climbing stairs, loading a truck. anything that involves moving mass).

Some of the common types of energy are: heat, light, kinetic energy (movement), chemical energy, gravitational energy and, of course, electrical energy.

In Physics, the Law of Conservation of Energy says that energy cannot be created or destroyed. It can only be transformed from one type to another. This means that to generate electricity, we have to use another kind of energy to fuel the process.

MICHAEL FARADAY

In the 1800s, Michael Faraday carried out the pioneering work that linked Electricity and Magnetism. In particular, he showed that an electrical current is generated in a conductor moving in a magnetic field.

The effect is greatly magnified if the conductor is replaced with a coil or coils of copper wire. If these coils are mounted on a rotating shaft or armature, continuous rotation will produce a continuous alternating electrical current. This is how nearly all electricity is generated today.

Now that we have a device (the generator, or alternator) that converts mechanical energy (rotation) into electrical energy, the next problem is how to obtain the mechanical energy to keep the alternator spinning. Here are some of the ways to generate electricity on a commercial scale.

GENERATING ELECTRICITY

FOSSIL FUELS

In a coal or oil fired power station, the fuel is burned (converting its chemical energy into heat) and the heat used to convert water into steam at very high temperature and pressure. This then drives a steam turbine, a device which harnesses the energy in the steam (heat and pressure) to produce rotational movement (mechanical energy). The rotating shaft of the steam turbine is coupled to the armature of the alternator, so the final result is electricity.

WIND POWER

Windmills have been around for centuries and all have harnessed the energy of moving air (wind!) through rotating sails or fan blades. Traditionally, the mechanical energy was used directly, to turn a mill wheel. A modern wind turbine simply couples the rotating shaft to an alternator armature. The last link in the chain is always the same - electricity from mechanical rotation.

HYDRO ELECTRIC POWER

Here, the source energy (there always has to be one!) is gravitational potential energy. A mountain stream is dammed in a high place, to create an artificial lake or reservoir. Farther down the mountain, the power station is equipped with water turbines. These are simply highly efficient versions of the old fashioned water-wheel; effectively they harness the kinetic energy of a carefully channeled waterfall to produce mechanical rotation. The rest you know.

TIDAL POWER AND WAVE POWER

These new technologies extract energy from the long-term bulk movement of water in a tidal estuary and from the short-term wave motion of the surface. The principle remains the same, to harness the 'free' natural energy in moving water to drive a mechanical turbine.

SOLAR POWER

In a sense. all energy on Earth is solar energy, as even fossil fuels are chemical 'memories' of ancient sunshine. But we're talking here about generating electricity from solar energy, and strangely enough, it's not very easy. The problem is that you can't easily convert sunshine into mechanical rotation to drive alternators on a commercial scale. Solar panels have no moving parts, and so the electricity they produce is 'DC' or direct current. This is like the electricity from a battery. It's great for local use, e.g. running a small irrigation pump, but the big problem with DC is that it is hard to distribute.

Photovoltaic units are best suited to localized applications like space or water heating. However, commercial-scale solar power plants, though still expensive to build, are becoming viable, the more so as the price of fossil fuels increases.

No single design for commercial solar power has yet won through, but all are based on the same idea - a large array of reflectors to collect the sun's rays and focus them onto a receiver which is effectively pipe-work containing a heat-absorbing fluid. Technologies are already well developed to store the collected energy as heat and to convert it to electricity using steam or gas turbines at a steady rate, night and day. The biggest problem is that the sun moves and so ingenious tracking mechanisms are needed to make the reflectors follow the sun through the daylight hours.

GEOTHERMAL ENERGY

This is another underdeveloped source. If you drill down into the Earth's crust, at first the temperature drops, because the sun's warmth can't penetrate. But deeper, the temperature rises. Volcanoes are evidence of this - molten lava is pretty hot! That well of energy is there to be tapped. As always, the final conversion process is the familiar steam turbine. And, like solar energy, it is environmentally friendly, provided you don't accidentally trigger a local volcano! But it is not as simple as it seems. The process of taking heat from a hot rock cools the rock locally.

NUCLEAR ENERGY

This is the controversial one. Nuclear fission is a process in which unstable (radioactive) atomic nuclei break down, releasing energy in the form of radiation (escaping particles). By concentrating these nuclei together, a controlled chain reaction is produced releasing huge amounts of energy which is used to convert water into steam. The process of generating electricity in a nuclear power plant is simply by steam turbine, exactly the same as in a fossil fuel plant. The public fear of nuclear power is twofold: the risk of meltdown - an uncontrolled nuclear reactor is not very different from an 'atomic' bomb; also the by-product, radioactive nuclear waste, remains a problem to store and dispose.

A QUICK TEST

INTRODUCTION

Here is a list of the specific things you should know and skills you should have in order to perform a job that requires a background in basic electricity. If you know and understand these things and can apply what you know, you should do well.

SKILL AND KNOWLEDGE CHECKLIST

Look through these topics and see just how much you know already

ELECTRICITY FUNDAMENTALS:

ELECTRICAL CONCEPTS

- Understand basic electrical principles
- Understand the laws of attraction and repulsion
- Understand the principle of charge
- Understand the concepts of current flow, electrical pressure, resistance and energy
- Understand the relationship of conductor size and length to current flow and resistance
- Identify various electrical units such as voltage, current, resistance and power
- Understand electrical static discharge and how it is generated

CIRCUIT MEASUREMENTS

- Use Ohm's law to solve for voltage (E or V), current (I) or resistance (R)
- Use the power formula to solve for power (P), voltage (E or V) or current (I)
- Understand the relationships of efficiency, power input and power output in a circuit
- Calculate the total voltage, resistance and current in simple circuits
- Understand the process for simplifying circuits in order to determine the voltage (E or V), current (I), resistance (R) or power (P) across any circuit component
- Know how to make circuit measurements using the appropriate test equipment

CIRCUIT IDENTIFICATION

- Know the three types of basic electrical circuits - series, parallel and series-parallel
- Understand the electrical operations of the three types of circuit

SCHEMATIC READING

- Recognize the basic elements of a circuit
- Recognize electrical components
- Identify schematic diagram symbols
- Understand the operation of an electrical circuit
- Understand the purpose, function and operation of circuit components

Reference Sheet

Formulas

$E = IR$ $\qquad$ $P = IE$

$V_{avg} = V_{peak} \cdot 637$ $\qquad$ $V_{rms} = V_{peak} \cdot 707$

Figure 1.

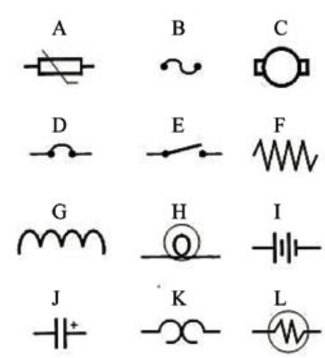
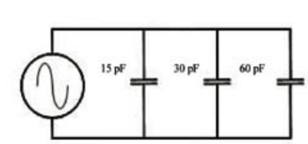


Figure 2.



ALTERNATING CURRENT AND REACTIVE ELEMENTS:

- Understand the concepts of capacitance, inductance and reactance
- Understand the relationship of reactance with frequency
- Recognize the symbols for reactance—capacitive and inductive
- Understand the voltage (E or V) and current (I) phase relationships in reactive (inductive or capacitive) circuits
- Understand the concept of true power (TP), apparent power (AP) and power factor (PF) in reactive circuits

MULTIMETERS:

- Understand how to connect a multimeter into a circuit to make voltage, current, resistance and power measurements
- Understand the proper operation of voltmeters, ohmmeters, ammeters and watt-hour meters
- Know how to interpret the results of multimeter operation
- Know how to use a multimeter to find shorts and opens in an electrical circuit
- Know how to use voltage multipliers (high voltage probes) with a multimeter to extend its range
- Know how to use current multipliers (current shunts) with a multi-meter to extend its range

SAFETY AND PROTECTION DEVICES:

- Understand the purpose and function of fuses and circuit breakers
- Recognize schematic symbols for fuses and circuit breakers
- Understand the purpose, characteristics and operation of devices that provide protection from current and voltage surges in electrical circuits
- Know personal safety practices for working around electrical apparatus

APPLIED MATH:

- Add, subtract, multiply, and divide whole numbers and decimals
- Manipulate positive and negative numbers
- Manipulate powers of ten
- Understand symbols for subunits of electrical quantities and be able to convert from one subunit to another (Examples: k = kilo = 1000,   = micro = 10-6)
- Solve equations given a formula such as Ohm's law
- Understand what direct and inverse relationships are

SOME SAMPLE QUESTIONS AND ANSWERS

Q: What device is used to convert direct current to alternating current?
A: Oscillator

Q: How does a digital meter's display differ from an analog meter's display?
A: Shows digital (numeric) readout instead of a needle pointing to a mark on a fixed scale

Q: Holding resistance constant, how does increasing current in a circuit affect voltage?
A: Voltage increases.

Q: How would adding a 20-& resistor in parallel with a 100-& resistor change the reading on an ammeter?
A: Current would increase

Q: When measuring DC voltage across a device with a multimeter, the meter indicates 0 volts. What is one possible explanation for this reading?
A: Switch is open.

Q: What is the resistance of a lamp which draws 120 mA when connected to a 12.6-V battery?
A: 105

Q: How should a multimeter's leads be connected when measuring resistance?
A: Connect the test leads to the terminals on the tested device.

...AND NOW, THE PRACTICE TEST

1. Which of the following wires has the greatest cross-sectional area?
   a. 9 AWG
   b. 14 AWG
   c. 22 AWG
   d. 30 AWG

2. What is the unit of measure for electrical pressure or electromotive force?
   a. amps
   b. ohms
   c. volts
   d. watts

3. Which of the following circuit configurations has the same amount of voltage drop across each of its components?
   a. parallel
   b. series-parallel
   c. series
   d. combination

4. As temperature increases, what happens to the current-carrying ability of a wire?
   a. There is no change.
   b. The wire can carry more current.
   c. The wire can carry less current.
   d. The wire can carry no current.

5. In a series circuit consisting of 3 resistors of 45 & each and a 50-V source, what is the approximate amount of heat produced?
   a. 16.6 W
   b. 18.5 W
   c. 135 W
   d. 150 W

6. In a two-branch parallel circuit containing one 30-& resistor in each branch and powered from a 10-V source, what is the total current flowing in the circuit?
   a. .33 A
   b. .67 A
   c. 40 A
   d. 60 A

7. Which of the following determines total power in a series circuit?
   a. source voltage times the current
   b. total voltage applied to the circuit
   c. current flowing through a switch
   d. average of the wattage consumed by each resistor

8. If a resistor suddenly decreases in value (resistance decreases), what will happen to the current through the resistor?
   a. increases
   b. remains unchanged
   c. decreases
   d. fluctuates

9. What is the applied voltage on a circuit in which .5A is flowing and 10 W is generated?
   a. 2 V
   b. 5 V
   c. 20 V
   d. 50 V

10. Refer to Figure 1 on the Reference Sheet. Which drawing is the electrical symbol for a source of energy?
   a. A
   b. C
   c. I
   d. J

11. What is the classification of an AC circuit in which the capacitive reactance is 50 &, the inductive reactance is 30 & and the resistance is 100 &?
   a. resistive
   b. inductive
   c. capacitive
   d. resonant

12. When using a standard multimeter to measure AC voltage, what type of measurement will the multimeter indicate?
   a. peak-to-peak
   b. peak
   c. average
   d. rms

13. What happens to current flow in a capacitive circuit when the DC voltage across the capacitor is approximately equal to the source voltage?
   a. Current flow is optimized.
   b. Little current flows.
   c. Current flow is maximum at the source.
   d. Current flow is maximum at the capacitor.

14. What is the term used to describe the ability of a device to store energy in the form of an electrical charge?
   a. inductance
   b. conductance
   c. reactance
   d. capacitance

15. Refer to Figure 2. What is the total capacitance of this circuit?
   a. 15 pF
   b. 30 pF
   c. 105 pF
   d. 160 pF

16. If the distance between the plates of a capacitor decreases while all other components of the capacitor remain the same, what happens to the capacitance of the device?
   a. increases
   b. remains the same
   c. decreases
   d. varies

17. In mutual induction, what passes between conductors in order to create voltage?
   a. radiation
   b. magnetic flux
   c. current flow
   d. resistance

18. The Henry is the unit of measurement for which of the following properties?

a. reactance
b. capacitance
c. resistance
d. induction

19. Which of the following devices can be used to test the windings of an inductor for continuity?

a. wattmeter
b. voltmeter
c. ohmmeter
d. Wheatstone bridge

20. Which of the following circuit conditions does a metal oxide varistor (MOV) protect against?

a. high voltage
b. high current
c. high circuit noise
d. high cross-talk

21. How should a fuse be installed in a circuit to insure proper operation?

a. parallel to the load
b. series with the load
c. in any way possible
d. at the ground point

22. In a parallel circuit operating with a source of 30 VAC, designed to carry a total current of 6 A, what happens to the protection device (fuse) when the resistance suddenly changes to 2 &?

a. closes
b. no change
c. shorts to ground
d. opens

23. How many watts are in 100 microwatts?

a. .01 milliwatts
b. .1 milliwatts
c. 1.0 milliwatts
d. 10 nanowatts

24. Which of the following is an appropriate use for a voltmeter?

a. To measure difference of potential
b. To measure current flow
c. To determine total resistance
d. To determine power output

25. What should be observed when connecting a voltmeter into a DC circuit?

a. rms
b. resistance
c. polarity
d. power factor

RESULTS

1. a	11. c	21. b
2. c	12. d	22. d
3. a	13. b	23. b
4. c	14. d	24. a
5. b	15. c	25. c
6. b	16. a	
7. a	17. b	
8. a	18. d	
9. c	19. c	
10. c	20. a	

EXPLANATIONS

1-a The larger the cross-sectional area of a wire, the greater the number of electrons it can carry. The American Wire Gauge (AWG) system provides guidelines on wire characteristics. The smaller the value of AWG, the greater the cross-sectional area of the wire. The 9 AWG wire will have the greatest cross-sectional area of any of the choices.

2-c Electrical pressure is the push given to electrons that causes them to flow through circuits. The unit of measure for electrical pressure is the volt.

3-a In a series circuit, the current is equal at each point in the circuit and voltage is divided among the circuit components. In a parallel circuit, the voltage across each component is the same and the current is divided among the separate branches.

4-c Increasing temperatures cause electrons to be more active. The random nature of the increased activity causes collisions between thermally excited electrons and current carrying electrons. The collisions tend to disrupt the flow of electrons through the circuit. This disruption reduces the net current flow.

5-b Resistive elements in a circuit dissipate energy in the form of heat. Resistors connected in series are added to get total resistance. The power formula P = IE is used to determine the power used. First, use Ohm's law to find the current (I).

I = E/R = 50/135 = .37 amps

The power dissipated in heat can then be found using the power formula:

P = IE = .37 * 50 = 18.5 watts

6-b Because the voltage drop across each component of a

lel circuit is the same, Ohm's law can be used to find the current in each branch. The total current is then found by adding the current in each branch. Since in this case, the branches have equal resistance, simply find the current in one branch and multiply by the number of branches.
Current in one branch: I = E/R = 10/30 = .333 amps per branch
Total current of the parallel circuit: .333 amps * 2 branches = .67 amps

7-a The total power consumed in any circuit is a function of the power formula:
Power = current (I) times voltage (E) or P = IE

8-a According to Ohm's law, I = E/R, current has an inverse relationship with resistance. As resistance (R) decreases, current (I) increases.

9-c Use the power formula, P = IE, to find this answer. Solving for E:
E = P/I = 10/.5 = 20W.

10-c The symbol for an energy source, in this case a battery, is symbol I.

11-c In a reactive circuit, the higher value of reactance will determine whether the circuit is capacitive or inductive. Here, the capacitive reactance is higher than the inductive reactance. Therefore, the circuit is capacitive.

12-d Electricity delivered to a wall outlet is stated in terms of rms voltage. A standard multimeter provides a reading of AC voltage in terms of rms.

13-b When a DC voltage is applied across a capacitor, there will be an initial flow of current. As the voltage across the capacitor charges up to the value of the source voltage, current flow will slowly decline. At the point where the voltage is approximately equal, all current in this circuit will stop flowing because there is no difference of potential.

14-d A capacitor is a device that stores electrical energy.

15-c Capacitors in parallel are measured like resistors in series. Add the three capacitors to get the total capacitance of the circuit.
15 pF + 30 pF + 60 pF = 105 pF

16-a The value of a capacitor (capacitance) can be increased by increasing the surface area of the plates, increasing the value of the dielectric constant, or decreasing the distance between the plates.

17-b Magnetic flux is created as alternating current changes direction and causes lines of flux to vary in the magnetic field. As the lines of flux vary, they cause current to flow in nearby conductors.

18-d The Henry is a unit of measure for induction.

19-c Ohmmeters are used for testing continuity. Inductor windings are usually coils of wire and if not broken, can be tested with an ohmmeter for continuity.

20-a MOVs react very quickly to over-voltage conditions. When the voltage threshold of a MOV is exceeded, it instantly acts as a conductor, shorting the transient spike to ground. MOVs are commonly used to protect equipment that is attached to a transmission line.

21-b A fuse responds to an over-current condition by opening. This separates the source from the circuit in the event of an overload. Therefore it should be connected so that it is between the source of energy and the circuit—in series with the load.

22-d A circuit designed to work with 30 volts at 6 amps has a load resistance of 5 & (Ohm's law). If the load resistance drops to 2 &, the circuit current will increase to 15 amps (Ohm's law) if there is no way to stop it. If the protection device (see question 21) works properly, it will open a circuit if current goes beyond its designed current carrying ability.

23-b 100 microwatts = 100 * 10-6 watts = .0001 watts = 0.1 milliwatts.

24-a Voltmeters measure difference of potential in electrical circuits.

25-c Polarity is of major importance in direct current circuits. Voltmeters are sensitive to polarity when making measurements in DC circuits. Correct placement of leads is very important when making these kinds of measurements.

If your score was from 20-25, you probably have the makings of an electrician.

ENERGY SAVING TIPS CHAPTER 7

ENERGY SAVING TIPS

ENERGY SAVING TIPS

Using electricity wisely means using it efficiently but also using it at times of the day when demand is typically lower. On weekdays, peak demand occurs in the late afternoon or early evening as people return home from work. Delaying energy use until later in the evening or the weekend will help reduce these peaks. As well, consumers can also benefit from keeping energy use to a minimum during extreme hot and cold spells.

Consult your local utility as to when the peak demand times are in your area. You will notice that demand increases through the day and starts to decrease by early evening. In the end, saving electricity will deliver benefits to both your pocketbook and the environment.

YEAR-ROUND TIPS:

• Turn off lights, TVs and other appliances when they are not needed.

• Wash laundry in cold water. This does just as good a job, keeps your colours bright, and saves lots of energy.

• Take short showers instead of baths. A five-minute shower uses about half as much water as a bath.

• Replace incandescent bulbs with energy-efficient compact fluorescents, which are four times more efficient and last about eight times as long.

• You can also control the intensity of your incandescent bulbs with dimmer switches to save money. A bulb dimmed by 25 per cent uses 10 per cent less energy.

• Install motion sensors on light switches.

• Using a low-flow shower head can save up to 15 per cent of hot water costs; aerators on your sink faucets can reduce water use by about 10 per cent.

• Use small appliances such as a microwave, slow cooker, electric kettle or toaster oven instead of the stove.

• Take clothes out of the dryer and fold them while they are still warm to prevent wrinkling; your iron uses a lot of energy.

• Shower and run your dishwasher, washer and dryer early in the morning or late at night.

• Try setting your dishwasher to start after 9:00 p.m. when off-peak prices begin. If your dishwasher has a timer – use it.

• Consider a home energy audit to find out how energy efficient your home is and the best way to spend your home-improvement dollars.

SUMMER TIPS:

• Proper maintenance of your air conditioner can increase its efficiency by about five per cent.

• Replace the air filters that keep dust out of the duct system – usually every three months for most models.

• Remember to check the SEER number (an energy efficiency rating) of an air conditioner before you make this important purchase. An energy efficient air conditioner may be more expensive but it could pay for itself during its lifetime.

• Get your air conditioner tuned up on a regular basis. You can clean the outside compressor yourself with a hose, removing debris that impedes airflow.

• Following instructions and safety precautions from your air conditioner's manufacturer, you can also clean the grilles and fan blades, clean and lubricate the fan motor, and clean the coil fins.

• Reduce the time your air conditioner is on.

• Raise the thermostat by 1 degree Celsius and lower your electricity bill up to five per cent.

• Open windows at night and use fans to blow in cool air. During the day, close your windows and draw the curtains closed to keep out solar energy.

• Use fans to cool your room. You can cool the main floor of a house by using a fan to blow cool air up from the basement.

• Go 'green' and lower your electricity bill

• Planting the right vegetation can lower your energy consumption. A tree or shrub that shades your central air conditioner can improve its efficiency by up to 10 per cent.

• Consider planting a deciduous tree on the south side of your lawn to block the sun during the summer, and let in solar energy during the winter when it sheds its leaves.

WINTER TIPS:

• Since up to 25 per cent of heat loss is through windows, plastic window covers can help reduce drafts. They can be purchased at most hardware stores.

• Keep window curtains open during the day to allow solar energy into your home.

• Put removable, temporary caulking on the inside of your windows that you can peel off in the spring.

• Reduce the temperature on your thermostat when you're not at home and overnight. Many new thermostats can be programmed to change the temperature automatically.

• If you have forced air heating in your home, give your furnace a break by having ducts cleaned regularly and checked for leaks. Leaky air ducts can cause distribution losses of up to 30 per cent.

Contributors

INFORMATION FOR THIS BOOK WAS DRAWN FROM

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- Energy for Keeps
- NoJolt.com
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