Chapter 25: Electromagnetism

The Principles of Electromagnetism

In the previous sections we have learned many different aspects of both electricity and magnetism, but we have learned them in a disjointed fashion. It was stated earlier that both electricity and magnetism are aspects of the same force: electromagnetism, but that they show their effects in different ways. In this section we will learn some of the ways that electricity and magnetism are linked together and how they are related. These concepts are summarized in a set of equations called Maxwell's Laws. Although Maxwell did not devise all of the laws (in fact he only added one little thing to an already existing law), he did unify them and show their interdependence. If the student had been studying calculus for a few years, all that would be necessary would be for me to list Maxwell's Laws and the student would understand all of the ramifications. Assuming this is not the case, our approach will be different. Instead, I have taken the things that the beginning student needs to know and presented them conceptually as statements called "Principles of Electromagnetism". Each one will be explained and then each one will have a number of "Results", which are the consequences and conclusions that result from each principle. Many of these results will lead to further principles.

As we proceed, it is important to remember that each principle comes from one of Maxwell's Laws. Thus, in a way we are over explaining things. The set of equations that Maxwell compiled are extremely beautiful and powerful. It is hard to overstate their simplicity and beauty. By bringing these four laws together, Maxwell combined electricity and magnetism, predicted the existence of electromagnetic waves (light) and set the stage for our understanding and manipulation of electricity which has led us to our electric based culture and methods of communication. Our simplified "Principles" are merely some of the many results that can come from understanding his equations, they are certainly not all the information that could possibly be gained from these statements.

Below are listed Maxwell's original equations, along with their names which give credit to their original formulators.

Maxwell's Laws of Electricity and Magnetism

$\oint E \cdot dA = q/\varepsilon_0$ (Gauss' Law for Electricity)

$\oint B \cdot dA = 0$ (Gauss' Law for Magnetism)

$\oint E \cdot dS = -d\Phi_B/dt$ (Faraday's Law of Induction)

$\oint B \cdot dS = \mu_0 \varepsilon_0 (d\Phi_E/dt)$ (Maxwell's Law of Induction)[1]

$\oint B \cdot dS = \mu_0 \varepsilon_0 (d\Phi_E/dt) + \mu_0 i$ (Ampere-Maxwell Law)

Ampere's Law

We have already been introduced to the first two basic principles of electromagnetism. Stated again, for the students benefit, they are:

An electric charge in an electric field experiences a force given by F=qE

and

A moving electric charge in a magnetic field experiences a force given by the Lorentz equation: F=q(vxB).

The next principle to discuss is Ampere's Law. The mathematical formula is presented above, but its meaning can be made clearer in words:

A moving electric charge (or an electric current) produces a magnetic field.

We have discussed moving electric charges previously, it now remains to discuss the meaning of current. An electric current is a flow of electric charges. The official definition is that current is a measure of the "flow" of electrons in a path, measured in electric charges per second. It is a vector and its direction is given by the apparent direction of positive charge

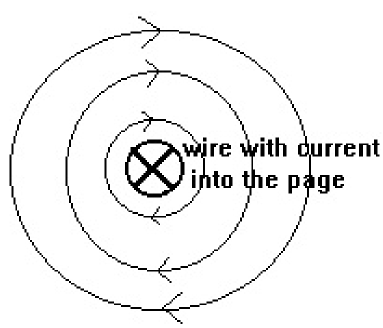
[1] Maxwell's Law of Induction is generally not included in Maxwell's Laws of Electricity and Magnetism, but is shown here for the sake of completeness.

flow. The units are Coulombs/second, which are called Amperes. Thus, a current (i) of 6 Amps is equal to 6 Coulombs per second flowing past a point in the path. Notice two things about current as defined. First, the direction of the current is the direction of positive flow. However, we have learned that electrons are actually the charges that move in most materials. Therefore, the direction of current is opposite to the direction of electron flow. The second thing to notice is that a high current does not necessarily mean that the electrons are moving quickly. Consider a river. In a river, current would be gallons passing a point in a second. You could have a small, fast flowing river or a very large, slow moving river and have the same current in each. It should also be noted that when the Coulomb was introduced as a unit, we said that it was a very large quantity of charge. Thus an Ampere is a very large current. One full Amp is much more current than is generally consumed by most household appliances. One last comment on current before we return to our discussion of Ampere's Law. An Amp is a defined unit, not a derived one. Thus Coulombs are actually derived as 1 C = (1 A)(1 sec).

Ampere's Law is very fertile for yielding useful results.

Result 1: A straight wire carrying current sets up a steady magnetic field around it.

A wire carrying current is essentially a line of moving electric charges, each producing its own magnetic field. These fields reinforce each other and produce a field that looks like this:



The magnitude of the magnetic field at any given point is given by:

$$B(r) = \frac{\mu_0 i}{2\pi r}$$

where r is the radial distance from the wire and μ_0 is called the permeability of free space (it is a property that describes the magnetic nature of the medium in which the field is present).

$$\mu_0 = 4\pi \times 10^{-7} \text{ T.m/A}$$

The direction of the magnetic field is given by the "Right Hand Current Rule". To find the direction, point the thumb of your right hand in the direction of the current and your fingers will naturally curl in the direction of the magnetic field.

EX. W.) What is the strength of the magnetic field produced by a high voltage line (60 A) at a distance of 1 m? Compare this to the strength of the earth's own magnetic field at the surface (B_e = 0.1 mT)

EX. X.) Imagine that the magnetic field of the earth was caused by a big wire running through the center of the earth (it is not), What current would the wire have to carry to achieve the present value of the earth's magnetic field at the surface?

Obviously, there is not a large wire carrying current through the middle of the earth, but there must be something causing the magnetic field to exist. Scientists are not sure yet what causes it, but it must either be a large quantity of moving charges are an extremely large amount of magnetic material.

The result that we have been working with is important enough to be classified as its own principle of electromagnetism.

A wire carrying current produces a magnetic field of concentric circles whose value is given by $B = (\mu_0 i)/(2\pi r)$.

Result 2: A wire carrying current through an external magnetic field experiences a force.

Imagine taking a wire with current passing through it and placing it in an external magnetic field. If we consider a wire carrying current to once again be a line of moving charges, we know that charges moving in external magnetic fields will experience a force. In a wire, all of these force combine together to "push" the wire to one side. The force on a segment of wire is given by:

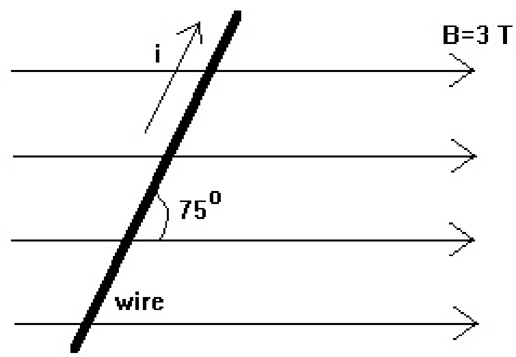
$$\underline{F} = i(\underline{L} \times \underline{B})$$

where i is the current and L is the length of wire, given as a vector and pointing in the direction of the current. Notice that this is a cross product, thus if the wire is parallel to the field lines, there is no force. If the wire is perpendicular to the fields lines there is a maximum force. The magnitude of the force can be found (in the usual cross product way) by:

$$F = iLB\sin\theta$$

where θ is the angle between the wire and magnetic field lines.

EX. Y.) What is the magnitude and direction of the force on the wire below (length = 30 cm, current = 2 A).



While this effect does exist in normal, household wiring (since the wires carry current and are in the earth's magnetic field), the effect is much too small to be seen and is complicated by the fact that the current is alternating.

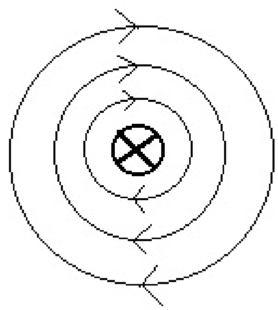
Once again, this result is important enough to warrant being a principle:

A wire carrying current through an external magnetic field experiences a force given by $\underline{F} = i(\underline{L}\times\underline{B})$

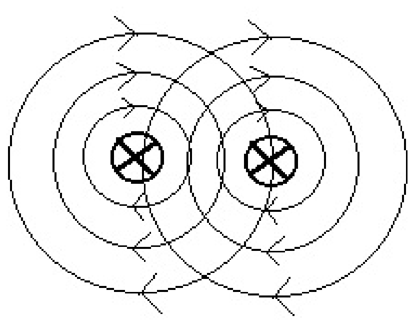
The student should remember this result, however they should also remember that this same result can be arrived at by considering moving charges in magnetic fields (as a matter of fact, the astute student should be able to derive this equation using the equation for the Lorentz force and a little logic).

Result 3: Two parallel current carrying wires exert forces on each other.

If we consider results 1 and 2 taken together, we can easily see that they can combined to produce result 3. Result 1 told us that a current carrying wire will produce a magnetic field around it as seen below:



Now imagine that another wire was placed near the first one. This wire would be immersed in the magnetic field of the first and would then feel a force. However, it would create its own field that would put a force back on the first wire.



We can calculate the force on either wire by using $\underline{F} = i_2(\underline{L} x \underline{B})$ provided we know the field B created by the other wire. This field is given by $B = (\mu_0 i_1)/(2\pi d)$ where d is the distance between the two wires and i_1 is the current of the first wire. Combining these and assuming that the wires are parallel, we get:

$$F = \frac{L\mu_0 i_1 i_2}{2\pi d}$$

Which is an equation for the force between two parallel wires of length L. By using the right hand rule, we can see the direction to be towards the middle. Therefore, in conclusion, two parallel wires carrying current in the same direction will attract each other and two wire carrying current in opposite directions will repel each other. The student should take a minute to convince themselves of the directions and also to note the role of Newton's Third Law in this situation. In fact, an excellent test question would be for the student to have to derive the above equation, using results already discussed and then explain in detail why it works out that parallel currents attract and antiparallel repel...

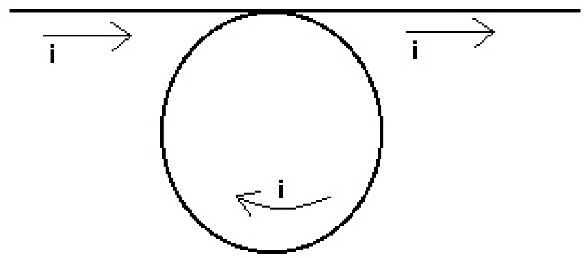
EX. Z.) If you had two parallel wires carrying identical currents, what current would be necessary for there to exist a force of 0.25 N per unit length of wire if they are spaced 15 cm apart?

One quarter of a Newton is a reasonable force to measure and the above problem should have shown you that it requires a very high current to produce a measurable force. Once again, these forces exist in your home, but not in noticeable quantities.

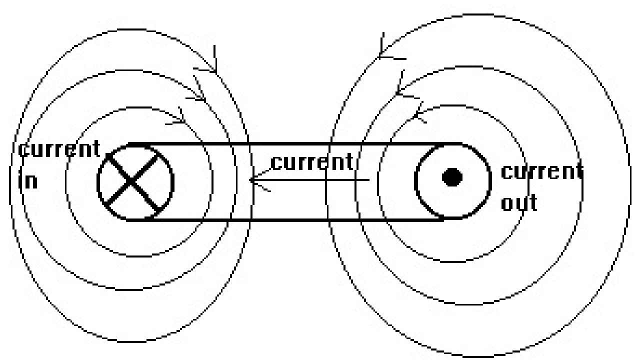
EX. AA.) A copper wire (density: 8.9 g/cm^3) with a diameter of 0.8 cm carrying a current of 0.2 A is to be suspended in mid-air by placing it 10 cm above another wire carrying current. How should the currents be arranged and what current should the other wire have passing through it?

<u>Result 4:</u> A current loop acts like a bar magnet.

Recalling result 1 (a wire carrying current sets up a magnetic field around it), imagine what would happen if such a wire were wound into a circular loop.



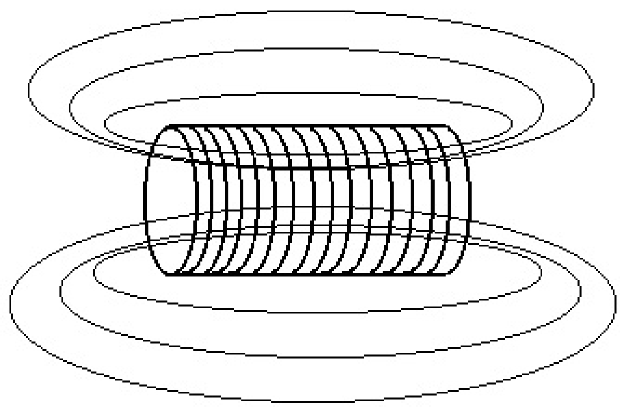
The magnetic field lines in the center would all be pointing down (into the page) and on the outside they would all be pointing up. If we imagine viewing the loop from the side it would look something like this:



We have seen such a field before, it is the simple magnetic dipole field, the same type of field created by a simple bar magnet. <u>Therefore, a current loop acts exactly like a bar magnet.</u> You may remember this result from middle school science when you wrapped a wire around a nail and made an electro-magnet.

In fact, you realize now that the nail was unnecessary. All that was needed was a current loop. The nail is added to make the magnet stronger. By placing a ferromagnetic material in the center, the material itself becomes magnetic, adding to the effect. Other ways to make the magnet stronger would be to make more coils or increase the current. Adding more coils does not always make the magnet stronger, however, since more coils means longer wire, which means more resistance. Besides that, more coils eventually make the wrapping so thick that any added on the outside contribute little to the overall effect.

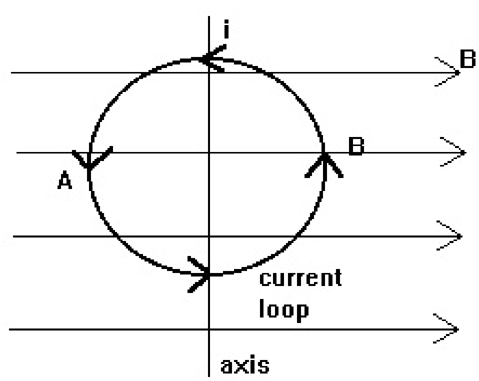
A wrapping of many coils in physics is called a solenoid and resembles a hollow cylinder. The field of a solenoid is shown below.



A coil of wire with current produces a magnetic field similar to the one produced by a bar magnet.

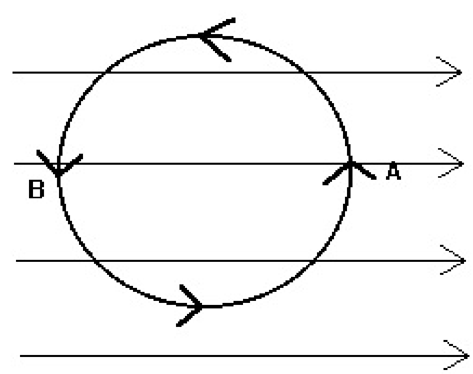
Result 5: The electric motor.

If we consider the past result and use a little imagination, we can arrive at the concept of the electric motor. Imagine a closed, special conducting loop of wire with an electric current running through it. For the sake of simplicity, imagine a perfect



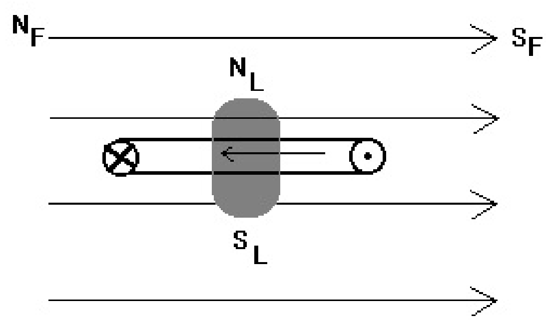
wire where the current would never decrease, but continue to run around and around. Now, place this loop in an external magnetic field.

In this case, we notice that at points A and B, the charges are traveling perpendicular to the magnetic field and thus will experience a force. At point A the force will be up, out of the page and at point B it will be into the page. The points along the labeled axis will have not have any force since the charges are moving parallel to the field. This will cause the loop to rotate around the axis. If we think about this for a while, we will see that an interesting thing happens after the loop has made one half turn. the situation will now look like this:



Now side A is on the right and B on the left. Side A will now be pushed up, and B down, the loop will return to its original position. In such a case, the loop will oscillate back and forth in simple harmonic motion. This is not a very useful motor (unless it is to be used for an egg beater). The problem is resolved by either switching the magnetic field at just the right instant, or more practically, switching the current direction at the right time. If the current direction were switched, side A would continue to be pushed down, while B would be pushed up and the loop would go in a complete circle. Reversing the current is done one of two ways. The most common is simply to use current that reverses itself every so often (called alternating current) or to use a system of "brushes and commutators" that physically switch the connection between the motor and the battery every half turn.

There is an alternate explanation for how a motor works that is not quite as accurate, but is perhaps easier to understand. Consider the loop in the field again, this time viewed from the side.



In this case, we remember that the current loop acts like a bar magnet, represented in light grey in the center, with its north and south poles shown by N_L and S_L (for loop). It is immersed in a field that also has a north and south as labeled. This would cause the bar magnet (loop) to rotate 90^0, and then its rotational inertia would carry it the rest of the half turn. At that point it would rotate back. Our problem now becomes reversing the poles of the magnet at the proper time.

In a real motor, many improvements are made over this simplified version. In large motors, electromagnets are used to create the magnetic field and many, many loops are used instead of one. Of course the loops are not super conducting and there is some energy loss to friction. Besides this, there must be room for the pole attached to the loop (to connect to what is being turned) and some way for the electricity to get into the loop.

Faraday's Law

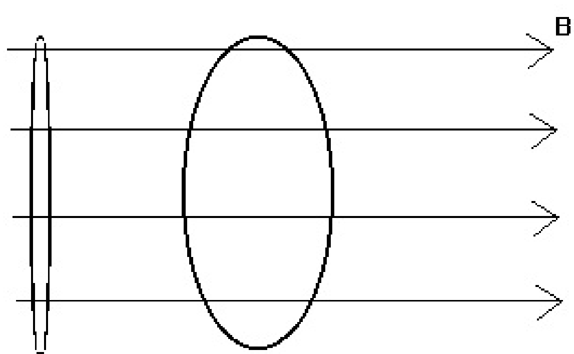
Ampere's Law told us that moving electric charges create magnetic fields. In the mid-1800s, two men noticed an interesting symmetry. Michael Faraday wondered if it was possible for magnetism to create electricity. He tried inserting a magnet into a coil of wire, wondering if electricity would come out (since electricity in a coil would produce magnetism). He did not find what he expected. Instead, he noticed that electricity was produced only when the magnet was inserted or removed. When it was just sitting in the loop there was no output. Thus he developed the principle of electromagnetic induction (along with Joseph Henry, who did many similar experiments). The mathematical law of induction has been stated already, in words it says:

A changing magnetic field creates an electric field.

There are many different ways to phrase this law and each is important because it points out a different aspect of induction. Another way of saying this is:

If the amount of magnetic field that passes through a wire loop changes, an electric current is produced in the loop.

Two notes should be made before we begin looking at applications of this principle. The first is that the amount of magnetic field that passes through a loop is often called the magnetic flux. Flux is actually the product of field strength times the area of the loop that the field cuts through. It is important to notice that the flux can be changed in two ways. You can either change the field strength or change the area of the loop that the field passes through. Consider the case below. On the left, the loop is perpendicular to the field and on the right it is



at some angle. Even if the two loops are identical, the amount of flux is different since the two loops present different areas to the field.

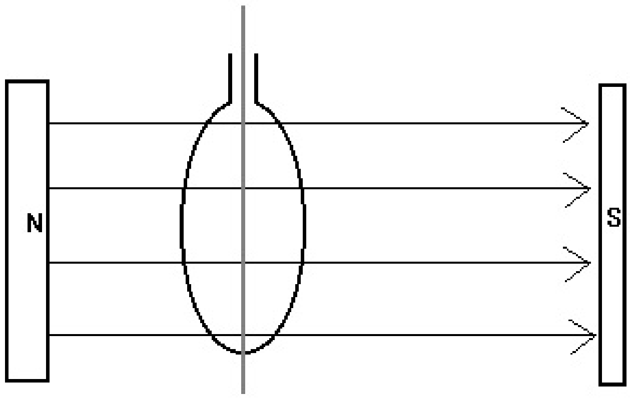
Thus there are three ways to change the magnetic flux: change the field, change the loop size or change the orientation of the loop with respect to the field.

The second comment to mention is that the mathematic form of the law tells us that the electric field produced (the current) is directly proportional to the <u>rate of change of the magnetic flux</u>. Notice it is proportional to the change of the flux, not the flux itself. If you have a strong magnetic field, that does not guarantee that you will produce a strong current in the loop. You must change the magnetic field quickly. Also, to keep the current going, you must continually change the magnetic flux.

Suppose you wished to produce an electric current with a wire loop and a magnetic field. You have three choices. Changing the size of the loop is awkward, continually changing the magnetic field is also difficult (you can only reduce it to zero or keep making it bigger) thus the easiest way is to change the orientation of the loop in the field. This leads us to result #1.

<u>Result #1:</u> The electric generator.

Consider the set-up below. We have a wire loop in a magnetic field (created perhaps by two magnets arranged as shown) and the loop ends in two leads that we use to measure the current.



If this loop is continually spun around the grey axis, we will continually be changing the magnetic flux through the loop and we will continually be creating a current. This is the principle of the electric generator. In order to create useful electrical current (like the kind that is available in your home) the power stations have huge loops of wire rotating in magnetic fields (naturally they are improved over this simplistic design, but the concept is the same). Notice the symmetry here between electricity and magnetism. If a current passes through a wire, it makes a magnetic field. If a magnetic field changes, it produces current. Also notice how the generator and the motor are the same device. If you put electricity in, the loop spins, if you spin the loop, electricity comes out.

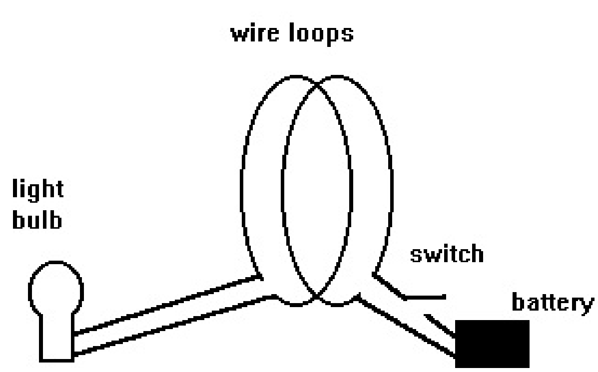
The astute student might have already noticed a slight problem with our generator, by recalling that there was also a problem with our motor. The problem was that the current needed to change directions every half turn in order for the motor to go in a complete circle. This same situation also occurs in the generator, but in reverse. According to the set-up described, the electrical current that comes out of our generator will change directions every half turn. This can be understood in the following manner: As the loop goes from perpendicular to parallel to the field, the amount of magnetism passing through the loop decreases. As the loop goes from parallel to perpendicular to the field lines, the amount of magnetism in the loop increases. Since the current is proportional to the change of the magnetic field, the current will increase, decrease, change direction and increase and decrease again.

This type of generator is called an alternating current (AC) generator. If we wished to produce DC, we would need to add a number of modifications to this design. Instead, what we do is use alternating current generators and alternating current motors. Our original motor design will work quite well when hooked up to a AC generator (recall that one solution to the motor problems was to use current that switches directions automatically). Part of the reason that we use AC current in our homes is because it is easier to produce and use (in motors at least) than DC or direct, one directional, current. The other reason is that it is safer.

Before we move on to the next result, I would like to take a moment to stress something mentioned earlier. Recall that Faraday's law says that a changing magnetic field will create an electric field. Our discussion up to now has focused on changing magnetic fluxes (the field through a loop) and electric currents. However, the law says that changing magnetic FIELDS create changing electric FIELDS. Thus no loop is actually necessary. If we simply change the magnetic field through an area, we will create an electric field in the area. However, recall that fields are the result of one thing and that thing is never affected by its own field. Also recall that fields cannot be seen and it is debatable whether or not they exist. We talk about the wire loop simply because to notice the presence of an electric field, we must have something (in this case, electrons in the metal) that will react to the field so that we know it is there. The wire loop is a kind of instrument we use in our explanations to demonstrate the presence of an electric field.

Result #2: Induction.

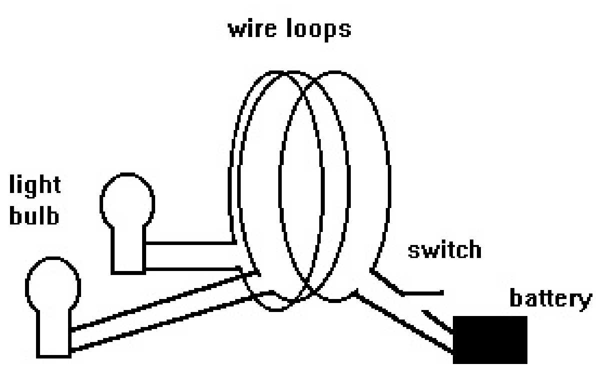
Now consider the setup as shown below. We have two wire loops placed near, but not touching, each other. The first is connected to a battery with a switch and the second is connected to a light bulb.



If we throw the switch, an interesting thing happens. The electrical current surges through the wire, creating a magnetic field around the first loop. Since this field is changing (because of the surge in current from zero to some value), the second loop finds itself in a changing magnetic field and a current is created in the loop which can be detected by a momentary glow in the light bulb. What we have actually accomplished is the transference of energy from one place to another without contact. We got our electricity to "jump" across the gap between the loops. This process is called induction. Induction refers to the creation of electrical energy in one situation by a changing magnetic force from another object. In this case, the changing magnetic force is also produced by electricity. Notice however, that the current is only created when the switch is either flipped on or off. Once the switch is activated, the bulb would glow dimly at first, then go out once the current reached its maximum level and stayed there. If it were then switched off again, the bulb would glow momentarily as the current in the first loop went down to zero. To produce electricity in the second loop, we need a changing magnetic field, and this only occurs if the current in the first loop is changing. If we were to connect this device to an alternating current (such as our wall outlets), the student should be able to see that the process will continue over and over again, creating a constant (but alternating) current in the second loop and that would cause the bulb to glow continuously.

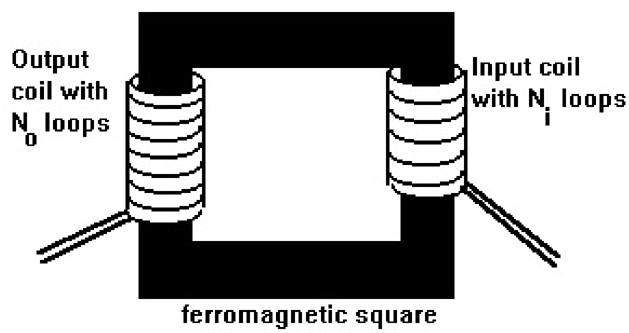
Result #3: The transformer.

Using the previous result, we can imagine a setup as shown below. Here we now place two loops on the left hand side.



In this case, we have two loop with light bulbs and when the switch is thrown, both bulbs will glow, but not as brightly as the first bulb did.

We can light two bulbs because we will find that the two loops on the left end up giving us twice the voltage as in the first situation. However, electrical power depends on voltage and current, thus although we get twice the voltage, we only get half the current. In this manner the conservation of energy is not violated. The device shown above is what is called a transformer. It allows us to send in a certain voltage on one side and get out a different voltage on the other. By changing the number of loops on either side, we can get out a higher or a lower voltage. This ability to easily step up or step down voltages was another reason why AC current was chosen for our homes (transformers only work on AC current. Why?). A typical transformer is shown below.



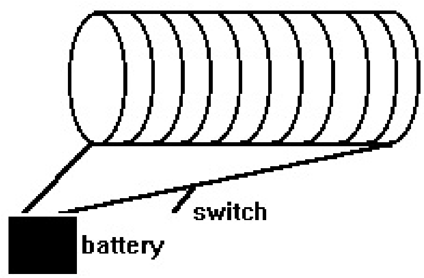
In such a transformer, a large square of ferromagnetic material is used to "guide" the magnetic field from the input side to the output side. On each side is a solenoid, or coil of wires. The number of loops, or turns, in the solenoids determines the output voltage. The output voltage is in a simple ratio with the number of turns and the output currents are in reverse ration to the number of turns.

$$N_i/N_o = V_i/V_o = i_o/i_i$$

The above equation is useful when working with transformers. The type of transformer shown is exactly the type that is used in power lines. It is more economical to send electricity to your house at very high voltages, but such high voltages are dangerous and unpractical in the home. Therefore, it is stepped down by a transformer before it enters your home. Transformers are also used in appliances to alter your house current to fit their needs.

Result #4: Self-Induction.

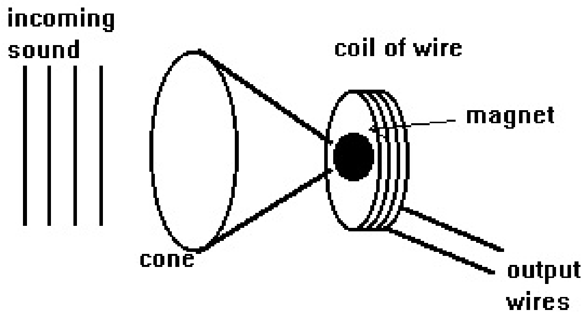
Consider a coil with many turns hooked up to a battery as shown. If we turn the switch off, what happens?



In this case, the current will change to zero, causing the magnetic field created by that current to change to zero. But now we have a changing magnetic field inside a wire loop. This will create a secondary voltage in the wire, not caused by the battery. The process is called self-induction, where a voltage is produced in a wire by a change in its own current. If there are enough loops, or if the original current was very high and changed quickly to zero, this self-induced voltage can be very potent. Potent enough to cause a spark to jump across the switch. This is called Back-EMF and this back lash effect is the reason you are told never to just yank a plug out of a wall socket without turning the device off. If you are using something that is drawing a lot of current, such as a vacuum cleaner, the back-emf might be enough to shock you. Often appliances have devices built in to prevent this from happening (how do you prevent this from happening?).

Result #5: Speakers and Microphones.

One interesting practical application of these principles is the operation of speakers and microphones. When you speak or play music, you are actually setting up vibrations in the air. The vibrations in the air reach a listeners ear and their brain turns these vibrations back to speech or music. A microphone is constructed by having a diaphragm or cone that catches these vibrations attached to a magnet (see diagram). Around that magnet is suspended a coil of wire. As the cone vibrates, the magnet moves through the coil in a pattern identical to the pattern of the sound vibrations. The motion of the magnet produces a current in the wire that matches the sound.



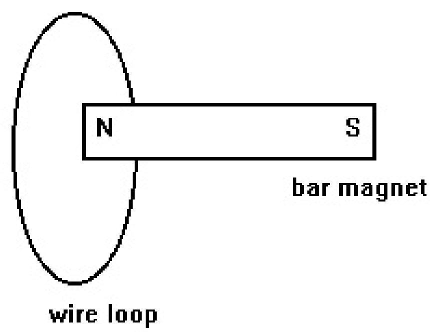
Now imagine connecting another microphone to those wires. The current would come in and now we have a magnet in a current carrying coil. The response would be for the magnet to be moved. This vibrates the cone and the same sound patterns are reproduced. In short, a microphone and a speaker are the same thing. In one, vibrations produce current and in the other, currents produce vibrations that match the original sound. In reality, the two a slightly different, because some design changes are made so that a microphone is better at encoding sound and a speaker is better at reproducing it. Also, an amplifier is generally used to increase the amount of current reaching the speaker (while not changing the pattern of the current). The astute student can consider the conservation of energy for an explanation as to why an amplifier is necessary in order to produce sounds of the same volume as the original.

Cassette Tape Recorders

A cassette tape recorder and player works in much the same fashion as a speaker. Sounds are inputed through a microphone and changed into electrical impulses. These impulses are sent to a very tiny electromagnet that hovers above the tape. The tape itself is covered with very tiny magnetic particles. The electrical impulses switch on the electromagnet, causing the tape to become magnetized in a pattern that matches the music (that is why you should keep magnets away from cassette tapes, it will destroy the pattern preserved on the tape). To play it back, the tape passes by the unpowered electromagnet and magnetized sections of the tape produce currents in the coil of wire (why?). These currents match the electrical impulses that created the tape in the first place and they are sent to the speakers to reproduce the sound. In a very similar manner, video cassette tapes and computer disks store and retrieve information.

Lenz's Law

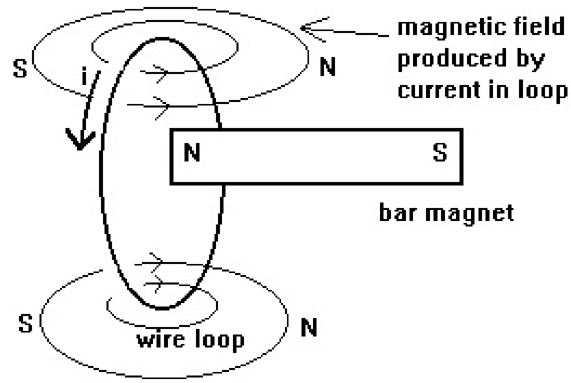
Throughout our discussion we have talked about induction in a very simple fashion, but we have never mentioned what direction the induced current is moving in. Below is shown a loop and a bar magnet, the simplest method for inducing a current. If the magnet is moved either into or out of the loop, a current will appear in the wire loop.



The question is, in which direction (clockwise or counter clockwise) will the current move? Lenz's Law (stated below) answers that question.

An induced current will always appear in such a fashion that it will attempt to oppose the change that created it.

This can be explained in the following manner. The induced current was created by moving the magnet into the loop. The movement of the magnet would be opposed if the loop itself were a magnet with its north pole to the right in the picture (to repel the bar magnets north pole). Thus the current will be produced in such a fashion to create its own magnetic field against the incoming magnet (recall that current loops act like bar magnets). By using the right hand current rule, we see that the current must be counterclockwise.



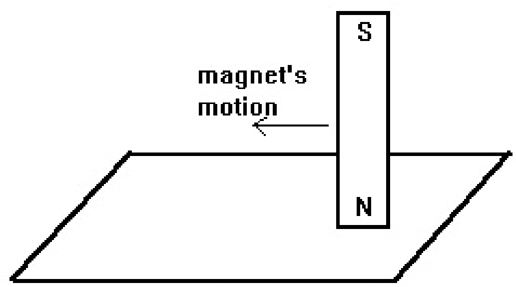
The above explanation may have been a bit confusing, so let us try an alternate approach. By moving the magnet into the loop, the right side of the loop lost some northerly magnetism and the left side gained some ("northerly magnetism" is not actually an accepted term, but it best explains what is going on). Therefore, according to Lenz's Law, the current will appear in such a manner that it will make a magnetic field that compensates for this loss. To make up for the loss of northerly magnetism on the right, it makes its magnetic field with a north pole on the right. In order to have a north pole on the right, the current must go counterclockwise (go back to the previous section about current loops producing magnetic fields if you need to review the explanation of direction of the field).

Using either explanation, we see that the loop will produce a magnetic field that will resist the motion of the magnet. Because of this, there is resistance to moving the magnet into the loop. The induced current will actually try to stop you from inducing it. This makes sense according the law of Conservation of Energy. By moving the magnet, you are producing electrical energy in the loop. This energy cannot be free, there must be a force used to produce it. If we did not have resistance, then pushing the magnet through the wire would produce electricity without any effort, violating the second law of thermodynamics and producing energy for free.

Let us look at applying Lenz's Law to some other situations. Think back to the concept of the Back-EMF discussed earlier. Using Lenz's Law, we see that the induced current must be in the same direction as the original current. The change that produced the Back-EMF was the loss of current. Therefore, the current will be induced to make up for that change.

Applying Lenz's Law to the transformer, we can see that as the right hand side is increasing in current, the left would attempt to compensate by producing a current in the opposite direction. When the right hand side decreases in current, the other side would increase to obey Lenz's law. Thus the currents that come out of a transformer are exactly out of sync with each other. They look like two ocean wave and when one has a crest, the other has a trough. This is called being out of phase by 180°.

Yet another interesting thing about Lenz's Law is its explanation of eddy currents. Eddy currents are currents that arise in materials when the magnetic field through the material is changed. Consider passing a magnet over a piece of non-metallic metal as shown below.



In such a case, the magnetic field passing through the metal will change. This will induce stray "eddy currents" in the material that will create their own magnetic field to oppose the motion of the magnet. The actual direction of the eddy currents is a bit complicated, but their effect on the magnet can be seen. Try passing a strong magnet quickly over a piece of non-magnetic metal and you can actually feel a force resisting your hand.

Eddy currents can cause great problems in some situations. One place they can be seen is in a transformer. Although we mentioned above that eddy currents arise in non-magnetic materials, there is no reason they shouldn't in magnetic materials as well. In our transformer diagram, we said that often a piece of ferromagnetic material is used to guide the magnetic field from one solenoid to the other. With alternating current, this means that the material is constantly undergoing exposure to a changing magnetic material. Thus eddy currents can develop in the material that will actually oppose the change in the current. This is exactly the opposite result we would want since it will cut down the efficiency of the transformer. If you look at a real transformer, you will see that the material (called the core) is usually made up of many thin layers to discourage eddy currents from forming.

Summary of the Principles of Electromagnetism

Listed below are the principles outlined in this chapter. The student should not only know these, but be able to explain them and use them to explain new situations.

- An electric charge in an electric field experiences a force given by F=qE
- A moving electric charge in a magnetic field experiences a force given by the Lorentz equation: F=q(VxB)
- A moving electric charge, or an electric current, produces a magnetic field.
- A wire carrying current produces a magnetic field of concentric circles whose value is given by $B=(\mu_0 i)/(2\pi r)$
- A wire carrying current through an external magnetic field experiences a force given by F=i(LxB)
- A current carrying loop of wire will produce a magnetic field similar to that created by a bar magnet.
- A changing magnetic field creates an electric field.
- If the amount of magnetic field that passes through a wire loop changes, an electric current is produced in the loop.
- An induced current will always appear in such a fashion as to oppose the change that created it.

Assignment #25A

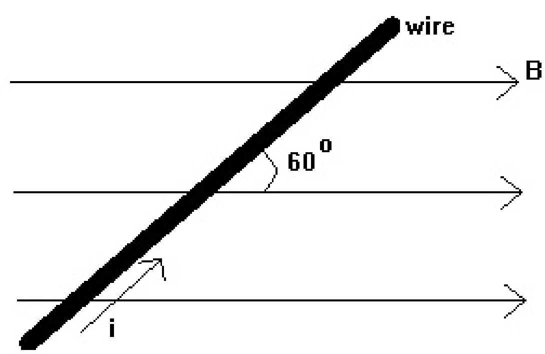
1.) What is the magnetic field at 10 cm from a wire with a current of 12 A?

2.) How far from the center of a wire carrying 4 A is the magnetic field equal to 0.3 mT?

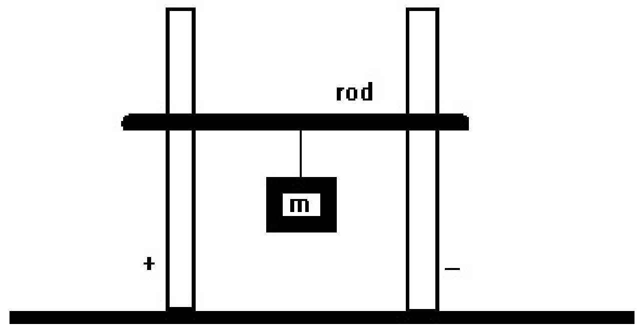
3.) What is the value of the magnetic field at a distance of 4 cm from a wire carrying a current of 450 mA? What is the value at 20 cm? What is the value at 1 m?

4.) Imagine two long, parallel wires carrying equal currents placed 5 cm apart. If you wanted to produce a magnetic field of 0.5 T at a location between the wires, 2 cm from the left wire, what currents must be running through the wires if the currents are parallel? What would be the answer if the currents were antiparallel?

5.) If the wire below is immersed in the B field as shown, what is the force per unit length if the current is 2 A and the field is 9 T?



6.) Consider the set up shown below. A battery is connected to two steel rods that are attached to the floor. Connecting the two rods is a thin (mass negligible) rod that is free to move up and down while still maintaining electrical contact with the supports. A mass m is suspended from the rod and a magnetic field B is pointing into the page. Determine an equation for the current necessary to suspend the rod in mid-air. Find the value of the current given that m=65 g, l=20 cm, and B=5 T.



7.) What is the force per unit length between two antiparallel wires carrying a current of 10 A each with a separation of 9 cm?

8.) Two one meter sections of wire in your house carry currents that flow in opposite directions. If they both carry 10 Amps and they are 0.5 m apart, how much force do they exert on each other ? (magnitude and direction) (B3)

9.) Consider two wires carrying identical currents positioned 5 cm apart. In order for the force between them to be noticeable, say, 5 N/m, what must the current in each wire be? How many electrons must pass through the wire in 10 sec in order to achieve this current?

10.) Two very thick and very heavy wires carrying antiparallel currents are set 50 cm apart and connected by a series of springs (with constant=3 kg/sec^2) attached one spring per meter. When currents of equal magnitude are run through the wires, they push apart and come to equilibrium 52 cm away from each other. What is the value of the current running through the wires?

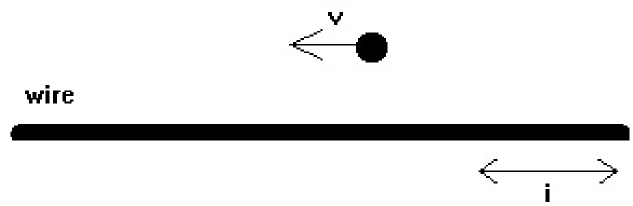
11.) How many turns would be required on the secondary side of a transformer with 200 turns on the primary side to boost 22 volts to 115?

12.) Decipher: "Unawarness of the force of local and national statuatory regulations will not enable one to secure understanding and forgiveness in a court of law." (DNCTHWG).

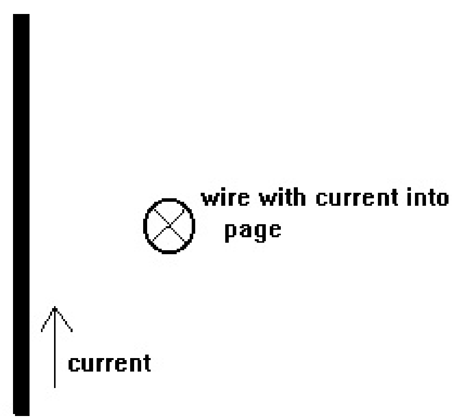
Assignment #25B

In each of the following problems, a situation is described involving the principles of electromagnetism. Explain in as much detail as possible, what will occur in each case. For each explanation, cite a reason.

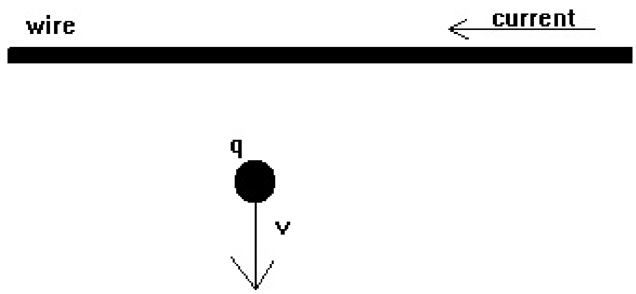
1.) An alternating current runs through the wire as a charge q is set in motion near the wire with velocity v.



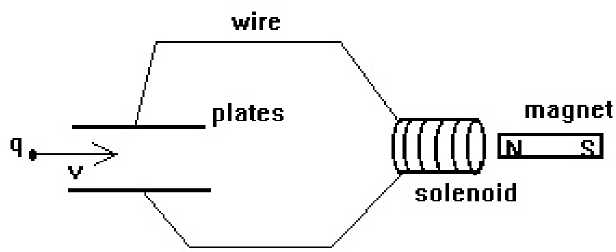
2.) Two wires are placed at right angles to each other and currents are passed through the wires as shown.



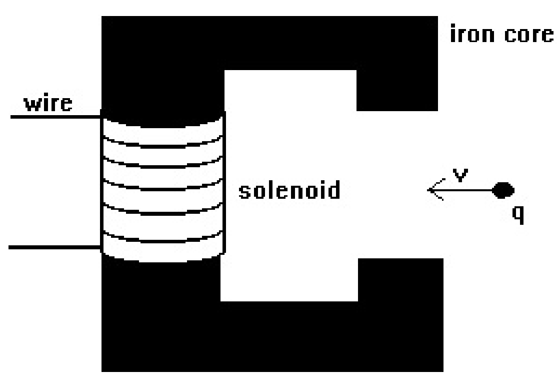
3.) A charge is set in motion with velocity v in the vicinity of a wire carrying current.



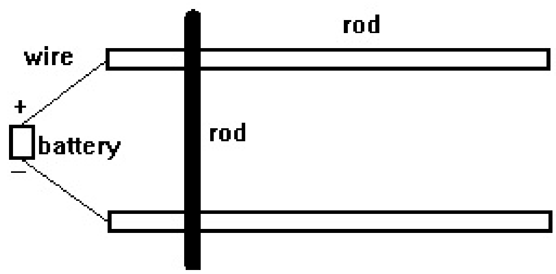
4.) A magnet is pushed through a solenoid which is connected by wires to two metal plates. At the same time, a charge is set in motion through the plates as shown.



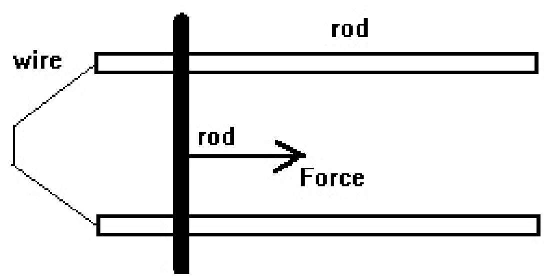
5.) Alternating current is passed through a solenoid which is wrapped around magnetizable core in the shape of a "C". At the same time, a charge is set in motion as shown below.



6.) Two long, frictionless metal rods are positioned parallel to each other and connected to a battery as shown. A third rod is laid across the two and the set up is placed in a magnetic field that comes out of the page.



7.) The set up is the same as the previous problem, except that the battery is left out and the rod is pulled to the right.



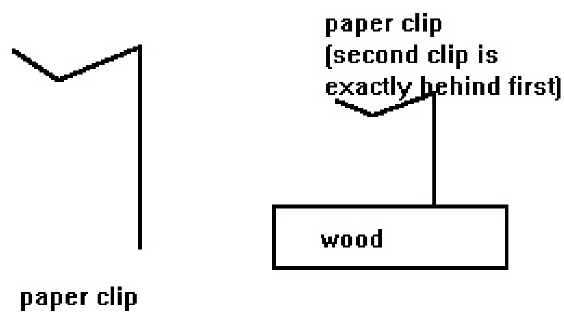
8.) Decipher: "A plethora of individuals with expertise in culinary technique vitiate the potable concoction produced by steeping certain comestibles."

Activity #23 - Constructing an Electric Motor

In this activity, you will use simple materials to construct a working electric motor. As we learned, all a motor needs is a coil of wire carrying current that is placed in a magnetic field.

Materials: copper wire, two paper clips, small magnet, battery, wires.

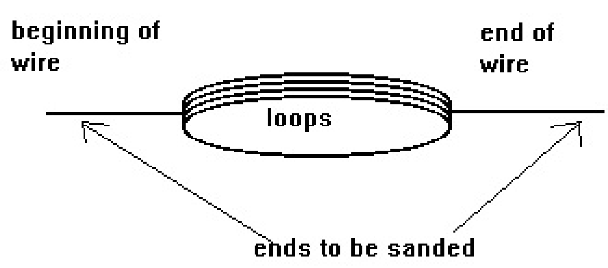
1.) Bend the paper clips to the shape shown below and tape them to the desk so that they are parallel.



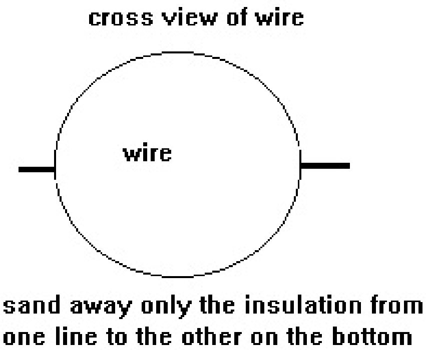
2.) Place the magnet in between the two paper clips, directly below their cradles.

3.) Attach one wire from one end of the batter to one paper clip and the second wire from the other end of the battery to the other end of the paper clip.

4.) Take a piece of wire and fashion it into a loop, with one end of the wire sticking out of each side of the loop (see below). Include about 10 coils in the loop.



5.) Using a small piece of sand paper, sand away the insulations one one half of each end of the wire (although this wire appears to be bare, it is actually covered with a thin layer of clear, plastic insulation). Sand only the insulation on the bottom half of each wire (see diagram)



6.) Place the loop of wire in the arms of the cradles formed from the paper clips. The loop might need a little push, but it should begin rotating.

Questions:

1.) Explain why the loop was rotating.
2.) Why was insulation only sanded from half of the wire?
3.) If the magnet was flipped, would this affect the motor?

Activity #24 - Speakers and Microphones

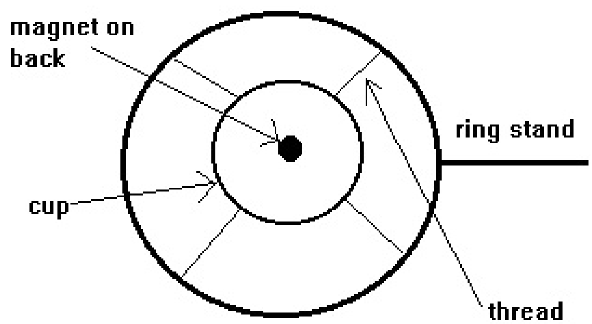
In this activity, you will construct a microphone and use it to investigate the principles of induction. After this, you will attempt to use your microphone as a speaker and make attempts to improve its performance.

Materials: Neodium magnet, thin wire, tape, small paper cup (dixie), two ring clamps, thread or rubber bands, cardboard, oscilloscope or sensitive galvanometer, radio with outputs.

Procedure:

1.) Glue the magnet to the back of the dixie cup in the center. Poke four small holes in the edges of the cup and tie a length of thread to each hole.

2.) Suspend the cup by the threads inside on of the ring stands as shown.



3.) Wrap about seven feet of wire into a coil and attach it to the cardboard. Cut a small hole in the middle of the coil through the cardboard. The coil should be relatively small and the hole should be just slightly larger than the magnet. Attach this cardboard to the second ring stand.

4.) On the wires leading out from the coil, sand the edges and attach alligator lead to each wire.

5.) Assemble the two ring clamps to a ring stand so that the cup sits above the coil. The magnet should be resting in the hole.

6.) Attach the two lead to an oscilloscope.

7.) Speak into your microphone and see if the voice pattern appears. Find two methods to improve the performance of your microphone.

8.) If one is available, attach the leads of your microphone to an amplifier and attach speakers. Speak and comment on the vocal quality of the arrangement.

9.) Now attempt to use your microphone as a speaker by hooking it to the outputs of a radio. Find two methods to improve the performance of your speaker.

Lab #18 - The Principles of Electromagnetism

The goal of this lab is to investigate and demonstrate the principles of electromagnetism. You will carry out a number of small experiments and draw conclusions from each. After you have drawn conclusions, you will identify the principle that each experiment demonstrated.

Note: An electromagnet can be substituted for a regular magnet in these investigations.

Investigation #1:

Materials: Solenoid, power supply, compass, paper.

Take the solenoid and attach it to a power supply, then place the solenoid on a piece of paper. Turn on the power supply and use the compass to map any field that may be present (as was done previously).

Investigation #2:

Materials: Van DeGraff Generator, pith ball, strong magnet.

Put the pith ball near the magnet and observe any effects. Using your finger, "flick" the pith ball so that it goes past, but very close to the magnet. Charge the pith ball with the VanDeGraff generator and "flick" it past the magnet again. Observe very closely and vary the procedure by "flicking" it the opposite direction. Be sure to routinely recharge the pith ball.

Investigation #3:

Materials: Ring stand, sheet of copper, magnet suspended as a pendulum.

With the magnet hanging very close to the table, swing the pendulum and time how long it takes to stop. Check the copper sheet for magnetism with the magnet, then place it between the magnet and the table. Swing the pendulum once again and time how long it takes to come to a stop.

Investigation #4:

Materials: Wires, light bulb, power source, compass.

Attach the light bulb to the power source with the wires, then turn it on. Move the compass around the wire and see if any fields are present.

Investigation #6:

Materials: Solenoids (of different sizes and number of turns), wires, oscilloscope or galvanometer, strong magnet.

For each solenoid, attach it to the galvanometer with the wires and insert the magnet, then remove it. Vary the speed of insertion and removal and comment on all effects.

Investigation #7:

Materials: Iron nail, thin wire, battery, paper clips.

Wrap the wire around the nail a number of times and attach it to the battery (you may need to sand the ends of the wire). Try to pick up the paper clips with the nail. Repeat the procedure by varying the number of coils on the nail.

Investigation #8:

Materials: Van DeGraff generator, insulated conducting sphere, compass.

Charge the sphere from the Van DeGraff and move it past the compass quickly. Observe the effects, if any.

Investigation #9:

Materials: Long wire, galvanometer or oscilloscope, strong magnet.

Attach the wire to the positive and negative terminals of the galvanometer and form a loop in the middle of the wire. Place this loop near the magnet and carry out the following motions: a.) swing the loop back and forth, b.) rotate the loop about an axis, c.) increase and decrease the size of the loop. Record all observations.

Investigation #10:

Materials: Two solenoids, battery, switch, galvanometer.

Attach the battery with a switch to one of the solenoids. Place the other solenoid near the first and attach the galvanometer to the second coil. Throw the switch and observe the galvanometer. Open the switch and observe again. Repeat a number of times, then open and close the switch in a rapid fashion for thirty seconds.

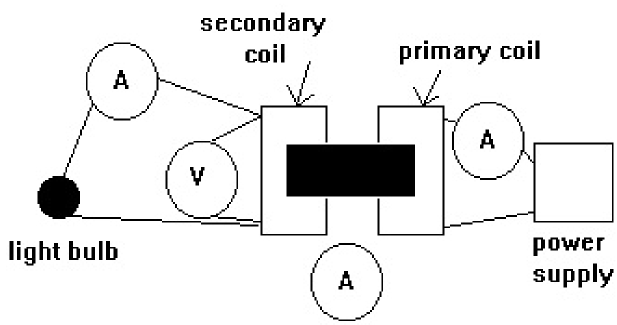
Lab #19 - Transformers

In this investigation, you will manipulate a dissectable transformer, varying the primary and secondary coils and measuring the current and voltage in each situation.

Materials: Dissectable transformer, AC power supply, light bulb, voltmeter and ammeter (must be suitable for AC measurements).

Procedure:

1.) Assemble the circuit as shown.



2.) For the primary coil, use the coil that has the middle number of turns from the coils available.

3.) Set the power supply voltage at approximately 4 volts AC.

4.) Use all the other coils as secondary coils. For each one, record the reading of all the meters and make note of the brightness of the light bulb.

5.) Compare all measured quantities with the theoretical values given by the formulas.

Primary # of Turns	
Primary Voltage	
Primary Current	

Secondary	Secondary Voltage		Secondary Current	
# of Turns	Value	% Error	Value	% Error

Draw conclusions about your results and be sure to explain exactly what is happening in the transformers in terms of the principles of electromagnetism.