**California Physics Standard 5a** Send comments to: layton@physics.ucla.edu E&M1

**5. Electric and magnetic phenomena are related and have many practical applications.** As a basis for understanding this concept:

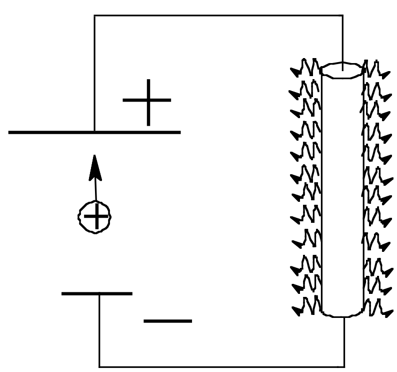
**a. Students know how to predict the voltage or current in simple direct current electric circuits (DC) constructed from batteries, wires, resistors, and capacitors.**

(Although the Standards begin the study of electricity with circuits, we feel it would better to begin with charge and field concepts. If you concur, look first at 5e.)

Students need to know that charge is the fundamental quantity of all electrical phenomena. Charge, like mass, is so basic it is hard to define. There is only one kind of mass in the universe and all masses attract one another. There are two kinds of electrical charge in the universe, called plus and minus. Like charges repel one another and unlike charges attract one another. The symbol usually used for electrical charge is q and the mks unit of charge is the Coulomb. (More will be said about this in 5e.)

Electric current is a measure of the amount of charge that passes a point in a circuit per time. Electric current is usually symbolized with an I and is defined as charge per time. That is, $I = q/t$. The unit of electric current is the ampere or amp. If a continuous flow of one coulomb of charge passes by a point in an electric circuit every second, the current in that part of the circuit is one amp.

Electric potential difference or "voltage" is a measure of the energy per charge. Batteries can use chemical reactions to provide energy to charges. These energized charges can then be made to pass through light bulbs or other devices that convert this energy to some other form such as heat and light. In the following discussions, we will make the assumption that plus charges carry the current (in what is called "conventional current") even though electrons usually carry the current in most solids.

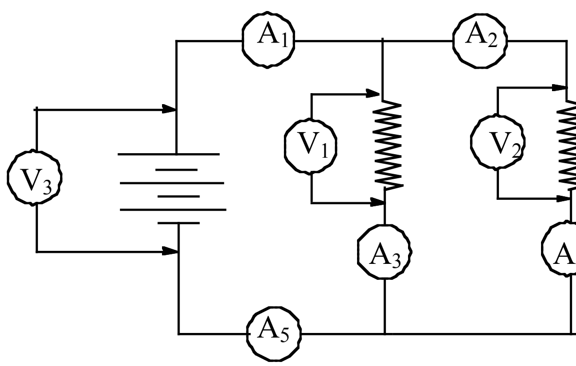



Consider a battery connected to some resistance material as illustrated on the left. The long line with the plus represents the plus pole of the battery and the short line with the minus is the negative pole. A plus charge inside of the battery is forced to move toward the plus pole requiring that work be done. Many plus charges are forced to move to the plus pole and then are released in the wire connected to the resistance material. These charges then crash their way through the atoms in the resistance material. This causes heat energy to be released from the resistance material. The energy provided by the chemical reactions in the battery is converted to heat energy in the resistance material. As always, energy is conserved. All that happens in this simple circuit is the chemical energy of the battery is turned into heat energy and is radiated out of the resistance material. Also, exactly the same amount of charge that enters the resistance material will leave the resistance material. (This discussion will be repeated in more detail on pages E&M 7 and E&M 8.

Charge is also conserved and is never used up. It is important to appreciate that the charge serves as a vehicle to transfer the energy from the battery to the resistance material and the charge itself is never destroyed. It only circulates around the circuit.

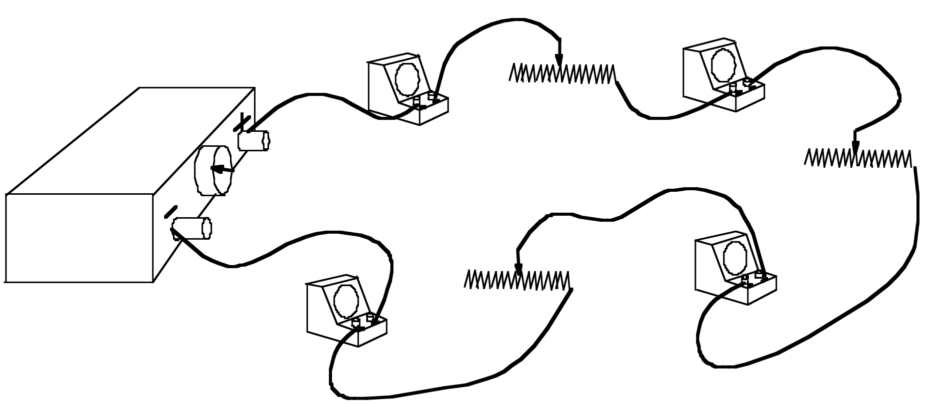
> When discussing electric circuits, students can be helped to understand the concepts of voltage and current if you always say "current through" and voltage (or potential difference) across". Voltmeters are always placed across the device to be measured and ammeters must always be placed in series with the device being measured. (Frequently ammeters are ruined when students incorrectly place them across a device being tested. This is a particular problem with multi-meters since students will have the meter attached across a device when measuring voltage then leave it across the device and snap from the voltmeter position on the selection dial to the ammeter position, perhaps ruining the meter and maybe even the circuit's source of potential difference.)

Devices that measure current are called ammeters and are symbolized by a circle with an "A" in it. Devices that measure voltage or potential difference are called voltmeters and are symbolized by a circle with a "V" in it. Ammeters must always be wired in series with the device being tested. Voltmeters will always be wired across the device under test. Consider the circuit illustrated below that no doubt has many more voltmeters and ammeters than you would ever have in a real circuit but which is presented here for purposes of discussion. The voltmeter $V_3$ measures the total voltage across the battery



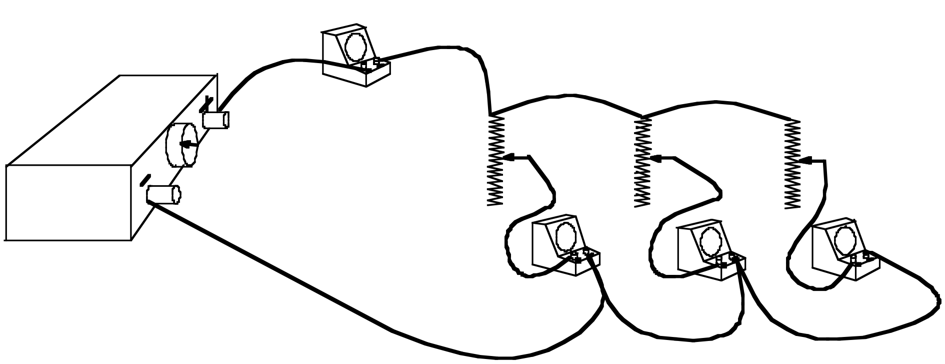

and, assuming all of the ammeters are perfect and have zero resistance, the voltmeters $V_1$ and $V_2$ will read the same as $V_3$. The ammeters $A_1$ and $A_5$ will read the same as each other and the ammeters $A_2$ and $A_4$ also read the same as each other. Ammeters $A_1$ or $A_5$ will read the sum of $A_3$ and $A_4$ . (Since $A_2$ equals $A_4$, either $A_1$ or $A_5$ would also read the sum of $A_3$ and $A_2$.)

An excellent demonstration to present to the students, perhaps even before they do experiments individually, involves comparing current and voltage in a series and a parallel circuit.



In a series configuration wire several identical ammeters in series with several identical adjustable rheostats. Before the demonstration discuss with the class how the rheostat (or adjustable resistor) works and carefully adjust them so they obviously have nearly the same resistance. Turn on the power supply and show that the ammeters all read the same value.

Select one of the rheostats, probably the one in the center, and ask the class what will happen to the current if you change this one only. Frequently, most students will answer that only the ammeters after the selected rheostat will change. When you change this rheostat and the students see that all ammeters change to read the same amount, you should be in a good position to discuss how the current in a series circuit is the same everywhere in the circuit. A follow up exercise is to measure the voltage across each rheostat and show that the sum of the individual voltages will sum to equal the total potential difference across the power supply.



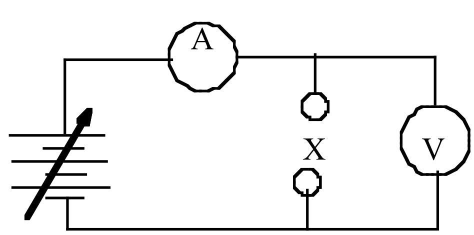
Now repeat the above demonstration only place the rheostats in parallel as illustrated on the left. Here the currents may be different and can be adjusted to make any particular value. The ammeter on the top will always read the sum of the individual currents. If a voltmeter is placed across any individual rheostat, it will always read the same value as the voltage across the power supply.

Be sure your students understand the meaning of "series" and "parallel" circuits. Statements like: "In a series circuit the current must pass through each circuit element in turn before returning to the source of potential difference" and "In a parallel circuit, the current can take alternate paths," can help.

After current has been defined as charge per time, $I = q/t$, and potential difference has been defined as electrical potential energy per charge, $V = PE/q$, it is finally appropriate to define resistance as the ratio of the potential difference across something to the current that passes through the thing, or $R = V/I$. Many devices will maintain a constant ratio of voltage to current over a wide range of values and are said to be "ohmic" (since they appear to obey Ohm's law.) However, many devices do not display a constant ratio of voltage to current and are called "non-ohmic". Although Ohm's law works for many things, most of the interesting devices used in electronics rely on their non-ohmic behavior to produce desired results. The Ohm is the unit of resistance and one Ohm is a Volt per Amp. (More about Ohm's law in section 5b.)

**Activities in basic electric circuits:**
**Simple test of Ohm's law:**

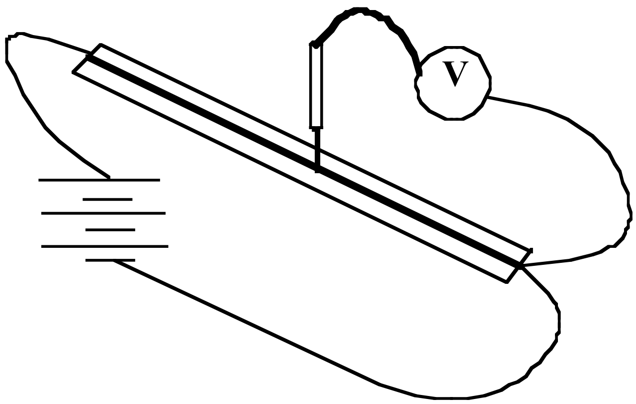
It is very instructive to have students spend time with very simple circuits to test the validity of Ohm's law. This would require a continually adjustable power supply, a voltmeter, an ammeter and assorted leads for each group.




Resistors, pieces of pencil lead, etc. can be inserted at "X". Adjusting the voltage and recording the current and voltage can obtain graphs of current vs. voltage. Probably several ohmic examples should be chosen but a properly chosen light bulb that can be made to glow brightly will make a very interesting example of a non ohmic device.

**The fall in potential along a uniform wire:**

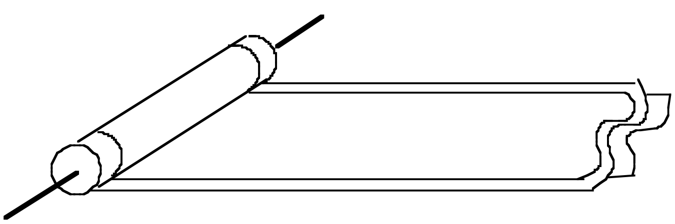
This experiment that can be performed with a battery as a power supply, a voltmeter, a piece of uniform diameter nichrome (or resistance) wire taped to a meter stick, and assorted leads. The battery should probably only be attached during measurements.

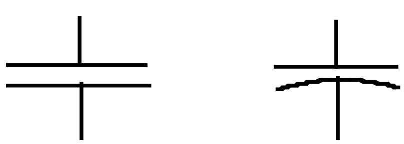



With the nichrome wire taped to the meter stick, the voltage across the entire meter of wire is measured. Then the probe of the meter is moved so that the potential difference across assorted smaller amounts of wire is measured. If the total voltage remains constant, it will be observed that the ratio of the total voltage to one meter of wire will equal the ratio of the fractional voltage to the corresponding fraction of wire. A graph of voltage vs. length of wire intercepted is instructive.

**Capacitors:**

Resistors dissipate electrical energy, capacitors store electrical energy. Analogies are often made between how resistors dissipate electrical energy and how friction dissipates mechanical energy. The capacitance of a capacitor is by definition the ratio of the charge the capacitor can store to the potential difference placed across it. That is, $C = q/V$. The unit of capacitance is the Farad and a one Farad capacitor will store a charge of one Coulomb of charge if a potential difference of one Volt is placed across it. (Since this is a rather large unit of capacitance, capacitance is often measured in micro Farads or uF.) Capacitance is <u>not</u> like the amount of water you can put into a jar, rather it more like the amount of air you can put into a rigid steel tank. The amount of air you can store in the steel tank depends upon the pressure. With a capacitor, the amount of charge you can store on the capacitor depends upon the potential difference you place across it.





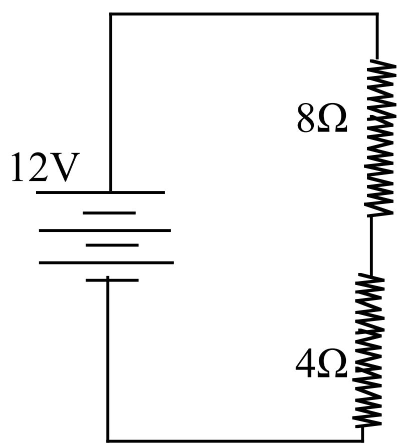
Capacitors often consist of metal plates separated by insulators. Often the metal plates are thin aluminum foil and the insulator is very thin plastic or waxed paper. This structure is then rolled up into a cylinder (like a sleeping bag) with leads attached to either plate sticking out of either end.

Other capacitors, called electrolytic capacitors, are made by chemically depositing metal and insulating layers on one another. The symbols for a capacitor are illustrated above. A valuable demonstration for you class is to carefully cut apart a paper capacitor to show how it is constructed.

**5. Electric and magnetic phenomena are related and have many practical applications.** As a basis for understanding this concept:
**b. Students know how to solve problems involving Ohm' law.**

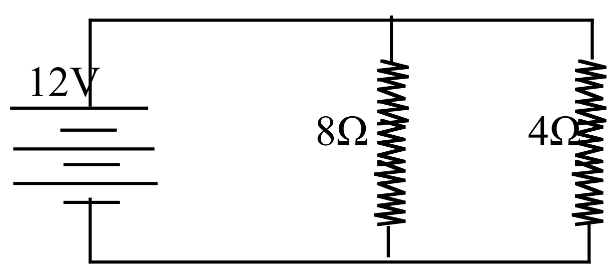
Before solving problems involving Ohm's law, it is well to appreciate that Ohm's law is an experimental result that applies to many materials but is not as universal as say, Newton's second law. Georg Simon Ohm experimented with many different materials and discovered that most of them would show a fairly constant ratio of the potential difference applied across them (voltage) to the current that passes through them. This ratio is not constant for a wide range of voltage nor do all materials display this property. In the previous section we defined potential difference (voltage) as electrical potential energy per charge (V=PE/q) and current as charge per time (I=q/t). Using these two defined quantities, the resistance of anything can be defined as the ratio of the voltage placed across it to the current that passes through it, or, R = V/I. This definition of resistance is known as Ohm's law and naturally can also be written as V = IR or I = V/R. As mentioned in the previous section, not everything obeys Ohm's law but things that do are called "ohmic". The unit of resistance is the ohm (Ω) and one ohm is one volt per amp.

Solving problems involving Ohm's law can be done in many different ways and can often be reduced to recognizing that resistors in parallel have the same voltage across them and resistors in series have the same current passing through them. In the following, a few simple problems will be solved applying these principles.




The problem is to find the current through and voltage across the 8Ω and 4Ω resistor in the circuit illustrated on the left. (Values have been chosen so the arithmetic is easy.) First it should be obvious that the resistors are in series since the current must pass through each resistor in turn as it moves from one side of the source of potential difference to the other. Most students also find it "obvious" that the total resistance of the circuit is the sum of the two resistors in series. (Deriving the expression R equiv series = $R_1 + R_2 + R_3 = \ldots R_n$ might be appropriate.) From Ohm's law I = V/R = (8 + 4)/12 = 1 amp, it can be seen that a current of one amp passes through each resistor. Again using Ohm's law V = IR = 1(8) or 1(4) it can be seen that the top resistor has 8 volts across it and the bottom resistor has 4 volts across it. It can also be seen that the sum of the potential differences across each resistor adds to give the total source voltage.

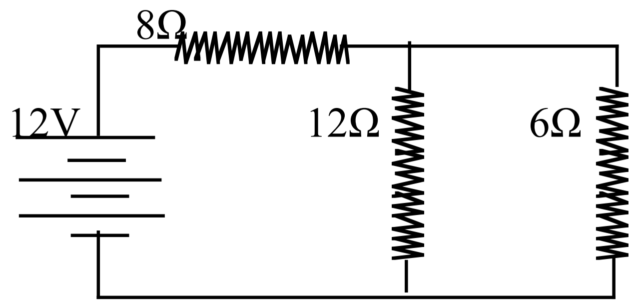
Now the same components are rewired to form a parallel circuit. (The resistors are in parallel since the current has alternate paths to pass through before they return to the battery.) In this case the voltage across each resistor must be 12 V and repeated application of I = V/R gives 12/8=1.5 amps and 12/4 = 3 amps through each resistor.



It might be appropriate at this time for the teacher to derive the following expression for equivalent parallel resistances: $1/R$ equivalent parallel $= 1/R_1 + 1/R_2 + 1/R_3 + \ldots 1/R_n$. With this you can solve to find the total current through the equivalent resistance and demonstrate that this also will equal the sum of the currents through the two resistors.

It should be noted that a common student misconception in using Ohm's law is to simply plug the values given in the problem without thinking. For example, if the first series circuit above is given and the students are <u>only</u> asked to find the current flowing through the 4Ω resistor, some students will simply plug into $I = V/R = 12/4 = 3$ amps, failing to realize that the current must pass through both the 4Ω resistor <u>and</u> the 8Ω resistor in series.

A slightly more complex problem is illustrated on the right. There are many ways to start this problem but one might begin by finding the equivalent resistance of the parallel combination. $1/R = 1/12 + 1/6 = 3/12$ or, $R = 12/3 = 4\ \Omega$. The 8 Ω resistor in series with this equivalent 4 Ω resistor produces an equivalent total resistance of (conveniently) 12 Ω




The source voltage of 12 V across this equivalent 12 Ω resistance will produce a total circuit current of $I = V/R = 1$ amp. This 1 amp will produce a voltage drop of $V = IR = 1X8$ volts across the 8 Ω resistor. Subtracting this from 12 V gives a potential difference of 4 V across the parallel combination. Now it is easy to use $I = V/R$ to show that there is 1/3 amp through the 12 Ω resistor and 2/3 amp through the 6 Ω resistor. Conveniently it can also be seen that the sum of these two currents adds to the total 1 amp total current.

**Ohm's Law Laboratory Activity:**

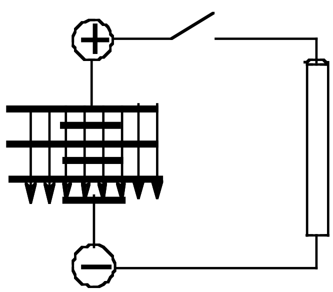
Students can learn much from an Ohm's law experiment that is essentially a reproduction of the problems discussed above. It will require a battery; three resistors, an ammeter and a voltmeter, and several clip leads. The students will measure the potential difference of the battery and then calculate the expected currents and voltages that will result when the three resistors are wired in any of the configurations discussed above. After they complete their calculations, they can gain real experience with the meters by properly wiring them at assorted points in the circuit. Make sure students clearly understand what it means to wire the ammeter in series with the resistor being tested. To prevent unnecessary drain on the battery suggest that it be connected only when making measurements and choose resistors that are in the neighborhood of 10Ω to 100Ω.

Should you choose to use a single multi-meter for this experiment, it is particularly important that students understand that the meter function selector is not simply turned to read amps while still connected across a resistor. It must be disconnected, set to read amps and then wired in series with the resistor to be tested. Finally, if the resistors you are using are small, do not use the mA connection, rather use the A connection. The resistance of the meter when in the mA connection is often large enough to cause significant error in the readings.

**5. Electric and magnetic phenomena are related and have many practical applications.** As a basis for understanding this concept:
**c. Students know any resistive element in a DC circuit dissipates energy which heats the resistor. Students can calculate the power (rate of energy dissipation) in any resistive circuit element by using the formula Power = (potential difference IR) times (current I) = $I^2R$.**
(Note: This is the first time the standards mention power. We feel that power should have been introduced with energy and previously, we added a "new" section 2i to correct this. We also feel that concepts related to electricity are best introduced first with the idea of charge and the electric field. For this reason, we feel section 5e should be presented first. Below is a more detailed discussion of how electrical energy is transferred in circuits.)

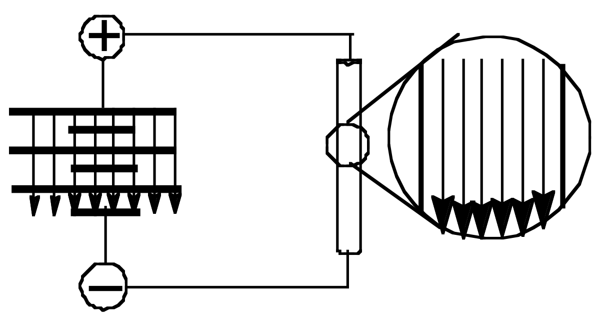
**How electric fields do work on charges and transfer energy.**

Understanding how electric fields act on charges is the key to understanding electric circuits. The field exerts a force on charges, if the charge moves as a result of this force, work is done on the charges, hence energy is transferred to the charge. As an example of this process, consider a simple circuit consisting of a battery and a piece of resistance wire. The chemical energy in the battery is to be transferred to the resistance wire, which, in turn, releases energy in the form of heat. Let's examine in detail how the chemical energy in the battery is transferred to the wire.



First we show the circuit before the wire is attached to the battery. The top plate of the battery is charged plus and the bottom plate minus. This means the electric field inside of the battery is directed downward. The chemical reactions inside of the battery separated the charges making the top pole plus and the bottom pole minus. As long as the switch is open, the charges are held in this separated position.

When the switch is closed, an electric field now appears in the wire, also in a downward direction. However, now that there is a conduction path, charges begin to move around the circuit. Inside of the battery they receive energy from chemical reactions as they are lifted against the electric field.



Inside of the wire, the charges collide with the atoms in the wire inelastically, releasing heat. (Note: In this discussion we have discussed all currents as the motion of plus charges. This is consistent with standard practice and is also the convention of the California Standards. We will always assume the direction of current is the direction plus charges flow even if electrons, or negative charges are actually flowing in the opposite direction.)

Think of the charges as vehicles that transfer energy. The charges themselves are never used up (they are conserved!) In the battery, the chemical reactions act to move the charges against the electric field giving them electrical potential energy. When the charges move with the electric field inside of the wire, they are constantly slamming into the atoms of the wire, which converts this potential energy into heat. The charges return to the battery where they receive energy only to release this energy again the next time they round the circuit. Chemical energy is converted to heat energy. Both charge and energy are conserved—energy simply changes from chemical energy to heat energy. This is exactly what happens in a simple battery and bulb circuit. As well as heat, the bulb also converts some of the energy from the battery to visible light energy.

**Power in Electrical Circuits**

Power is, by definition, work or energy per time. That is, P = W/t or Energy/t. When we look at the definition of electric potential difference (or voltage), V = PE/q, and the definition of electric current, I = q/t, we see that the product of current and voltage is power. That is, P (electric circuit) = IV. This very useful result allows us to measure power in an electric circuit with a voltmeter and an ammeter! The unit of power is the watt and one watt is a joule/sec. A watt also equals a volt times an amp. Using Ohm's law we can write two other expressions for the power dissipated by a resistor:
P = IV but V = IR so $\mathbf{P = I^2R}$ . Also, from I = V/R, $\mathbf{P = V^2/R}$. This means you can easily determine the power dissipated by a resistor by measuring the current through it or the voltage across it.

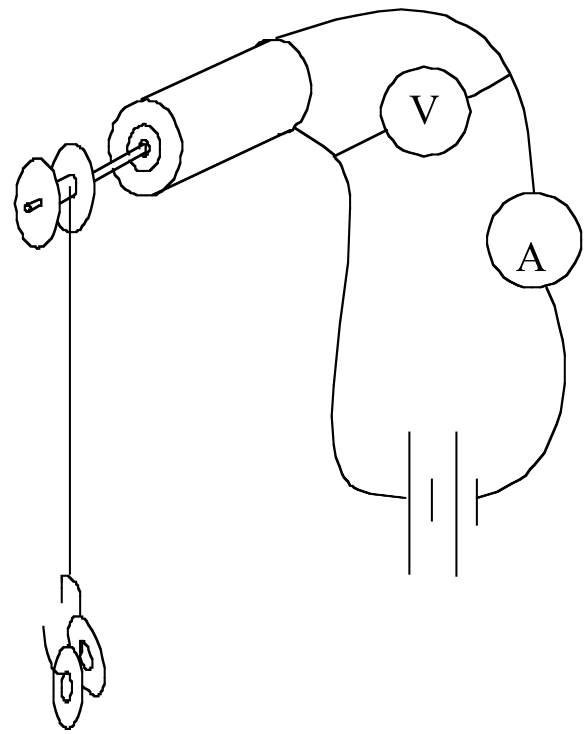
**Activities involving power in electrical circuits:**

**The power developed by a small electric motor.**
Earlier in our section 2i we describe an experiment to measure the power of a small electric motor. (Copied on the next page.) This might be a better place to perform this experiment.
**The energy produced by a light bulb or a length of resistance wire.**
An experiment is described in section 3a, which was intended to measure the mechanical equivalent of heat or the "Joule equivalent." In this experiment we assumed the power printed on the bulb was a "given". With are new knowledge of power in electric circuits this experiment could be performed using an ammeter, a voltmeter and a resistor instead of a light bulb. It is suggested that the experiment be done with a low voltage DC power supply and either a power resistor or a length of nichrome (resistance) wire carefully wound and shaped to fit into the Styrofoam cup. Care should be taken not to allow the wire to touch and melt the cup, etc. (More discussion of this on the next page.)
**The power of assorted electrical appliances used around the home.**
Give students an assignment to discover the power, voltage, and current requirements of assorted appliances used around their home. In most cases the voltage will be about 120 volts but the current will probably have to be computed using the stated power of the appliance. Also have them estimate the average length of time the appliance is used per month to discover the energy used. Help them to understand that a Kilowatt-hour is a

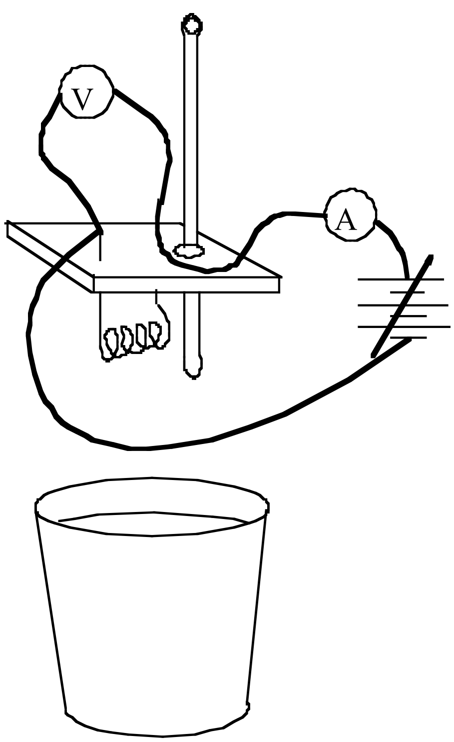
unit of energy and that it equals $10^3$ X 60minutes./hour X 60sec./minute = 3.6 X$10^6$ joule. Have them try to discover how much energy is used in a monthly electric bill.

**Measuring the efficiency of a small electric motor.**
(Copied from 2i.)

A small electric motor that operates on around 3V DC can be used to measure its power efficiency. A small pulley can be made using a short section of dowel with two circles of cardboard glued to either end. This pulley can be drilled along its axis to enable a tight fit to the motor shaft. Using a piece of thread with a bent paperclip on the lower end, a few washers can be hooked to the paperclip and the weight adjusted to enable the motor to pull the washers up at a constant speed. By measuring the time and distance the washers are lifted in a single run, together with the voltage and current through the motor windings, the power into the motor can be computed (P = VI)* as well as the output power (P = Wh/t). The weight of each washer will have to measured and adjustments will have to be made to find the correct load to have a constant power in. Students can experiment with different loads perhaps to find an optimum efficiency.
[Since Voltage = Work/Charge and Current(I) = Charge /time, it follows that their product = power.]




**Activity to measure the relationship between work and heat.**




Now that the students understand that the product of current and voltage equals power, the experiment previously discussed in Section 3a. can be better understood. Rather than using a light bulb, you could use a resistor or even a section of resistance wire that has been formed into a coil. Constructing the apparatus is not too difficult but the coil (or resistor) should be attached to bolts that pass through the wood top so excess heating will not occur near the wood. Also, the coil should be mounted so it will not touch the sides of the Styrofoam cup while being heated. The volume of water used should be measured, the current and voltage during the run, as well as the change in temperature of the water. From the time of the run the total energy placed into the water can be determined. With the volume of the water and the temperature change, the number of calories put into the water can be computed and the Joule equivalent can be determined.

**5. Electric and magnetic phenomena are related and have many practical applications.** As a basis for understanding this concept:
**d**. **Students know the properties of transistors and their role in electric circuits.**

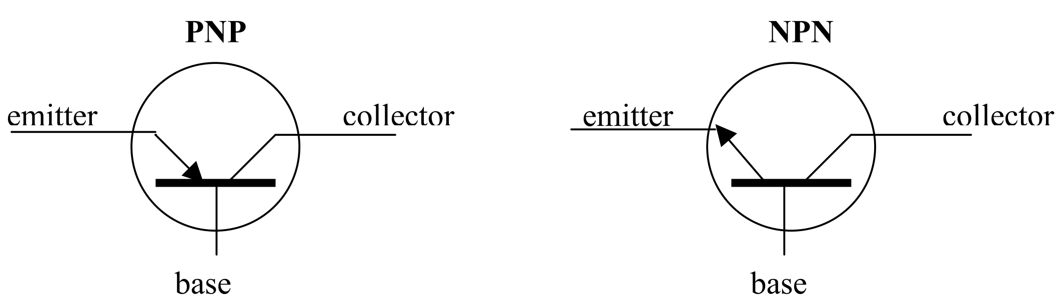
(Again this discussion will rely on the concepts introduced in the later Section 5e. It is our decision to make this discussion considerably more complete than was apparently the original objective with the California Standards. Probably the only things your students will need to know to satisfy the requirements of this Standard are:
1. Transistors can be used as switches or amplifiers in electric circuits.
2. The transistor has replaced the vacuum tube in most modern electronic applications.
3. And perhaps that a modern integrated circuit used in a computer probably has over one million transistors etched into it.
Should your students want to know a little more about transistors, how they can be made to operate as switches or amplifiers and the physics behind how they operate, the following might be useful.)

First, let's understand what a simple switch is. A **switch** is a device that can be made to have a very large resistance when "open" and a very small resistance when "closed".

Next let's understand what an amplifier is supposed to do. An **amplifier** is a device that takes a small (electrical) signal and changes it to a large (electrical) signal. The amplifier does not violate the conservation of energy principle; it simply allows a small signal to control the output of a more powerful source of energy.

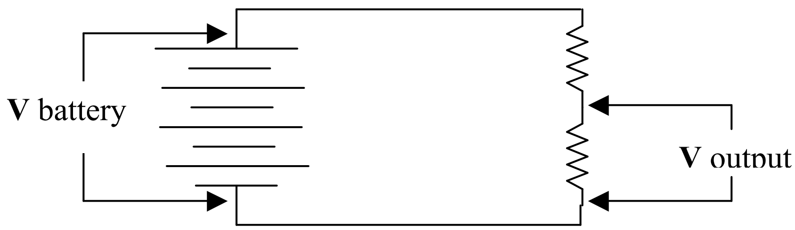
A **transistor** is a device that can change its effective resistance[1] (a more general term would be "impedance") by the application of an electrical signal. (We shall see that this amazing property can turn the transistor into a high speed switch, necessary for digital electronics and computers, **or** can allow the transistor to be used as an amplifier, essential in analog electronics applications.)

There are two basic types of transistors, the **NPN** and the **PNP.** Their symbols are illustrated below: (A helpful mnemonic is to note that the arrow in the NPN is "Not Pointing iN")



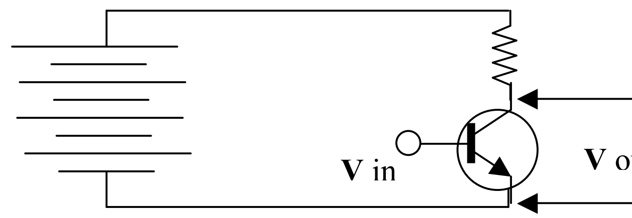

The transistor is a three terminal device and the essential thing to remember about its performance is that a small electric signal applied to the base of the transistor can cause a very large change in the resistance of the transistor, as measured across the emitter and the collector.
1. Use of the term "effective resistance" will be replaced with simply the word

"resistance" in further discussions. Since we have introduced the definition of resistance earlier in this section and since the more general term "impedance" will not be a part of the Standards, we choose to use the more familiar term resistance, even if it is not strictly accurate in this context.
To understand how this might be useful, let's look again at the simple electric circuit involving a battery and two resistors in series:




If the battery voltage remains constant and the resistance of the lower resistor could somehow be made to get larger and smaller, the "output" voltage across the lower resistor will also get larger and smaller.

When a transistor replaces the lower resistor, a small change in the input voltage can cause a large change in the output voltage.




There are details that must be added to this circuit before it can be used as an amplifier or a switch, but the important idea to appreciate is that a small signal on the input to the transistor's base can make a large change in its resistance and therefore make a large change in the output voltage across the transistor. We will discuss the physics behind what makes a transistor display this property later, but for now, the essential idea to understand is that a small change in the electrical signal at the base of a transistor can cause a very large change in the resistance of the transistor, as measured across the emitter and collector.

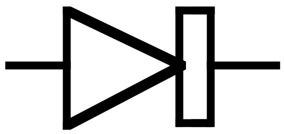
**How transistors, diodes and other solid state electronic devices do what they do.**

Elements in the center of the periodic chart such as carbon, germanium and silicon, are usually semiconductors. Since carbon has an extremely high melting point, it is essentially impossible to purify as is required in modern semiconductor devices. Germanium was the first substance used in the manufacturing of semiconductor devices but its low melting point caused these devices to be easily damaged when soldering them into circuits. When silicon, with its higher melting point, was developed for use in semiconductor devices, it rapidly became the universal material for most electronic applications. Most diodes, transistors and integrated circuits in use today use silicon as the primary semiconductor material.

Pure Silicon is an insulator. The Silicon atom has 4 outer valence electrons. If pure silicon is "doped" with a small amount of material with 5 valence electrons, the result is an N type semiconductor that conducts by electron, or negative charge flow. If the silicon is "doped" with a material with 3 valence electrons, the material conducts by "holes" and replicates positive charge flow. This is called a P type semiconductor.

**Diodes**

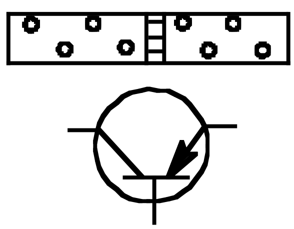
When a P type and an N type semiconductor are joined together, a solid-state diode is formed. When the P is attached to the plus side of a source of voltage and the N is attached to negative side, the holes and electrons are driven together at the junction and any voltage above a minimum amount (0.7 volts for silicon) will cause the diode to conduct. If the polarity is reversed, the holes and electrons are pulled apart at the junction and the diode becomes an insulator and will not conduct unless a high "breakdown potential" is exceeded. The symbol for a diode is shown below:



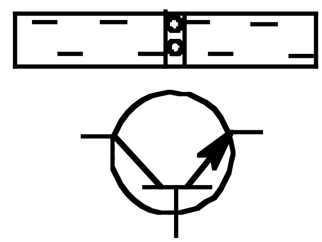
The arrow points in the direction of conventional current when the diode is conducting. This means, if the left end is connected to plus and the right is connected to minus, conventional current will flow in the direction of the arrow. Many simple circuits have been developed using diodes that will convert AC to DC.

**Transistors**

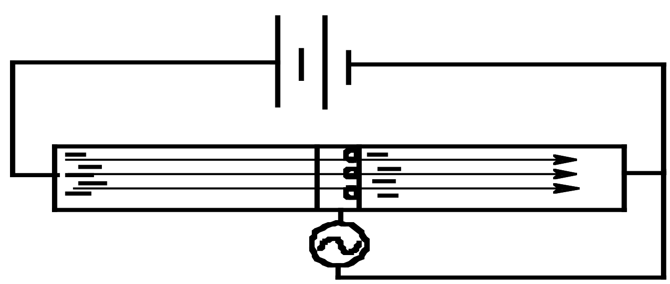
The transistor is a three terminal device. A junction NPN transistor consists of a thin piece of P type semiconductor sandwiched between two pieces of N type semiconductor. Likewise, a PNP transistor consists of a thin piece of N type semiconductor sandwiched between two pieces of P type semiconductor. The internal makeup and corresponding symbol of each type of transistor is shown below:



On the left is a PNP transistor and on the right is a NPN transistor. (To help you remember, NPN could stand for "not pointing in".) The electrode with the arrow is called the emitter*, the flat electrode in the center is called the base and the one to the left with no arrow is called the collector.



A quick explanation of how the transistor works follows: The power source is connected across emitter and collector with the collector reverse biased. (For example, the collector in an NPN transistor would be connected to the positive pole of the battery and the emitter to the negative pole.) The transistor will not conduct since the base collector diode is reverse biased. However, the holes in the P type base are driven toward the N type emitter and if the plus signal voltage is higher than 0.7 volts (for silicon) the holes will cross the junction, combine with the electrons in the emitter and give them enough energy to cross into the base. Since the base is very thin, the electrons can be given enough energy to cross into the collector and cause a current. A very small signal voltage can cause a current into the much higher voltage power circuit, amplifying the signal.



*The arrow on the emitter symbol indicates convention current direction when the transistor is conducting.

**5. Electric and magnetic phenomena are related and have many practical applications.** As a basis for understanding this concept:
**e. Students know charged particles are sources of electric fields and experience forces due to the electric fields from other charges.**

As we mentioned previously, since charge is the essential fundamental quantity basic to all electric phenomena, we feel this is the appropriate place to begin the discussion of electricity and magnetism. Charge, like mass, is so basic it is not defined in terms of other quantities and can be discussed only in terms of its properties. Perhaps a comparison between the properties of charge and mass would be informative. All masses have inertia. There is only one kind of mass. All masses attract one another according to the relationship given by Newton's law of universal gravitation: $F = Gm_1m_2/r^2$. There are two kinds of charge, called plus and minus. Like charges repel one another and unlike charges attract one another according to a relationship known as Coulomb's law:

$F = kq_1q_2/r^2$ where k is $9 \times 10^9$ $Nm^2/C^2$

A mass could have no charge but all charges have some mass. For this reason all charges have inertia but the inertia of a charge is determined only by its mass. (For example, consider subatomic particles. A neutron has mass but no charge. All neutrons have the same mass, hence the same inertia. Electrons have mass and charge, as do protons. Electrons and protons have the same magnitude charge only one is minus and the other plus. However, electrons and protons have vastly different mass, hence vastly different inertia.)

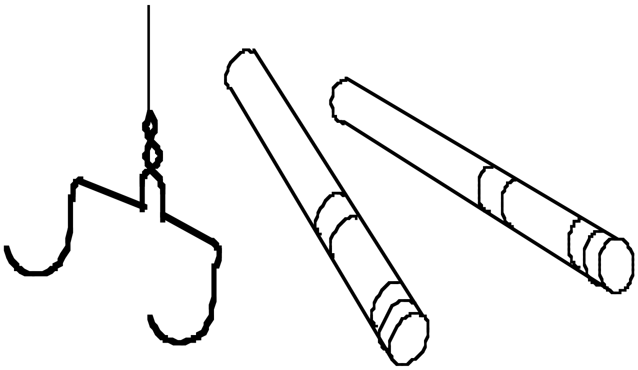
Originally, the unit of electric charge was defined using Coulomb's law. However, advances in technology made it possible to measure electric current much more precisely than the force between charges. Today, the ampere is the precisely defined basic electrical quantity and from the definition of current: $I = q/t$, the coulomb (C) is defined. One coulomb of charge is the amount of charge that passes by a point in a circuit carrying a current of one amp in one second. That is, one coulomb = one amp second.

Matter can contain an enormous amount of charge but since most matter contains a nearly perfect balance of plus and minus charge, the electrical force neutral matter exerts on other neutral matter is very small, except at very close distances. Students can find a discussion of the following question fascinating:

**When you bring your hand near a tabletop you feel no force until you get very close and "touch" the tabletop. Why is the force zero before you "touch" the tabletop but then after you "touch" it, the upward force on your hand can become as large as you are willing to push down on the table top?**

The discussion of this question might begin by pointing out that you never did touch the tabletop. There was always a space between your hand and the tabletop! (Thus explaining why we always placed the word touch in quotes.) The discussion should lead to a realization that although your hand and the tabletop are electrically neutral, at very close separation the electrons in the outer layer of your hand and in the outer layer of the tabletop, all being negative, will repel one another, since like charges repel. As you try to drive your hand closer to the tabletop, the repulsive force between electrons becomes larger but still you never make "contact" with the tabletop.

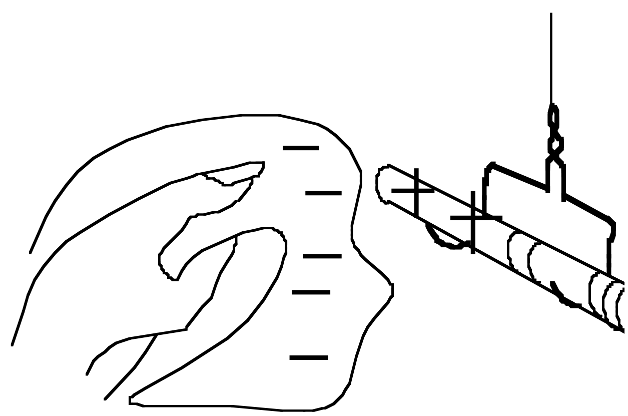
**Activities to introduce the basics of electric charge:**



A simple to construct yet very effective apparatus to investigate the forces between charges is illustrated on the left. The "cradle" on the far left is made from a piece of soft iron wire or copper wire and the two "wands" are made from thin pieces of plastic sheet. One wand is made from acetate and the other from vinyl. (These can be purchased from plastic supply houses in sheets 0.010" thick.) Roll the thin plastic sheet into cylinders and tape them on one end with scotch tape. Holding the taped end in one hand and rubbing the other end with a paper towel will produce opposite charges on each wand.

The cradle is supported with thin monofilament nylon fishing leader and can either be attached to a support stand or perhaps another student can hold it, allowing the cradle to rotate freely. Rubbing one of the wands and carefully placing it in the cradle, then bringing another wand that has also been rubbed with paper near it will cause an attractive or repulsive rotation depending upon whether the charged wands are the "same" or "opposite".

To show that rubbing the paper on the plastic wand does not "create" charges but only separates them, bring the recently rubbed paper near the associated wand and note that the paper will always attract the wand. This is true no matter which plastic material you begin with. Finally, to illustrate the basics of <u>electrostatic induction</u>, bring a charged wand near the uncharged metal cradle. Students may be surprised to see that the cradle will always be attracted no matter which rod is used. Since the cradle is a conductor, the charged wand will attract the opposite charges to the near end and force the same charges to the far end, always causing attraction. (The separation of plus and minus charges in a conductor by an electric field is called <u>electrostatic induction</u>.)

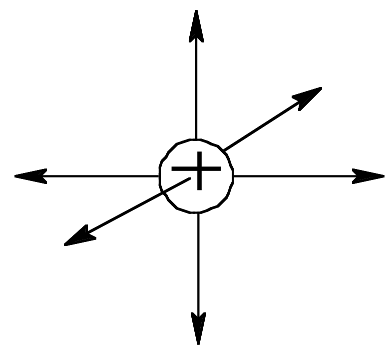


**Introduction to the Electric Field**

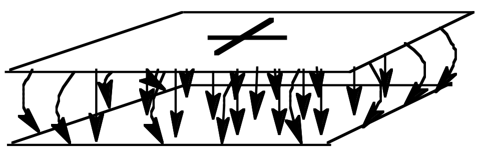
Understanding the physics behind electric circuits, transistors and many different electrical devices is greatly enhanced by having an appreciation of the concept of the electric field. Newton did not have the field concept and discussed gravity only as "action at a distance". With the work of Michael Faraday, a new and powerful way of looking at the force of gravity, electrical and magnetic forces as well as many other physical ideas, was born. A more quantitative discussion of the electric field will be given in section 5k, but here we will simply introduce the concept.

Newton admitted he did not know why the earth could attract the moon at such a great distance or why the earth could attract an apple without any visible connection between them. Although he described in great detail how this "action at a distance" operated, he did not explain why it operated the way it did. Faraday's insight was to suggest that the space surrounding a charged object was actually modified by the charge. Although this still did not explain why the space was modified, it provided a way to visualize and calculate how this modified space could affect other charged objects. Faraday suggested that the electric field could be illustrated with directed lines. The direction of the lines would represent the direction that a plus charge would be forced in the field, and how close the lines were together represented the strength of the field. Consider the electric field around a single positive charge:

The illustration is supposed to represent three-dimensional space. The field lines are directed outward because if another plus charge (or test charge) were placed anywhere around the charge, the force on it would be directed outward. The lines are close together near the charge and far apart at a great distance from the charge. This represents that the force on the test charge would be strong near and weaker at a greater distance. (In fact, these lines will spread out as $1/r^2$.)



Let us consider the electric field between two large plates, charged oppositely.

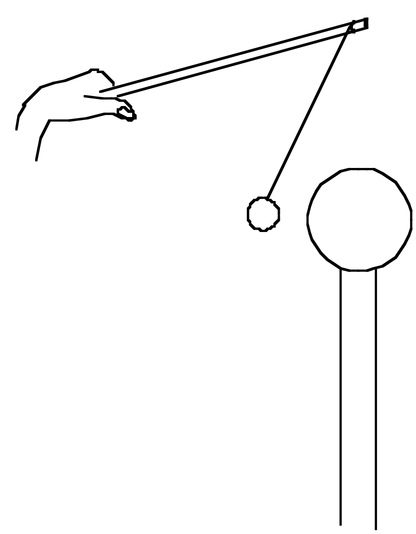


The top plate is plus and the bottom minus, hence the field lines are directed downward. Near the center of the plate the field lines would be evenly spaced all the way from the top plate to the bottom plate because the electric field is uniform in the center of two large oppositely charged plates.

Carefully drawing field lines around charged structures can reveal how other charges will be forced when they pass through the electric field region. For example, if a small object with a positive charge were fired horizontally at a high velocity between the above charged plates, it could be concluded that the moving charged particle would be deflected downward. In fact, since the field is uniform in the region between the plates, it could be concluded that the charged particle would move in a parabolic path much like a rock thrown horizontally in a gravitational field near the surface of the earth.

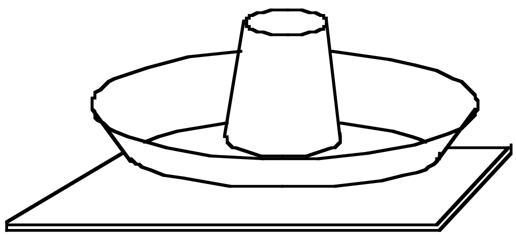
**Demonstration of the electric field:**

If you have a Van de Graaff generator a simple but impressive demonstration can introduce students to the concept of the electric field. Charge the Van de Graaff and turn it off. Using a stick with a small conducting sphere[1] (See next page) hanging from it by a piece of fishing leader, bring the small sphere near and let it acquire charge by conduction. The sphere will jump away and can be moved around the Van de Graaff illustrating the presence of the electric field. While holding the small sphere near the Van de Graaff under the force of the field, ground the Van de Graaff and the small sphere will fall. This illustrates that the electric field was a result of the charge on the Van de Graaff. This very simple demonstration can help students to appreciate the action of the invisible electric field.



**The Electrophorus** 

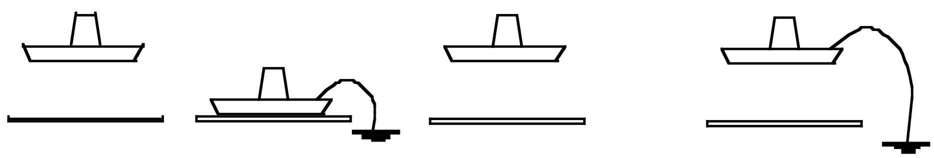
Allesandro Volta invented the "voltaic pile" or what we call the battery, but he gained fame earlier for a device he improved and popularized, the electrophorus.



You can easily make an electrophorus using a metal pie plate with a Styrofoam cup taped in the center. This structure then rests on an insulated plate that could be a square of acrylic or even a flat plastic dinner plate. With the pie plate structure held away from the bottom flat plate, the bottom plate is rubbed with a paper towel, charging it.

With the bottom plate charged, the steps for operating the electrophorus are illustrated below: A. The uncharged pie plate is lowered down to the charged plate.

B. With the pie plate on the charged plate, it is grounded and then the ground is removed. C. The pie plate is lifted to the original position. It is now charged. D. The pie plate is again grounded producing an audible spark. The process is returned to step A and can be repeated again and again seemingly producing an unlimited charge. Challenge your students to explain what is going on. A search on he web will have numerous references to how all of this works.



A B C D

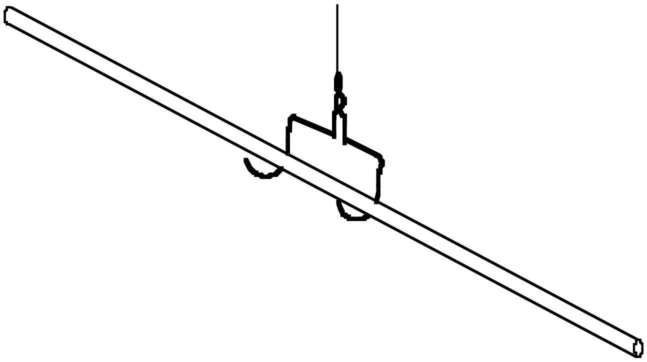
1. A small conducting sphere to use as a "test charge" can be made by taking a small Styrofoam sphere (available at craft supply stores) and carefully wrapping it with aluminum foil. A ping-pong ball is probably too heavy but it can be made conducting by carefully covering it all over with soft pencil lead.

**California Physics Standard 5f**

**5. Electric and magnetic phenomena are related and have many practical applications.** As a basis for understanding this concept:
**f. Students know magnetic materials and electric currents (moving electric charges) are sources of magnetic fields and experience forces due to magnetic fields of other sources**.

Students are usually quite familiar with magnets and know that they can be made to attract or repel one another and that magnets will attract anything with iron in it. A common misconception, however, is that magnets will attract all metals. A suggested way to begin this section on magnetism to is demonstrate that the electrostatic force applies to all materials but that magnets will attract only certain materials. This can be done with small bits of paper, aluminum foil, small pieces of copper wire, iron filings, etc. Compare a charged rod vs. a magnet in attracting these materials. It can also be demonstrated with long rods of assorted materials as described on the next page.

**Demonstration to show electrostatic attraction vs. magnetic attraction:**



Suspend one of the cradles made in the previous section (best if made from copper wire) in the front of the room. Have on hand several long rods made of wood, PVC, copper, steel, etc. Using long thin materials will take advantage of the sensitivity of this "torsion balance". Show that all different kinds of material placed in the cradle will be attracted to a charged rod but a magnet will attract only select materials. The electrostatic force is universal but the magnetic force only applies to particular materials.

**What the "north" end of a magnet means**

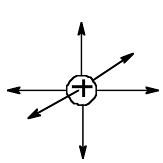
Suspend a bar magnet in a cradle so all can see it and allow it to swing for some time until it finally aligns itself in the earth's magnetic field. Stress that the "north" end of the bar magnet is the end that seeks geographic north. With the basic statement that unlike poles attract, bring another bar magnet near the suspended magnet and establish the second magnet's north and south pole. Help your students understand the difference between north and south poles for magnets and plus and minus electrostatic charges. Also help them to understand the trivial but confusing fact that in the geographical north polar region of the earth, there must be a south magnetic pole. Finally, point out that a compass is really just a small magnet suspended so it will rotate freely and the north end of the compass is a north magnetic pole and will seek the earth's south magnetic pole that is located near the north geographic pole of the earth.

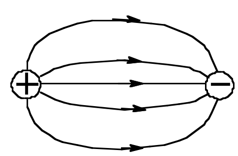
**Contrasting Electric Fields and Magnetic Fields:**

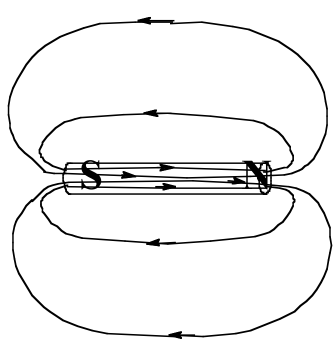
1. The direction of an electric field is, by definition, the direction a plus charge will be forced when placed in the field.
2. The direction of a magnetic field is, by definition, the direction the north end of a compass will point when placed in the field.

Electric fields can begin and end on charges. Magnetic fields are always closed on to themselves. Although it might seem that magnetic fields can begin at the north pole of a magnet and end at the south pole of the magnet, it can be shown that magnetic field lines actually continue back around to themselves inside of the magnet.

Electric fields can do work on charges, magnetic fields cannot. This is a consequence of the fact that magnetic fields can only exert forces on charges at right angles to their direction of motion. Illustrated below is the electric field around a single plus charge,



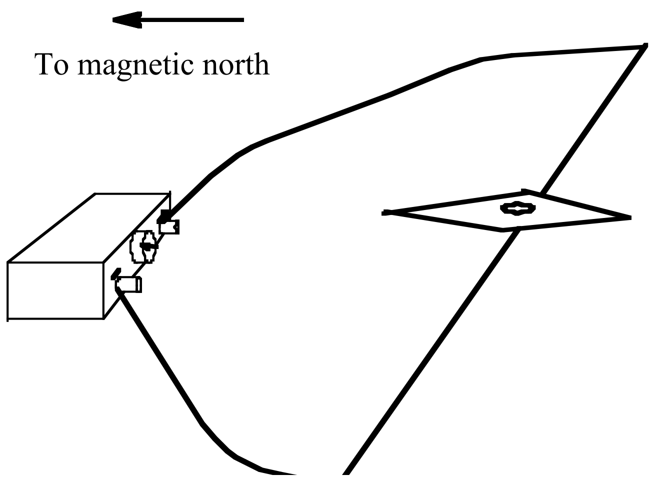




next to it is the electric field around two equal charges of opposite sign called "an electric dipole" and the third illustration is the magnetic field around a single bar magnet called a "magnetic dipole." Notice that the magnetic field lines are closed on to themselves inside of the magnet.

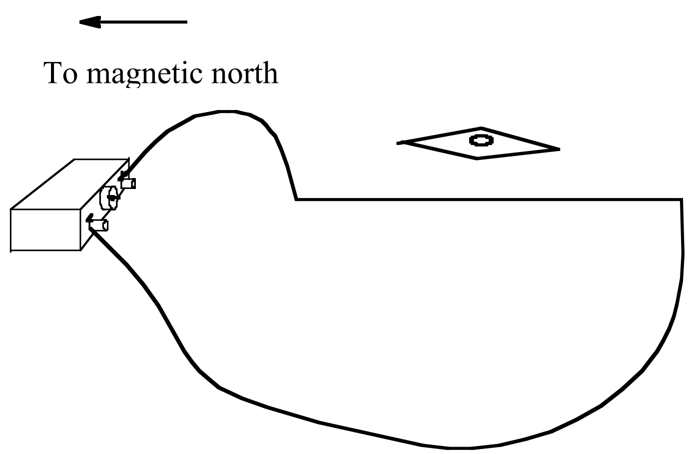
Classical physics predicts that since magnetic field lines are always closed back on to themselves, there can never be a magnetic "monopole" like a single electric charge. It is interesting to realize that quantum physics does predict the possibility of a magnetic monopole, but so far, none has been found.

**Repeating Oersted's famous experiment to show a current produces magnetism:**

The history of the discovery that electric currents create magnetism is fascenating and might be an interesting web search. Essentially, Oersted had one of Volta's new batteries and predicted that an electric current should produce a magnetic field. According to the story, he decided to do the <u>first</u> experiment to show his prediction in front of an audience. However, he did not anticipate the now well known fact that the magnetic field would be produced <u>perpendicular</u> to the wire. You can duplicate his failed experiment as follows:



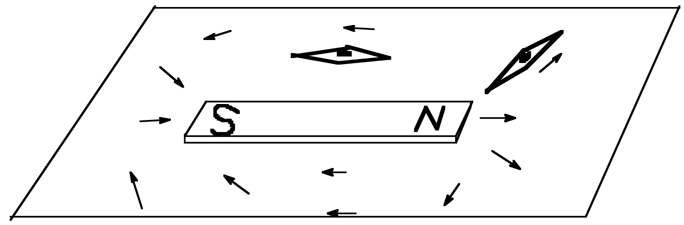

With a power supply attached to a long copper wire, stretch the wire so that a long straight section runs perpendicular to the earth's magnetic field. Hold a large demonstration compass above the wire and have a student turn on the current. Nothing much will happen except perhaps for a little motion of the compass needle. (Be properly amazed that the experiment did not work. When Oersted failed his audience began to file out of the room disgusted.) Now this time arrange the apparatus so that the straight section of the wire is parallel to the direction to magnetic north. (Make sure the return wires are far enough away so that the field from them will not confuse the demonstration.) This time when the current is turned on, the compass will swing perpendicular to the wire. This was the first time in the history of science that a field effect was found to be at right angles to the source.




With this setup you should be able to move the compass carefully around the wire to show that the magnetic field is everywhere perpendicular to the wire. (Use a large current to override the earth's magnetic field. A smaller compass may work better for this demonstration. This will show that the magnetic field around a wire is in circles around the wire.

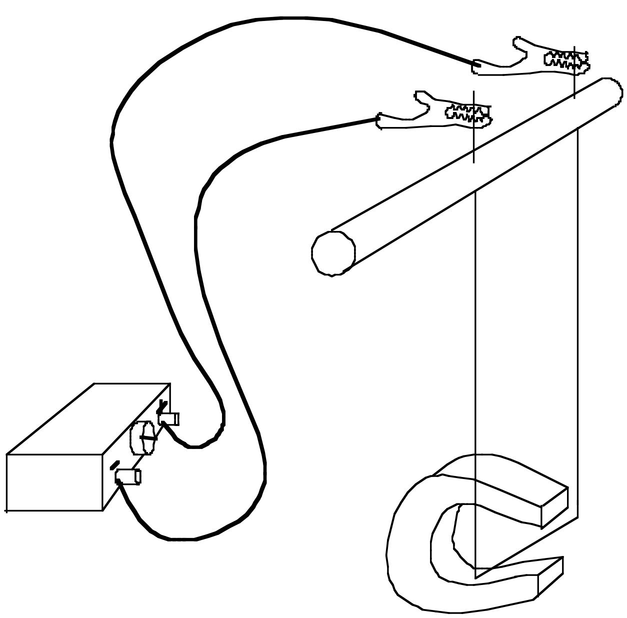
**Activity to trace out magnetic field lines:** 

A simple experiment that involves nothing more than a small compass, a bar magnet and a sheet of paper is illustrated on the right. Have the students move the compass at many different places on the paper and make a small mark showing the direction the north end of the compass points. After making many marks, have them trace in lines that include in a single sweep each the direction of the multiple indicated compass directions. There will be many attempts to draw many lines and suggest that the lines should be closer together in places where the field is the strongest. There are two advantages of this method over the usual iron filing method. First it is not as messy and second, it should be apparent to the students that the field is everywhere, not just on the apparent lines where the iron filings line up. Students need to know that representing fields with lines does not mean there is no field in between the lines. How close together they are is an indication of the strength of the field.




**Demonstrating the force on a current in a magnetic field**

Place a strong magnet near a wire that is freely suspended and that can carry a large current. Some of the "new" neodymium iron magnets or samarium cobalt magnets will work or if you are lucky and own an old radar magnet, this also will work quite well. Orient the wire so a straight section is near the magnet yet allows the rest of the wire from the power supply to hang free. A quick pulse of current through the wire should cause it to jump out of the field or be drawn into the field. "Hand waving" (to be discussed later) can be used to discover the direction of the force when the direction of the current and the direction of the magnetic field are known.



On the left is an illustration of the apparatus using a large radar magnet. In this case the magnetic field is vertical and the force on the current will either be to the left or to the right, depending on the direction of the current and whether the magnetic field is up or down. The experiment can be duplicated with a strong flat magnet resting on a table directly below the hanging wire with the wire in a region where the magnetic field is vertical.

The above will be discussed again with more detail in Standard 5n*.

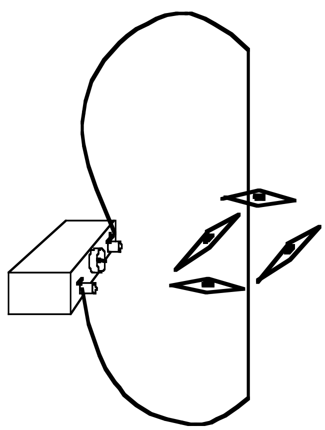
**California Physics Standard 5g**

**5. Electric and magnetic phenomena are related and have many practical applications.** As a basis for understanding this concept:

**g. Students know how to determine the direction of a magnetic field produced by a current flowing in a straight wire or in a coil.**

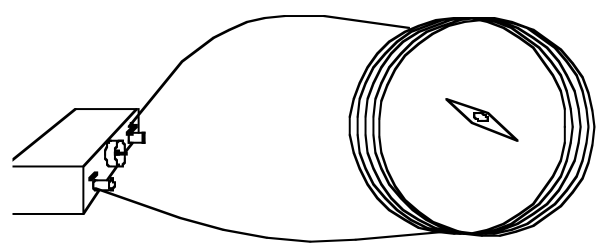
**Demonstrations to show the direction of magnetic fields around wires, loops and coils or solenoids:**

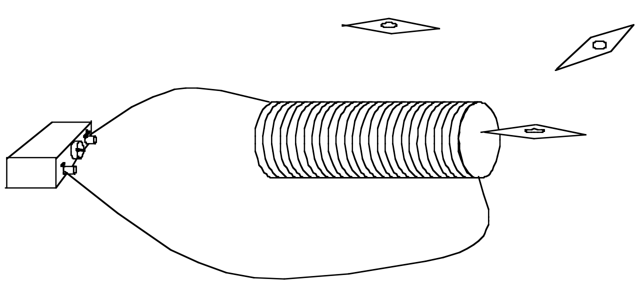
Remind students that the direction of a magnetic field is the direction that the north-seeking end of a compass needle will point when placed in the field. The following demonstrations will help students to see the connection between the direction of the currents and the direction of the resulting magnetic field. (As always, the direction of current is the direction of positive charge flow.)



Attach a long section of wire to a power-supply and support a long straight section in a vertical position. Using a demonstration compass, move around the wire and note how the compass points. Since you will be competing with the earth's magnetic field, point out to students that the compass is pointing out a vector sum of these two fields. However with a large enough current, it should be clear that the compass indicates that the magnetic field of the current is in a circle around the wire. Note the direction of the current from the polarity of the power-supply and indicate how the compass is pointing, depending upon whether the current is directed upward on downward. We recommend that the students clearly see how the compass points related to the current direction before you show them the mnemonic of hand waving.

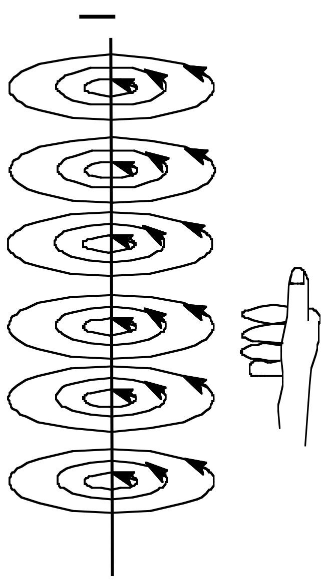
Make a "loop" of wire that consists of 10 or 20 turns of copper wire in a large flat circle. The loop does not need a cardboard or plastic form to wind the wire on but if one is available, it makes it a little easier to manipulate. Using the demonstration compass show that the field inside of the coil is always in the same direction, essentially parallel to the axis of the loop. Carefully move near the wire to the outside of the loop and observe that the compass changes direction.



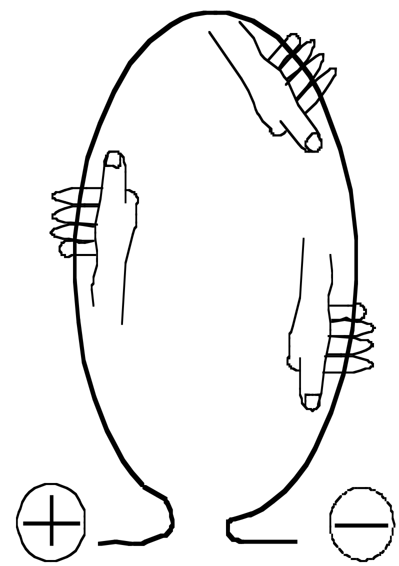


Repeat the demonstration with a solenoid. As you move the demonstration compass around in the field of the solenoid, students should notice that the field is the same as a bar magnet. However, with the solenoid, it is possible to move the compass inside of the coil and show that the field does in fact close back on to itself. In all cases, show the effect of reversing the direction of the current on the magnetic field. Carefully note the direction of the current and the subsequent magnetic field direction.

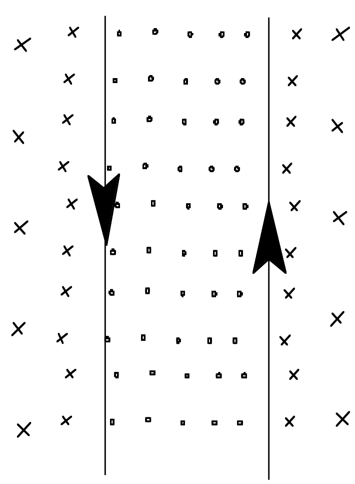
**Using the right hand rule to determine the direction of a magnetic field**



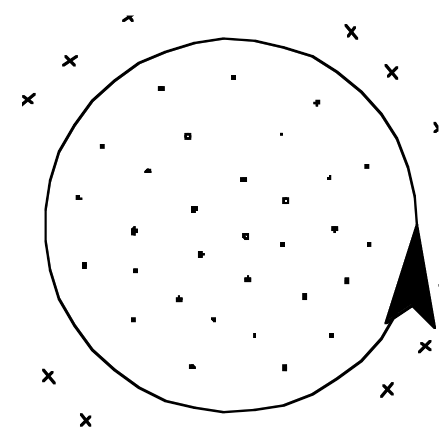
Determining the direction of the magnetic field around a current is easily found by the “right hand rule”. Point the thumb of the right hand in the direction of the current and the fingers will curl around the current in the direction of the magnetic field. This works for any current configuration as shown with a single wire on the left or with a loop as shown on the right. The fingers will always point in the same direction inside of the loop as the thumb points around the loop in the direction of the current. This is also true for the solenoid. Inside the solenoid the field points in one direction and outside it points in the other direction. Often the end of the solenoid where the field points outward is called its north pole, just as with the bar magnet.



Since magnetic fields are definitely a three dimensional phenomena, it is often difficult to represent them on two-dimensional surfaces. A commons trick is to represent vectors directed toward you with a point and vectors directed away from you with an X. (Think of an arrow with tail feathers.) Below is a representation of the field around two wires



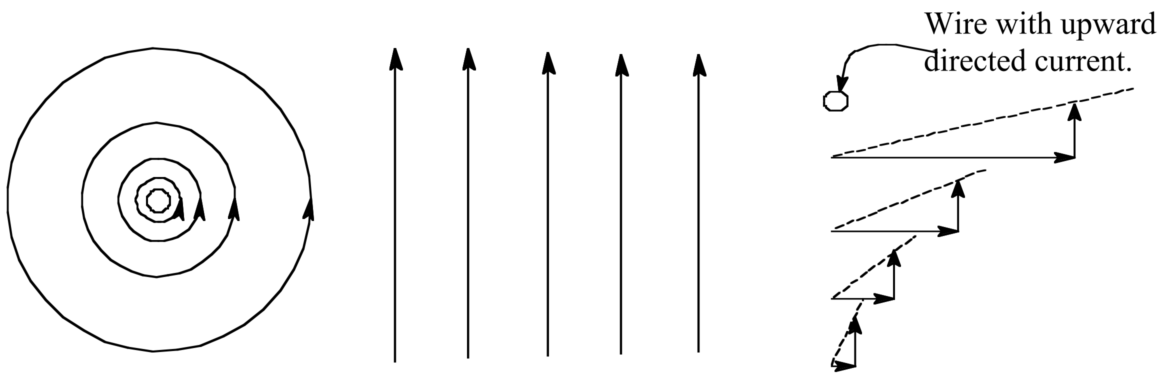
carrying current in the opposite direction (shown on the left) and the field around a current carrying loop (shown on the right.) Excellent three-dimensional illustrations of magnetic and electric fields can be found in most college physics texts. Recalling that the intensity of a field is indicated by how close together the field lines are spaced, a correct representation using the dot and X method should also represent this. Although the drawings shown here are not strictly correct, the correct representation would show different dot and X densities.



We have been discussing the right hand rule used for finding the direction of magnetic fields produced by currents. If the “current” is a flow of negative charges, such as electrons, simply use the left hand rather than the right hand. Also, it should be understood that there is a different “right hand rule” used to explain the directions of the <u>force</u> on charges moving through magnetic fields. Failing to appreciate this difference can cause confusion. We will discuss the hand waving rule for <u>forces on charges</u> moving through magnetic fields in Section 5. n*.

**Activity to measure the relative strength of magnetic fields produced by currents**

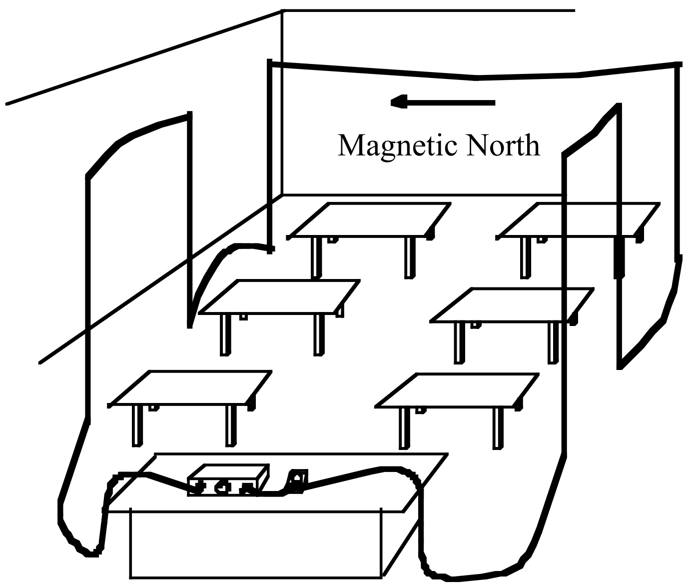
The Standards do not include how current, and distance from the current, influence the strength of the magnetic field. In the case of a long straight wire, it can be shown that the strength of the magnetic field is directly proportional to the current and inversely proportional to the distance from the wire. (This is known as the Biot-Sevart law.) An experiment to demonstrate this relationship can be challenging to perform but requires modest equipment and a special cooperative spirit between students and teacher. Before describing this experiment it is important to appreciate that all experiments involving magnetism can be made difficult if even a small amount of iron is in the space where the experiment is conducted. Metal tables, belt buckles, even steel fasteners in wooden tables can contaminate the results.
First, let us consider a description of the concept of the experiment. Below are three illustrations. The first is the top view of the magnetic field around a wire with a current directed upward toward us. The second is the horizontal component of the earth's magnetic field as seen from above. The third illustration represents the vector sum of the field of the (vertical) current and the horizontal component of the earth's field.




**Current's field only.** **Earth's field only** **Vector sum of two fields**

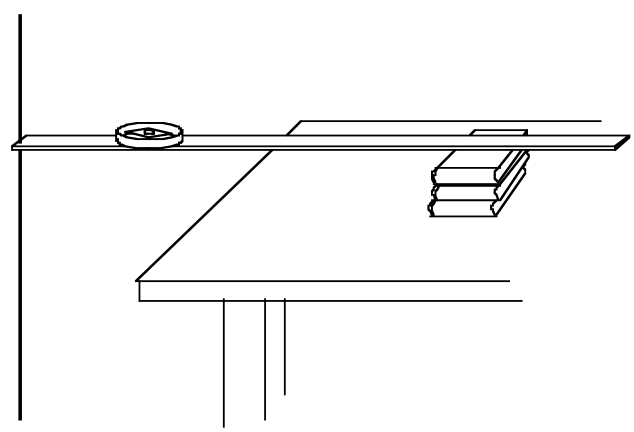
In this experiment the magnetic field around a current carrying wire will be measured with a compass. With the current on, the angle the compass points away from magnetic north will be recorded and this angle can be used to compare the strength of the current's field with the strength of the horizontal component of the earth's field. (Students who understand basic trig will see that the tangent of the angle the compass needle is directed away from magnetic north is the ratio of the current's magnetic field to the horizontal component of the earth's magnetic field.) In order to be successful, this experiment will require currents of up to10 amps (or more) and a space to move the compass that is some distance from ferromagnetic materials. Since most classrooms do not have classroom sets of large current power supplies, the following page describes a possible approach using only a single large power supply and a very long wire distributed around the room.

**Experiment to measure the magnetic field around a long straight wire:**
A single large variable power supply with a good ammeter is located in a convenient spot in the room and will probably be controlled by the teacher. A long piece of enameled copper wire (probably #18 or larger) that can be strategically is passed up and down around the room. Supporting the upper end can be a problem but we have had luck with light fixtures. The lower end of the vertical straight wire can be held down with a weight




or perhaps a book. This setup can provide several stations with vertical wires to carry currents that the teacher can control from a single power supply in a single location. The students will have a meterstick with one end taped to the wire running in a magnetic north south direction. To avoid the influence of ferromagnetic materials, books can support the meterstick high above the table, or even a student could hold the stick in a horizontal position. One part of the experiment would be to have the current fixed at a fairly large value while the students measure the field at different distances from the wire. Another part of the experiment would be to have the students fix the compass fairly near the wire and have the teacher call out different currents.

On the right is shown an individual station. The meterstick is aligned with magnetic north and the zero end of the meterstick is taped to the vertical wire. The books hold the meterstick above the table and may require a student to hold it down. If the desks are not conveniently aligned, it might be required that students hold the stick. Again make sure that no ferromagnetic materials in student's pockets, etc. ever be near the compass. If a large enough diameter wire is used, the wire should not heat appreciably during the higher current settings. (A test in advance with a small piece of the selected wire at the highest current settings is advised.)



The analysis of the data will involve comparing the current's field at different distances with a fixed current and at a fixed distance with different currents. If the students know trig, they will note that the field of the current = the earth's field X the tangent of the angle of deflection from magnetic north. Students who don't know trig can use the graphical method of adding vectors as discussed in Section 1 j*.

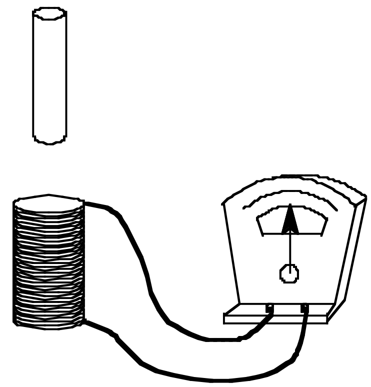
**California Physics Standard 5h**

**5. Electric and magnetic phenomena are related and have many practical applications.** As a basis for understanding this concept, students know:

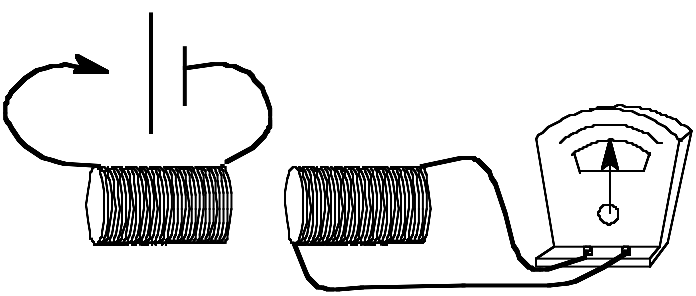
**h. Changing magnetic fields produce electric fields, thereby inducing currents in nearby conductors**.

Electromagnetic induction was one of the major discoveries of the early 19th Century and the applications of this discovery play a major role in the electrical industry today. Very simple demonstrations can be performed to illustrate the basic principle of EM induction.

Don't overlook doing the most straightforward demonstration of simply thrusting a bar magnet into a coil of wire attached to a galvanometer that can swing either way about zero. Stress that the magnet must be moving relative to the coil (or the coil relative to the magnet.) Reverse the magnet so that the opposite pole enters first. Show the effect of moving rapidly vs. slowly. (Be advised that the galvanometer meter has a finite inertia and may not be able to respond to very rapid motions.) Show what happens when the magnet is put through one end of the coil and pulled out of the other end. These demonstrations are fundamental and should be stressed.



After showing electromagnetic induction with a permanent magnet, show essentially the same thing only with an electromagnet. Two coils near one another might work as shown below if the galvanometer is quite sensitive. If the galvanometer is not too sensitive, place a bar of iron through both coils. However, this will so vastly increase the effect; use caution when you connect the battery since you could exceed the limits of the galvanometer. Show what happens when you change the polarity of the battery, the number of cells, etc. These demonstrations should easily lead to the basics of how a transformer works.

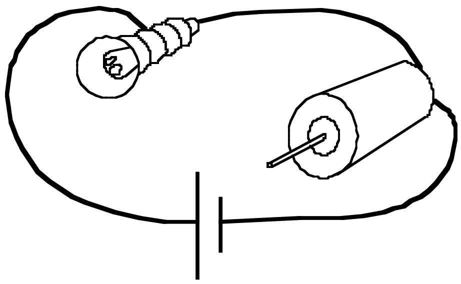


**Lenz's Law and back emf.**

Faraday, Henry and Lenz discovered electromagnetic induction at approximately the same time. All three appreciated that a <u>change</u> in magnetic field was required to produce a current in the coil but at first, apparently only Lenz understood that the current must be in a direction to <u>oppose</u> the change. Discuss with your students what must be the direction of the current in a coil of wire when a particular pole of the magnet is thrust into the coil. Relate this to the conservation of energy principle. Extend the discussion to what must happen when the magnet is pulled out of the coil. A discussion of the direction of the current should lead to the direction of the emf causing this current.

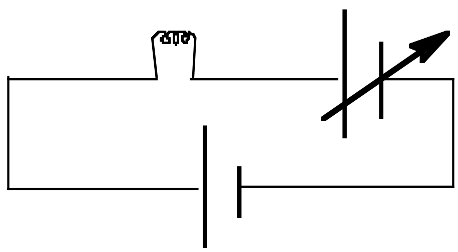
**The light bulb in series with the motor demonstration:**

A very thought provoking demonstration involves a DC motor wired in series with an appropriate light bulb. Choose the DC motor and the bulb so that they are designed to operate on approximately the same voltage. With a slight adjustment of the applied



voltage it is possible to get the motor to spin at a fairly high rpm and the light bulb to appear unlit. When you grasp the spinning motor shaft and slow it down, the bulb will light. Stress that the two are in series hence the same current is passing through each. Ask your students: "Why when the motor is stopped the bulb lights but when it is spinning, the bulb is dark?"

They will probably suggest that it is in response to the conservation of energy principle but question that conclusion since somehow we must explain why a stopped motor has more current passing through it than it does when spinning at high speed. Remind them of how the motor armature is simply a coil of wire and it is spinning in a magnetic field.



Since the spinning armature is experiencing a change in magnetic field through it, as it spins, (in other words, it is a generator), it must develop an emf. By Lenz's law, this emf must be a back emf that opposes the battery emf. Hence, the faster the motor spins, the greater opposition it puts up to the battery emf, hence, the current decreases.

A useful conclusion to draw from this demonstration is that when an electric motor, driven by a constant applied voltage, slows down, more current passes through it. One consequence is that large electric motors on tools like table saws will sometimes blow fuses or circuit breakers, but only when they are stalled or are just starting. Also, as the motor slows with a constant voltage applied across it, the torque supplied by the motor increases. This is why electric cars and electric trains do not need transmissions, as do cars with internal combustion engines. Electric motors have maximum torque at zero rpm, whereas, internal combustion engines need a minimum rpm to develop the torque necessary to start moving the car.

**California Physics Standard 5i**

**5. Electric and magnetic phenomena are related and have many practical applications.** As a basis for understanding this concept:
**i. Students know plasmas, the fourth state of matter, contain ions and/or free electrons and conduct electricity.**

Here on earth we commonly experience only three states of matter: solids, liquids and gasses. However, in the universe at large, the most common state of matter is plasma. Heat a solid element and it melts, heat the resulting liquid further and it turns to gas. In all three states, the atoms of the original solid are still held together by the electrostatic attraction between the nucleus and the surrounding electrons. However if this gas is heated further, at a sufficiently high temperature, the electrons will separate to form free electrons and positive ions. This plasma state is common in stars and most of the rest of the universe. A fraction of the air in a lightening bolt will be in the plasma state for a very short time. A small fraction of the mercury vapor in a fluorescent light will be in the plasma state while the light is on.

**Basics on how a fluorescent light works:**
Since fluorescent lights are everywhere, students might appreciate a discussion of how they work. The basic idea is that mercury vapor at a fairly low pressure is inside of the fluorescent tube. When a current is passed through this mercury vapor, the electrons in the atoms are moved to a higher energy level and when they return to a lower energy state they emit light, mostly at the ultraviolet end of the spectrum. This ultraviolet light excites a special solid fluorescent coating inside of the glass tube. When the electrons in the coating's atoms fall to a lower state, white light in the visible spectrum is produced. (Note: atoms in the gas state are far apart produce line spectra but the energy levels in a solid are so close together, do to the proximity of other atoms, a solid when excited will produce what seems to be a continuous spectrum.) Different solid fluorescent material can be used to produce different shades of light and even to produce different colored light. A plasma TV consists of a huge number of tiny fluorescent lights with coatings designed to produce three different colors per pixel and these are individually addressed with the TV signal to produce the desired picture. Although neither the fluorescent light nor the plasma TV contains many atoms in the plasma state, there are perhaps enough to earn the name "plasma."

Details on how fluorescent lights and plasma TVs work are easy to find on the web.

**California Physics Standard 5j***
**5.j* Electric and magnetic phenomena are related and have many practical applications.** As a basis for understanding this concept:
**Students know electric and magnetic fields contain energy and act as vector force fields.**

**Another look at the concept of the field**
The electric field was discussed in 5c, however, since the field concept is so important and fundamental to the understanding of many physics ideas, it should be helpful if fields are revisited here. One definition of a field that seems more mathematical than physical is: "a field is something that assigns a value to every point in space." A good physical example of this definition is a temperature field. Suggest to your students that there is a temperature field in the room. This means that if a thermometer is placed anywhere in the room, it will indicate a temperature. Near the floor it may be 15ºC, at eye level it may be 20ºC and near the lights it may be as high as 60ºC. The idea to stress is that there will be a temperature at every point in the room, that is, a "temperature field". Since temperature is a scalar, the temperature field is a <u>scalar</u> field. An example of a <u>vector</u> field would be the force of gravity on a "test mass" placed at any point in the room. The force is always downward and equals the weight of the mass. You could even define the "gravitational field intensity" as the force per mass placed at any point. in space. That is, the gravitational field intensity, $g = F_G/m$. (Students may not immediately see that this "gravitational field intensity" is also called "the acceleration of gravity" but this

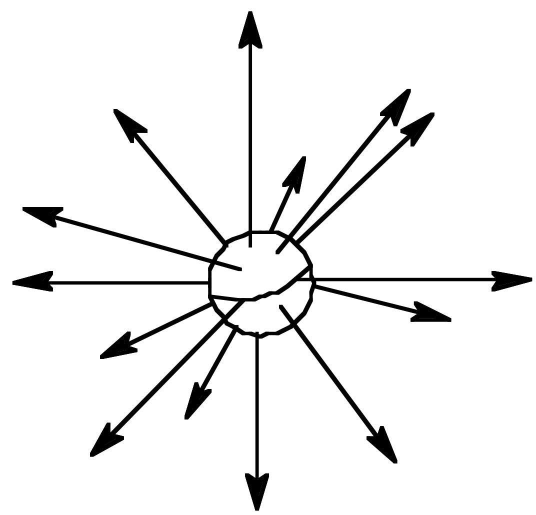
introduction may help them to better understand the concepts of electric and magnetic fields.)

**The definition of electric field intensity and drawing electric fields.**

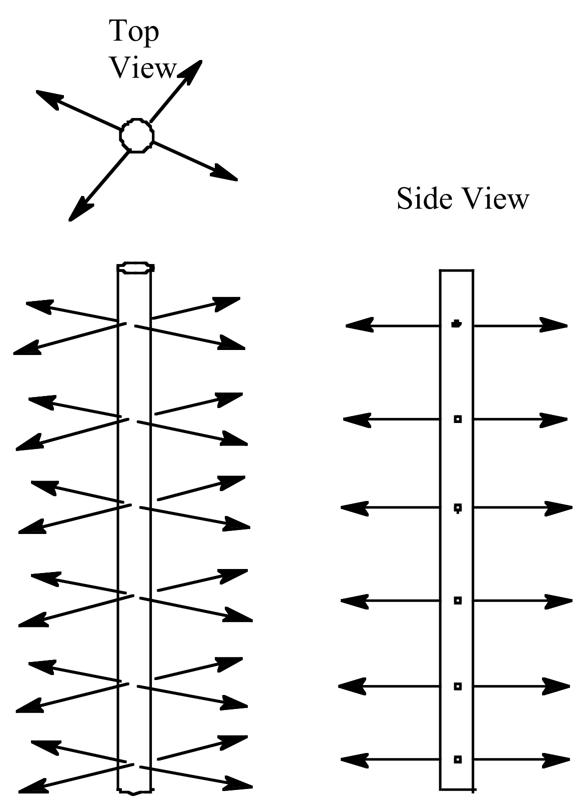
The electric field intensity, E, at any point in space, is by definition, the ratio of the electrical force on a test charge placed at that point in space, to the magnitude of the test charge. That is, $E = F_E/q_{test}$ As discussed in 5c, electric fields can be represented as directed lines. The direction indicated on the line is the direction of the force on a plus charge and the spacing of the lines indicates the strength, or intensity, of the electric field. Electric fields surround stationary charges.

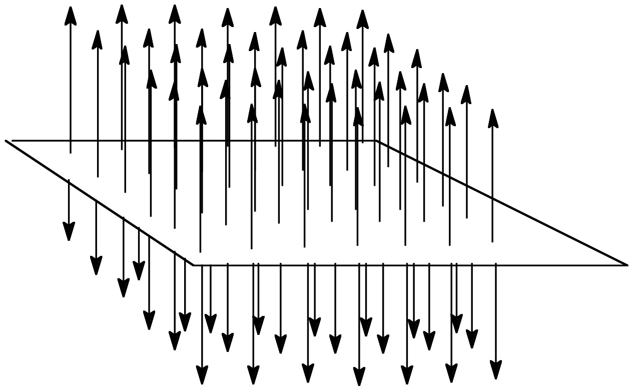
**Three-dimensional sketches of electric fields.**

Although sketching three-dimensional representations of electric fields can be difficult, students can learn much from the attempt. The illustration on the right is an attempt to show the electric field around a plus charged sphere. When drawing the field lines the student should become aware that they spread out in all directions. Some thought about the geometry of the situation might lead the student (with Faraday) to conclude that the intensity of the field must decrease with distance and might even see a reason for an inverse square law.



Sketching the electric field around a long uniformly charged cylinder will help the student to appreciate that the lines can not spread equally in all directions. The sketch on the right of a section of a long straight positively charged cylinder shows that from top view, the lines are spreading with distance but from side view the lines remain the same distance apart. Again, an appeal to the surface area of a cylinder and some careful thought might help the student to appreciate that rather than having the field decrease with distance as an inverse square law, but that the decrease with distance is only as an inverse first power. An interesting demonstration to help students see this fact is to use a light meter to measure the intensity of light as a function of distance from a small clear bulb and compare the result to that of a long fluorescent tube.





The illustration on the left attempts to show a section of the electric field extending from a large uniform plane of positive charge. (The plane would have to be infinite; otherwise the field lines would bend outward at the edges.) This configuration has no room in three-dimensional space to spread. Therefore, the field from a large plane of charge will not decrease with distance.

**Stationary charges are one source of electric fields. Moving charges, or currents create magnetic fields.**
When stationary charges are the source of an electric field, the field lines can start and end on charges. (We learned in section 5h that changing magnetic fields could also create electric fields. In this case the electric field lines will close on to themselves.) Magnetic fields, on the other hand, are produced by charges in motion. (We will also learn later that changing electric fields can create magnetic fields.) An interesting consequence of the way magnetic fields are created is, unlike electric fields, they always close on to themselves. (Demonstrations and discussions of this are given in 5g.) (More about magnetic fields in 5n.)
**The energy of fields:** Electric and magnetic fields contain energy and this energy can be determined by the amount of work required to establish the field.

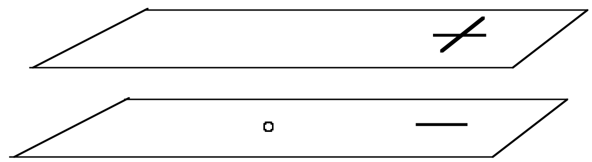
**California Physics Standard 5k***
**5. Electric and magnetic phenomena are4 related and have many practical applications. As a basis for understanding this concept:**
**k.* Students know the force on a charged particle in an electric field is qE, where E is the electric field at the position of the particle and q is the charge of the particle.**

This is nothing more than a restatement of the definition of electric field intensity. (See the second paragraph in 5j.) Students may be helped to understand the definition of electric field intensity if you once again discuss the definition of "gravitational field intensity". The gravitational field intensity is the ratio of the gravitational force on a mass (in other-words, its "weight") to its mass or, $g = F_G/m$. The gravitational field intensity varies as you move away from the surface of the earth. The gravitational field intensity on the surface of the moon is about one sixth as much as on the surface of the earth. Another name for the gravitational field intensity is "the acceleration of gravity" but the important idea here is that it is the ratio of the gravitational force on an object, to the mass of the object.

Likewise, the electric field intensity is the ratio of the electric force on an object to the charge of the object. $E = F_E/q$. This means that if there is an electric field somewhere in space, if we place a "test charge" at that point in space, it will experience a force and the ratio of that force to the charge is the electric field intensity. Electric field intensity is measured in newtons/coulomb. (There is no single name for this unit. Also, often the electric field intensity is simply called the electric field, E. Finally, there is no simple equivalent alternate physical idea of the electrical field intensity as "acceleration of gravity" was to the "gravitational field intensity".)

**Example problem involving accelerating charges in an electric field:**

Two charged plates have an electric field between them of magnitude E. A small negatively charged object of charge q and mass m is released very near the negative plate and accelerates to the positive plate a distance d.




Find the acceleration of the negatively charged object and its velocity when it reaches the positive plate.

Finding the <u>acceleration</u>: $F = qE = ma$, or $a = qE/m$

Finding the <u>velocity</u> could be either done by kinematics or work to kinetic energy. Using the latter approach, the work done on the charged object will equal its kinetic energy when it reaches the positive plate. That is, work = $Fd = Eqd = 1/2mv^2$ Or, solving for v,

$$v = \sqrt{2Eqd/m}$$

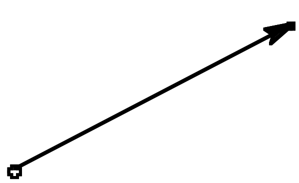
This probably sounds like a pretty abstract and useless problem but it might have more meaning if the charged object is identified as an electron (charge and mass can be easily found) and the two plates are a part of the electron gun structure in an (old) cathode ray tube television set. Although the Standards decide not to stress the important relationship between the voltage across parallel plates and the electric field between them, it is easy to show that $V = Ed$. In the TV tube, $V = 10{,}000$ volts and $d = 2$cm.

**California Physics Standard 5i***

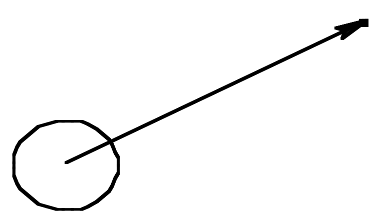
**5. Electric and magnetic phenomena are related and have many practical applications. As a basis for understanding this concept:**

**l.* Students know how to calculate the electric field resulting from a point charge.**

The Standards are starting to sound redundant but let's assume it will be good for the students to know specifically how to compute the electric field around point charges. First, let's understand that Coulomb's law, as stated, is assumed to apply only for point charges* or at least only for uniform charged spheres, providing the distance is always measured from the center of the sphere.



In either case, $q_1$ is the charge of the point or of the sphere; $q_2$ is the charge of the "test charge" placed at a distance r from the center of either source.

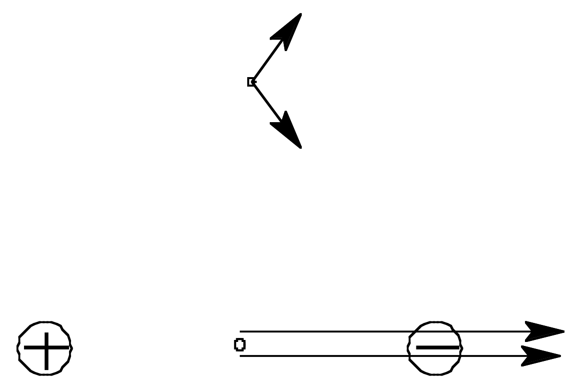


Recalling the definition of the electric field, $E = F/q$ and Coulomb's law: $F = kq_1q_2/r^2$. From $F/q_2 = kq_1/r^2$, it follows that the magnitude of the electric field from a point charge will be: $E = kq/r^2$. (The result will be a vector directed away from the charge if it positive and toward the charge if it is negative.)

If the problem is to find the electric field produced by several point charges at some place in space, compute the electric field from each charge separately and use vector addition to find the total electric field at the place in question.

**An interesting fact about an electrostatic charge of one Coulomb:**
When dealing with electric currents, the unit is the ampere (or amp) and an ampere is a coulomb per second. In the wires where currents usually flow, the moving negative charges (electrons) are never very far away from their parent positively charged atoms so no net electrostatic force is noticed around the wire. However, one coulomb is an enormous amount of electrostatic charge. An interesting problem is to compute the force between two charges of one coulomb each placed one meter apart. (About $10^{10}$ N.) Now how many average automobiles would it take to weigh this much? (About 1 million.) This is why it might be more realistic to use micro-coulombs rather than coulombs in assorted electrostatic problems.

**Example problem:**
A plus and minus charge of 2 micro coulombs each are separated by one meter. Find the electric field midway between them.
$E = 2(kq/r^2)= 2(9X10^9)2X10^{-6}/ (1/2)^2$ N/coul
Find the electric field at a point above the two charges that forms the vertex of an equilateral triangle with the two charges. (Since the vectors formed are equal and at 120º, just one will solve the magnitude,)
$E = kq/r^2 = (9X10^9)(2X10^{-6})/(1)^2$ N/coul
in a horizontal direction.

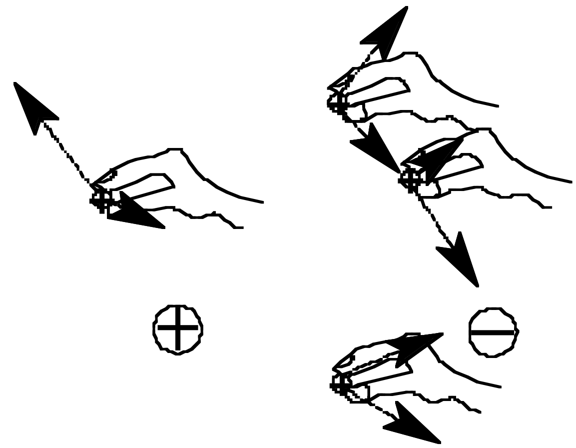


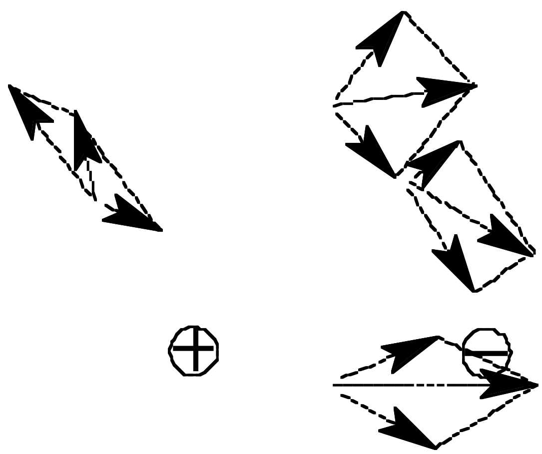
* Naturally, with calculus, infinite sums of point charges can be used (in principle) to find the E field around any charge configuration such as lines and planes.

**California Physics Standard 5m***
**Electric and magnetic phenomena are related and have many practical applications. As a basis for understanding this concept:**
**m. * Students know static electric fields have as their source some arrangement of electric charges.**
The intent of this Standard (as revealed in the Framework) is to have students know how to draw electric fields around assorted charge configurations. It is important to appreciate the standard is involved with static situations. (Electric fields not only have as their source charges, but as discussed in 5h, changing magnetic fields also create electric fields. Electric fields that are due to static charges will begin and end on charges. Electric fields due to changing magnetic fields are always closed on to themselves, like magnetic fields.)

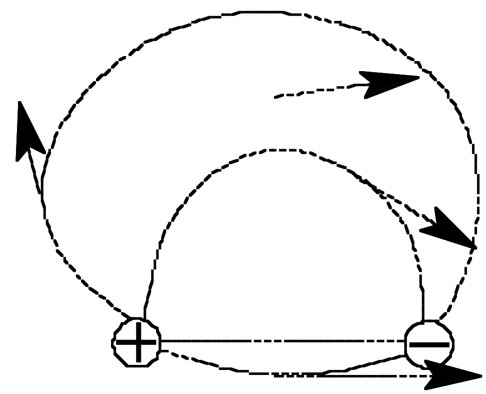
**Sketching electric field configurations around charge distributions:**
The important word is "sketching". The details that follow should be used only to help students have an understanding of what electric field lines mean and how to sketch them.

On the right is an illustration of the initial step in preparing to sketch the electric field around an electric dipole. That is, two equal charges of opposite sign, separated by a distance. In your imagination, place a small positive test charge at various places in the space surrounding the charge. At each location, "compute" the two electric field vectors from each charge. (It is not necessary to actually compute using $E = kq/r^2$, just estimate the relative lengths of the vectors and have them in the right direction on a line to (or away) from the charge in question. Each of these pairs of vectors will then be added (perhaps with a simple parallelogram sketch) to find the resultant. (See

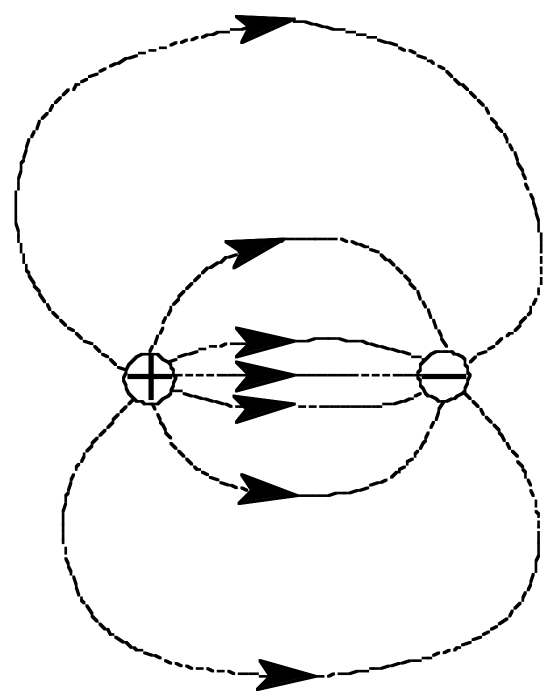




Using the resultant of the sum of the two vectors at each point in space, try to generate a smooth pattern of lines that pass through these vectors and are tangent to the vectors at the point of contact. Some of the vectors will have to be missed (see diagram on the right) in order to meet the condition that line spacing indicates field strength.



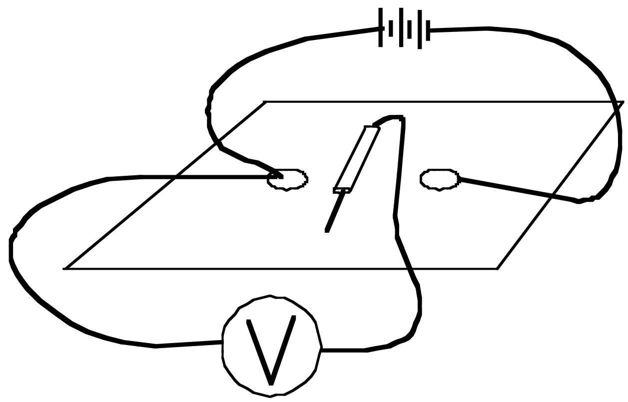
The sketch on the right illustrates a general idea of how the field lines are closer together at places where E is more intense and the direction of the lines would correctly indicate the direction a positive test charge would be forced if placed near that line. Stress that the spaces between the lines do not indicate that there is no field. Classical physics demands that the field is continuous and everywhere. The Framework incorrectly suggests that a free positive charge would move along the line. This would only be true if the charge had no mass. (Since all charges do have mass, the inertia of the charge would cause it to depart from the line as it increased its velocity.) It would be more correct to say that the direction of the line simply indicates the direction of the <u>force</u> on a positively charged particle. Equipotential lines would be constructed everywhere perpendicular to the field lines.



A nice exercise would be to repeat the above procedure for two charges of the same sign electrical charge. (Such sketches are available in almost any first year college physics text.) The following link has a much better discussion than the above on drawing electric fields: http://www.glenbrook.k12.il.us/GBSSCI/PHYS/Class/estatics/u8l4c.html

**Lab exercise in mapping equipotential lines around static charge configurations:** The basic idea behind this lab is to use a special conducting paper (Sargent Welch WL1960A 25 sheets for $15) that has a uniform resistance per unit area. A simple charge configuration is painted on this paper with conducting paint.

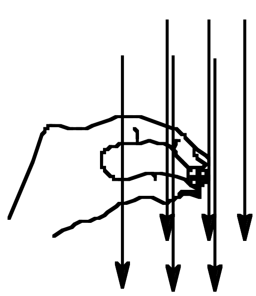
These "charges" are connected to a battery or low voltage power supply that establishes a current flow throughout the surface of the conducting paper. Using an inexpensive DC voltmeter with one probe attached to a reference "charge" the other probe can be moved about on the paper keeping the voltage reading constant, therefore plotting out an euipotential line. This plotting can be repeated for several different constant potential traces, mapping out several different equipotential lines.




The result of this exercise is to produce many different equipotential lines and constructing lines everywhere perpendicular to the equipotential lines can generate the electric field lines from the charge configuration. A point to stress with all field line sketches is that in the real world, all fields are three-dimensional. The electric field lines and lines extending into three-dimensional space and the equipotential lines are really equipotential surfaces.
Several more detailed discussions of this lab can be found by searching for "Mapping Equipotentials" in your browser.

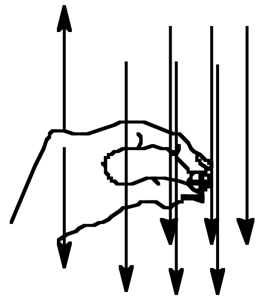
**Electric and Magnetic phenomena are related and have many practical applications.**
As a basis for understanding this concept**:**
**n. * Students know the magnitude of the force on a moving particle (with charge q) in a magnetic field is qvB sin (a) where a is the angle between v and B (v and B are the magnitudes of vectors v and B, respectively), and students use the right-hand rule to find the direction of this force.**

**Stressing the differences between the Electric Field and the Magnetic Field.**
Begin by reminding students that the direction of an Electric field is the direction a plus charge would be forced when placed in the E field. Also remind them that the direction of a magnetic field is the direction the north end of a compass needle will point when placed in the B (magnetic) field. Now introduce them to the peculiar way magnetic fields exert forces on charges:

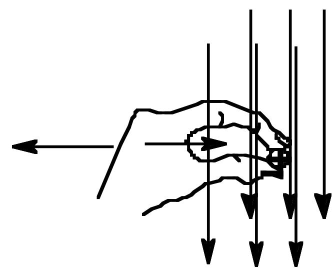


Pretend you have a plus charge in your hand and that a huge uniform magnetic field exists in the room pointing downward. Hold the imaginary plus charge still and ask which way they think the force will act on the charge. (That there is no force might be a surprise.)

Now move the imaginary charge up and down again asking the direction of the force on the charge. Assert again that there is no force.



Finally, move the imaginary charge in a horizontal direction (at right angles to the B field) and stress how the force will be perpendicular to both the field and the direction of motion. At first simply stress that the force will be perpendicular to both the velocity and the B field. Then discuss that if the velocity is at an angle to the field, only the <u>component</u> of the velocity perpendicular to the field will cause any force.



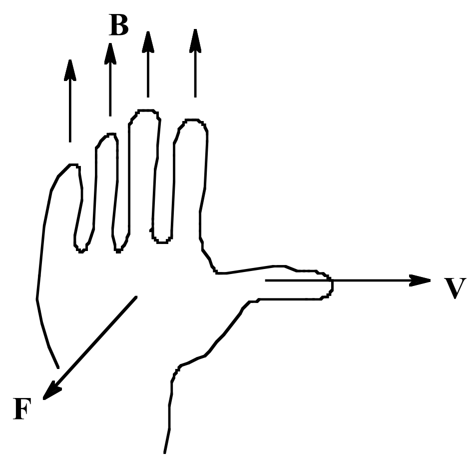
Once the peculiarities of the direction of velocity and force on a charge in a magnetic field is understood, introduce and discuss the "Lorentz Force" expression:

$$F = qvB \sin (a),$$

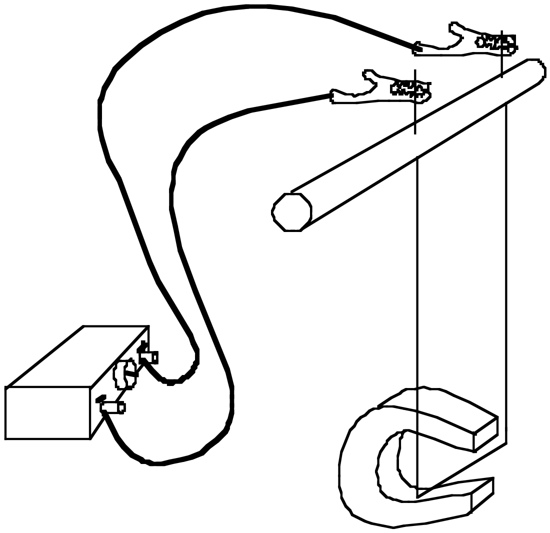
where a is the angle between velocity, v, and the magnetic field, B.

**Hand waving and the direction of the force on a moving charge in a B field.**
It should be discussed that the right hand is used in two different ways when attempting to describe the relationship between moving charges and the magnetic field. In section 5g we discussed how to use the right hand to determine the direction of a magnetic field that resulted from a current (or a moving charge.) Now we assume the magnetic field already exists and we will be using the right hand to find the direction of the <u>force</u> on a charge moving through the field. This can easily confuse students if the two different uses of the right hand rule are not discussed. There are several different ways of stating this mnemonic but we like the following called the "flat hand rule" to distinguish it from the "curled finger rule" previously used to describe the magnetic field around a current.

The field, B, velocity, V and force F form a three-dimensional coordinate system. The palm of your (flat) right hand is used to push things; hence it is logical to have it represent the direction of the force. When you thumb a ride, you point your thumb in the direction of your intended velocity; hence the direction of your thumb is the direction of the velocity. Finally, your fingers (begins with "f") point in the direction of the Field. Hence fingers in the direction of the field, thumb in the direction of velocity and palm in the direction of force describe a positive charge moving through a magnetic field. If the charge is negative, use the left hand.



**Demonstration to illustrate how moving charges are affected by B fields:**



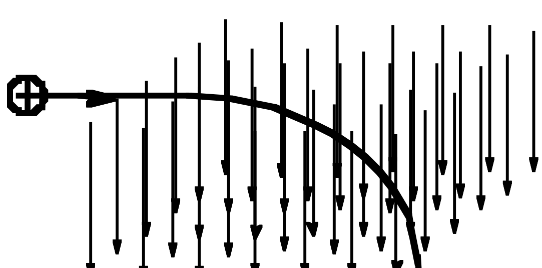
Illustrated on the left is a demonstration that can effectively show the direction of the Lorentz force. It requires a strong magnet and a power supply that can produce a short burst of current in the 10-amp range. The suspended loop of wire is bent so a horizontal section passes through the most intense region of the magnetic field. The suspended wire is supported by a wooden dowel that has been drilled to pass the wire enabling easy connection of the power supply leads with clips. The dowel is supported by a ring stand and the magnet should be firmly held so it won't move. Changing the clips can easily reverse direction of the current.

Using a compass needle determine the direction of the magnetic field of the magnet. Knowing the polarity of the power connections, the direction of the current will be known. Before you momentarily turn on the power, have the students use the right hand rule to predict the direction the will move in the field. After the first demonstration, perhaps reverse the direction of the current and/or turn the magnet upside down.

**The units of electric field intensity, E and magnetic field intensity, B:**
The electric field intensity is defined by: E = F/q and the electric field intensity unit has no special name. It is simply a Newton/Coulomb. However, the unit of magnetic field intensity is the Tesla. If a charge of one Coulomb moves at a velocity of one meter per second at right angles to a magnetic field of one Tesla, it will experience a force of one Newton. Using the Lorentz force expression gives $B = F/qv = N/Cm\ s^{-1} = N\text{-}s/C\text{-}m$ or one Tesla = one Newton sec/Coulomb-meter. (There are several other names for the unit of magnetic field intensity and they all mean the same thing. These are given here just for reference: Tesla= Weber/$m^2$ = Newton/amp-meter. A common unit of magnetic field intensity is the Gauss. One Tesla = $10^4$ Gauss. The intensity of the earth's magnetic field at the earth's surface is about one half a Gauss.)

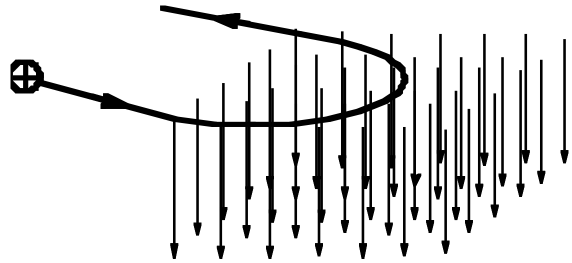
**How charged particles move in E fields and B fields:**

When charged particles move through E fields, the force on the charge can change its direction as well as speed it up or slow it down. However, since a B field can only exert a force on the moving charge at right angles to its motion, the B field can only change the direction of the particles motion. Consider the difference between the motion of a positive charge entering an E field at right angles to the field and the same charge entering a B field at right angles to the field.



When a charged particle enters an E field at right angles to the field, the force on the particle will accelerate it in the direction of the field (if it is positive) and it will both turn and speed up. The particle will assume a parabolic path in much the same way that a rock thrown at right angles to a gravitational field moves in a parabolic

When a charged particle enters a B field at right angles to the field, the only force on the particle is always at right angles to the particle's motion, hence it will move in a circle until it is no longer in the field. It will not speed up or slow down. Should the particle be fired at an angle to the field, it will move in a helical path.



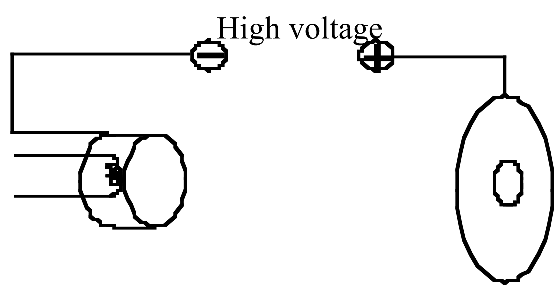
If a charged particle is fired <u>within</u> a magnetic field at right angles to the field, it can move in a complete circle. If it is fired at an angle to the field and remains within the field, it will move in a helix. The component of the velocity parallel to the field will advance the particle and the component of the velocity perpendicular to the field will determine the radius of the helix. Finally, magnetic fields can not do work on free charge particles, hence they can not speed them up or slow them down (that is, change their kinetic energy. If the kinetic or potential energy of a charge changes, it probably was due to an electric field and certainly was not due to a magnetic field.

**5. Electric and magnetic phenomena are related and have many practical applications**. As a basis for understanding this concept:
**o. * Students know how to apply the concepts of electrical and gravitational potential energy to solve problems involving conservation of energy.**

In Sections 2a, b and c we discussed ways of presenting the relationship between work, kinetic energy and potential energy in a gravitational field. This section simply extends this discussion to charges in electric fields. The key idea here is that "voltage" or potential difference is work (or potential energy) per charge. V = PE/q. If we move a charge against the force exerted by an electric field we give the charge energy and the work done <u>per</u> charge is called voltage, or perhaps more correctly, potential difference.

**An electron gun as an example of energy exchanges in an electric field:**
Older television sets, and computers produce their images through the interaction of high velocity electrons and a phosphor coating on the inside face of a cathode ray tube.

The essential electron gun structure is illustrated on the right. The can on the left has a hot filament inside of it that causes electrons to be emitted from the surface of this can. Since this can is connected to the negative side of a very high voltage, it s called the cathode. The electrode on the far right with the hole in




it is attached to the positive side of the high voltage and is called the accelerating anode. An intense electric field exists between the accelerating anode and the cathode that causes the electrons to achieve a high velocity as they move in this field. (Other structures called "focusing electrodes" are between the cathode and accelerating anode that create an appropriate electric field to force the electrons to pass through the hole in the accelerating anode.) Computing the energy and speed of the electrons as they pass through the hole in the accelerating anode is a simple application of V = PE/q. The negatively charged electron will move against the E field toward the accelerating anode, gaining kinetic energy as it looses potential energy. When it passes through the hole, all the PE will be converted to KE so, from V= PE/q:

$$PE = Vq = 1/2mv^2 \qquad \text{or,} \qquad v = \sqrt{2Vq/m}$$

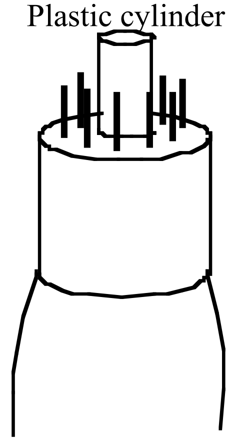
A typical accelerating voltage in a large TV set is around 10,000 volts. Using the charge and mass of the electron in the above gives:

$$\text{Approximate electron speed, } v = \sqrt{2x10^4\,(1.6x10^{-19}/9.1x10^{-31})} = 10^8 \text{ m/sec}$$

This is approaching the speed of light and although the Standards do not address special relativity, it is interesting to note that even in an ordinary TV set, relativity can play a role. One of several links on the web to "electron gun CRT" is:
http://electronics.howstuffworks.com/question694.htm

**Exercise extreme care with old Cathode Ray Tubes:**

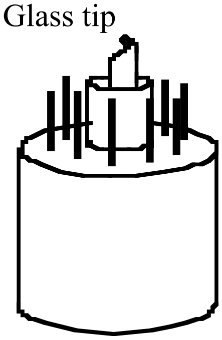
Plastic cylinder



A valuable object to have to show your class is the electron gun from an old TV set or from an old Oscilloscope. However, breaking an evacuated CRT can be dangerous! The following is only an outline of a possible procedure:

1. Place the entire tube inside of a metal trash can face down. Cover all but the rear end where the electrical pins are located with a heavy cloth.
2. The plastic cylinder with the pins sticking out of it will probably have a large center cylindrical plastic extension. (See illustration on the right.)

Glass tip



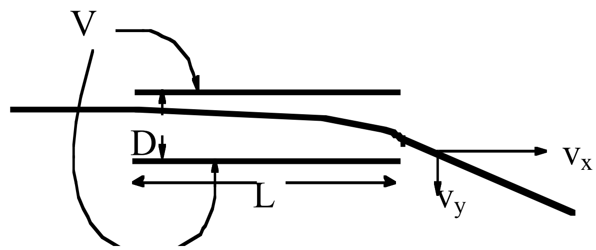
3. Using a hacksaw, carefully cut around the plastic extended cylinder being careful not to have the blade touch the glass tip on the inside. (This glass tip is where the air was evacuated from the tube and then was sealed off with heat in the final construction of the tube.)
4. Place a long metal rod against this glass tip and standing some distance away from the end of the tube, use a hammer to tap the rod breaking the glass seal.
5. You should hear a loud hiss as the air refills the tube. Now that the air has been returned to the tube, you can safely break the remaining glass away from the gun.

Some might feel that the above should never have been discussed but if you are brave, your effort can result in a nice classroom exhibit. Using the above procedure, we have never experienced a mishap.

The CRT from a TV (or Computer monitor) will not have electrostatic deflection plates since the beam is deflected in these devices using a magnetic deflection “yoke”. If you have an old oscilloscope, the gun will have electrostatic deflection plates that can give a concrete experience to the following discussion.

**The basics of electrostatic deflection and finding the angle of deflection:**

In an oscilloscope, the electrons from the electron gun are fired between deflection plates where the electron beam can be directed to any point on the face of the CRT. There are two sets of deflection plates, one to deflect the beam horizontally and the other to deflect the beam vertically.



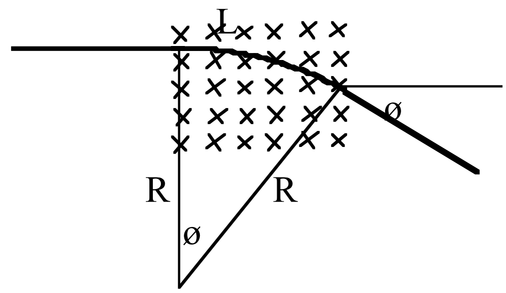

In the illustration, the electron beam from the electron gun enters from the left and passes through the vertical deflection plates and is deflected downward (since the upper plate is negative.) The length of the plates, L is assumed to be large compared to their distance separation, D, making the field between the plates fairly uniform. To find the electric field intensity between the plates, divide the potential difference across the plates by the distance between the plates, or, E = V/D.* The analysis of the motion of the election in the electric field is exactly the same as the analysis of a rock thrown horizontally in a gravitational field. The horizontal component of velocity, $v_x$ remains constant and the vertical component of velocity, $v_y$, increases downward as it is accelerated by the electric field. Using $E = F/q = ma_y/q$ we can find the vertical acceleration of the electron or, $a_y = Eq/m = Vq/Dm$. Next, from the time the electron is accelerated downward we can find the vertical velocity of the electron. But, since the horizontal velocity remains constant, the time the electron is between the plates is $t = L/v_x$ Now we can find the downward component of velocity as the electron leaves the plates:
$v_y = a_y t = (Vq/Dm)(L/v_x)$. Finally the tangent of the angle of deflection will be $v_y/v_x$.

If you have an oscilloscope, the above discussion can be made more real by showing the students how adjusting the vertical and horizontal position controls on the scope control the position of the beam with the horizontal sweep set to a minimum to produce a spot on the screen. The voltages across the horizontal and vertical plates are adjusted with the horizontal and vertical position controls therefore controlling the spot position.

*The fact that E = V/d is an important result that should be understood. In a uniform field the work done to move a charge a distance d against the force of the field is:
W = Fd =Eqd. Dividing both sides of the equation by q gives: W/q = Ed. But, W/q is the potential difference the charge moves through. Therefore, V = Ed in a uniform field where d is the distance moved parallel to E. This result is frequently used and often the intensity of the electric field, E, is not only measured in newtons/coulomb but alternately, often in volts/meter

**The basics of magnetic deflection and finding the angle of deflection:**

In a TV tube or an older CRT type computer monitor, the deflection is accomplished by a magnetic deflection yoke. This deflection yoke consists of two sets of coils that are placed around the CRT near the electron gun and just before the CRT begins expanding to the larger size on the way to the face of the tube. When the electron beam passes through this magnetic field, it will be turned into a portion of a circle but since magnetic fields only act perpendicular to the direction of motion, the electrons will not change their speed. Illustrated on the left the beam enters and is turned into a portion of a circle of radius, R. From the Lorentz force expression and the expression for centripetal force, $F = qvB = mv^2/R$ we can find the




radius of the electrons path in the magnetic field: $R = mv/qB$. Notice that the angle of deflection is the same as the angle swept out by R. If the horizontal length, L, of the magnetic field is known, then it is easy to see that $\sin ø = L/R$ and using the R computed above, the sin of the deflection angle ø, can be determined.