Chapter 24: Magnetism

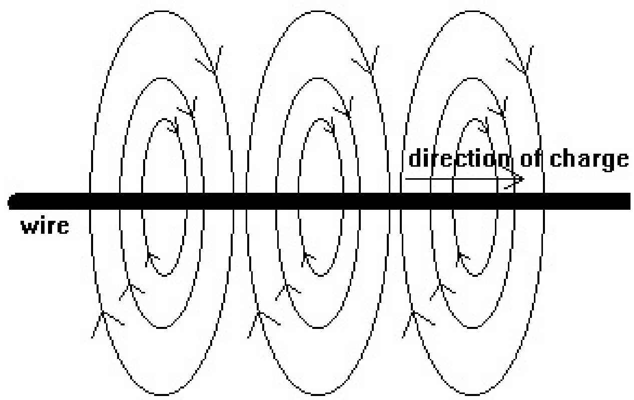
The Magnetic Field

We have discussed the concept of the electric field (and its corresponding topics: force, potential energy, and potential) in some depth and now it is time to begin discussing the magnetic field. Recall, from our discussion of forces, that both the electric and magnetic field are aspects of the same fundamental force; electromagnetism. Both fields are simply different aspects of this one, underlying force. The magnetic field, however, is quite a bit more complicated and harder to understand. Because of this, magnetism is often treated in basic physics textbooks simply on a conceptual level. Even in more advanced books, the qualitative aspects of magnetism are only covered in a very simple way and often approximations are used. Although this seems like a cop-out, it should be said that magnetic fields affect things differently than electric fields and thus need to be examined differently. Most of the important magnetic effects do not require the same type of calculations as electric effects and many of the important aspects of magnetism fall under the category of material science.

One of the main reasons for magnetism's complexity is the important fact that there are no magnetic charges. Unlike gravity (which is a field due to a mass) or the electric field (due to a charge), there is not a characteristic of a particle that directly produces a magnetic field. Magnetic fields are created by charges in motion. If an electric charge stands still, it creates an electric field. If an electric charge moves, it creates both an electric field (which is distorted due to the charges motion) and a magnetic field. Thus magnetism never arises without electric charges and electric fields accompanying it. Often, the magnetic field can be very strong while the electric field is weak, thus it can seem that the magnetic field is standing on its own. This brings us back to the fact that there appears to be no magnetic charges. Because there is no "magnetic particle" (the correct terminology is magnetic monopole), the fields are strikingly different than those created by the electric monopole (a single point charge) or a gravitational monopole (a single point mass). Magnetism is created by moving electric charges, thus in some ways, magnetism can be understood as an electric field viewed from a moving frame of reference.

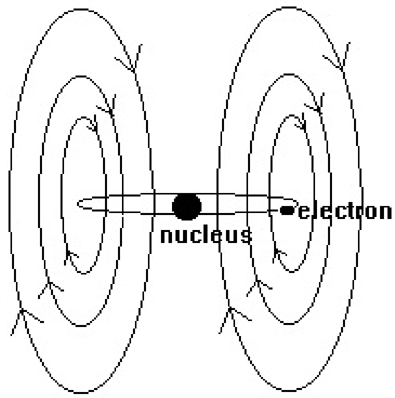
There are three ways an electric charge can move to produce a magnetic field: linearly, circularly or rotationally. The linear motion of an electric charge results in a magnetic field that surrounds the line of motion like concentric circles (or more precisely, concentric cylinders). One excellent example of this would be charge moving through an electric wire. Every electric wire carrying a flow of electricity (a current) creates a magnetic field around it. In fact, this was the first discovery that convinced people that electricity and magnetism were somehow connected. Hans Orstead, a physics teacher, one day happened to be teaching magnetism immediately after finishing a lecture on electricity. On his table he had his demonstrations set up, and he had a compass very close to his electrical wires. He noticed that when he connected the battery to the wires, the compass needle turned away from magnetic north. It was this seminal discovery that led the way to unifying the two effects under the same force.

The field line of the magnetic field around a current carrying wire are shown in the diagram below.

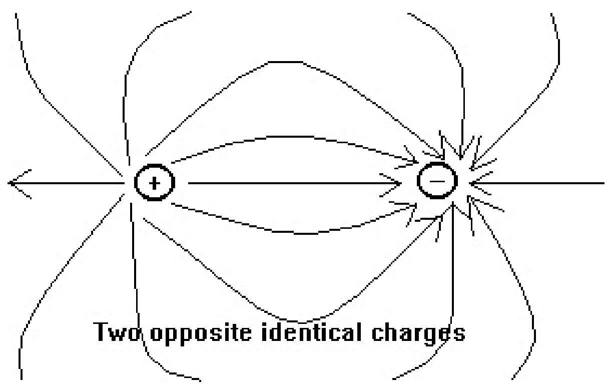


While it is true that these fields exist around all wires carrying current, they are not generally noticeable in your household wiring for two reasons. First, a large amount of charges must be flowing by for the field to be "noticeable" and secondly, since the electricity in your home is AC or alternating current, the resulting magnetic field switches direction 60 times a second.

The second type of motion that can cause a magnetic field is orbital or circular motion. The best example of this would be an electron in orbit around the nucleus of an atom. We should recall that electrons actually exist in clouds, and not as single, orbiting particles, but the approximation can be used to best understand the phenomena. The field created by an orbiting electron looks like this:

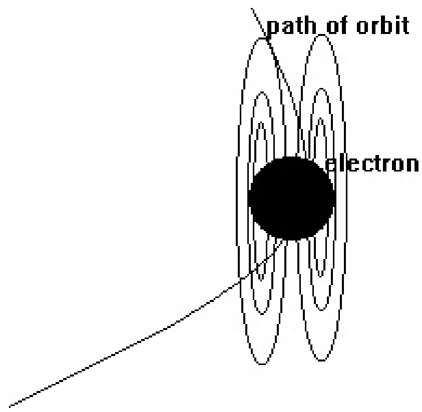


The field in this instance looks like concentric, misshapen "donuts". This shape is very, very important. The field produced in this way is called a dipole field. Notice the resemblance to an electric field created by a positive and negative charge separated by a short distance. That particular field looked this:



If we imagine such a field, and then move the positive and negative charges infinitely close together, we have a magnetic dipole field. Since there are no such things as magnetic charges, a dipole field is considered the simplest possible magnetic field. It occurs often and it essential that the student understand the characteristics and shape of the field.

The third method of motion that was mentioned was rotational motion. We know that electrons "spin" in their orbit much like the earth rotates as is orbits the sun. In actuality, the characteristic of spin for an electron is really not describing the electrons rotation, but it is helpful to view it in that manner. Such a motion results in the magnetic field as shown below:



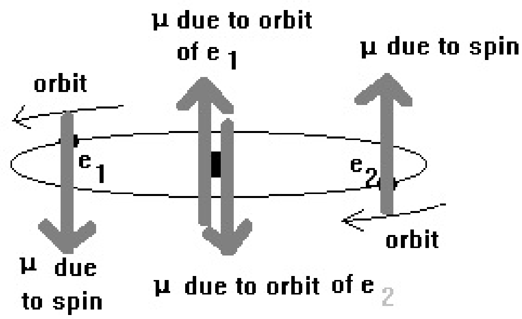
We see that in this case, the magnetic field is once again a dipole field, this time centered on the charge itself. In a piece of material, the rotational magnetic fields tend to be much much greater than those caused by the orbital motion of the electron.

An astute student may have noticed that in all the magnetic fields shown, the field lines are forming loops. This is an important aspect of the magnetic field. If we recall that our field lines must always begin or end on a charge or at infinity, and we recall that there are no magnetic charges, we can see that magnetic field lines should form closed loops.

Since so many magnetic fields turn out to be dipole fields, it is only logical that we should talk about a magnetic dipole moment for magnetism. The symbol for such a moment is usually given as μ and it is a characteristic of the source of the magnetic field. Since there are no magnetic charges, μ is as close as we can get to describing the source of magnetism. It is helpful and informative to consider the parallels between gravity, electricity and magnetism. In this case, μ is the source of a magnetic field, just as m is the source of a gravitational field and q is the source of an electric field. When you ask what is causing a magnetic field, your answer would be the dipole moment μ. Dipole moments can also react to magnetic fields, just as masses and charges can react to gravity and electricity, respectively. However, since the simplest field is a dipole field, and the simplest characteristic is a dipole moment, the simplest interaction is that of a dipole in a dipole field, not always an easy thing to analyze or calculate.

Magnetic Materials

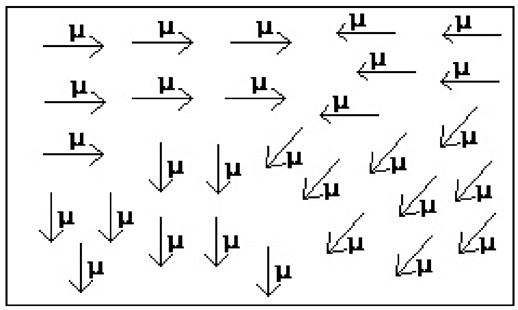
We know from experience that some materials are magnetic, and some can be made magnetic by bringing them in contact with a magnet. Thus we should take a few minutes and discuss what makes a material magnetic. If we think about our previous discussion of the motion of the electrons in an atom, we can see that each electron contributes two dipole moments (one from its orbit and one from its spin) to the overall atom. In most materials, these moments (and thus the fields) contributed by all the different electrons in an atom tend to cancel each other out. The diagram below illustrates this for an imaginary atom.



On this particular atom, all the moments cancel out and there is no overall moment for the atom.

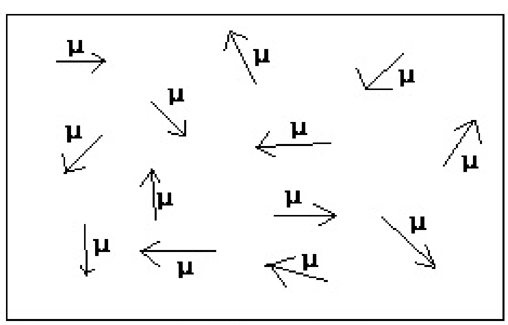
However, often there is some tiny residual moment left over for the entire atom (consider the case for the atom above if one electron were removed). In certain atoms, this moment can be very large due to the position and spin of its particular combination of electrons. This in and of itself is still not significant, since atoms in most materials tend to be randomly oriented and even if each individual atom has a magnetic moment, the overall material might not (again due to cancellations of all the individual moments adding together to equal zero). There are three particular types of magnetic materials where these contributions become significant.

The first and most familiar type of magnetism is called ferromagnetism. This is the strongest form of magnetism present in materials and is what is commonly considered when magnetic materials are discussed. We have already stated that the rotation of electrons contributes most strongly to the magnetism of a material and you may have learned in chemistry that electrons tend to "pair up" with opposing spins. This pairing effect tends to negate the overall magnetic moment of the atom. However, some material contain unpaired electrons (such as iron) due to either an odd number of electrons, or more importantly, a break in the usual pattern of subshell filling in the atom. These atoms tend to have strong magnetic moments and near-by atoms align themselves by a process known as exchange coupling. This process is a complicated (quantum) effect that cannot be explained by ordinary physical means. This causes the atoms in certain regions to become aligned all in the same direction, giving that region an overall magnetic moment. The diagram below illustrates this principle.

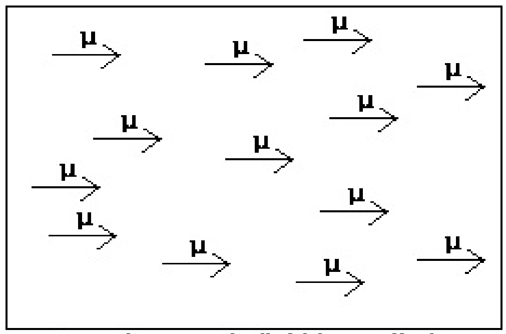


The regions where all the dipole moments are aligned are called domains. Each domain acts like a little magnet with a moment created by the reenforcement of all the little moments in the atoms. In general, these domains will tend to cancel each other out, instead of each atom canceling each other atom. These domains often consist of billion and billions of atoms and the exchange coupling is strong enough that normal collisions of atoms have no effect on the domain.

When a ferromagnetic material is placed in an external magnetic field, all of these domains line up in the same direction and the material becomes highly magnetic. This is the reason that a piece of iron, when in contact with a magnet, acts like a magnet itself. The pictures below illustrate how this occurs, but each arrow represents a domain, not a single atom.

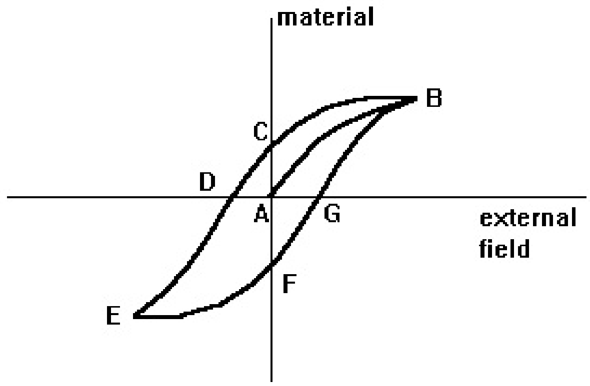


Before external field is applied



After external magnetic field is applied

As long as this field is applied, the domains remain aligned. When the external field is removed, the natural jostling from the motion of atoms causes most of these domains to return to the random states they occupied before the external field was switched on. However, some of these domains remain aligned, thus leaving the material with a residual amount of magnetism (consider the experiment often done in middle school science classes of rubbing a piece of steel in one direction with a magnet - the steel remains magnetized for some time after. This is because the repeated rubbing causes more and more domains to remain aligned.) The phenomena of residual magnetism left over in a ferromagnetic material after an external field is removed is called hysteresis. Each and every material behaves differently under these conditions and a material's behavior is usually represented by what is called a hysteresis curve. On such a graph, the independent variable (x-axis) is the external field being applied to the material and the dependent variable (y-axis) is the magnetic field of the material (how magnetic the material has become). Consider the diagram below:



In this diagram, we begin a point A where there is no external field, and no magnetism in the material. The segments from there represent:

A-B: The external field is turned on and slowly increased, causing the material to become more and more magnetic.

B-C: The external field is reduced to zero, leaving a residual amount of magnetism in the material.

C-D: The external field is once again increased, but this time it is reversed, causing the material to become less and less magnetic, eventually returning it to zero.

D-E: The external field continues increasing negatively, causing the material to once again gain a field.

E-B: The reverse process of B-E.

It is this type of process that is used to store information magnetically (such as on a cassette or video tape or a computer disk). In those cases a magnetic material (the tape) is exposed to a magnetic field (created by the recorder or disk drive) and the material gets a residual magnetic field in a certain spot (or in a certain pattern) that can be reread later.

Although this explains how something can become magnetic, it does not necessarily explain how something loses its magnetism. If we consider the concept of domains, we can see that losing magnetism equates with the disordering of domains. Any process that causes the domains to become unaligned will reduce magnetism. For example, dropping a magnet will reduce its magnetism, as will heating a magnet. Every ferromagnetic material has what is called a Curie Temperature (named after its discoverer, Pierre Curie) where the thermal effects exactly cancel out the exchange coupling which keeps the atoms aligned.

When the Curie temperature is reached, the material no longer exhibits magnetic effects.

The second category of materials are called Paramagnetic materials. If a material that does have some magnetic moment left over in its atoms (recall that often the pairing of electrons result in the overall moment being zero) is exposed to an external magnetic material, all of the atoms will line up with their moments in the same direction (recall our treatment of an electric dipole in an external field). Notice that here we are talking about atoms, not domains as in ferromagnetism. The overall moments of paramagnetic materials are not strong enough to engage exchange coupling, which creates domains. Instead, we deal with atoms individually and have much less of an effect. When all the moments are aligned, the material itself becomes one large magnet and has its own magnetic moment. Although the external field aligns all the moments, they do not often stay aligned due to the collisions of particles in the material. If the external field is shut off, all the moments tend to scramble back to their original positions. Thus the paramagnetic effect is very weak and very temporary. This is not the effect that is normally though of when one considers magnetism (such as steel, etc).

The third type of magnetic material, or effect, is diamagnetism. This is a very, very weak effect that is present in all materials, but rarely noticed. If a material is brought into a magnetic field, the field will actually attempt to force the electrons into an orbit that aligns their magnetic field with the external one. If the electron is not already spinning that way, it will resist the attempt and a slight repulsive force will be produced. Diamagnetism actually causes materials to be repelled by the magnet causing the external field. As was mentioned, all materials are slightly diamagnetic, but the effect is too slight to notice.

Electric Charges in Magnetic Fields

We have learned that a stationary electric charge creates a stationary electric field and that a moving electric charge creates both a magnetic and electric field. If we then consider a moving charge to be a "magnet" we would expect that when an electric charge moves in an external magnetic field, it will be affected by the field. That is indeed the case. When an electric charge moves in an external magnetic field, it experiences a force from that field. This force is called the Lorentz Force and is given by the vector equation of:

$$\underline{F} = q(\underline{v} \times \underline{B})$$

Where F is the force, q is the charge on the particle, v is the velocity of the particle (as a vector) and B is the external magnetic field (B is the normal variable assigned to magnetic fields). Since this is a cross product, a few notes can be immediately made. First, the magnitude of the force is given by

$$F=qvB\sin\theta$$

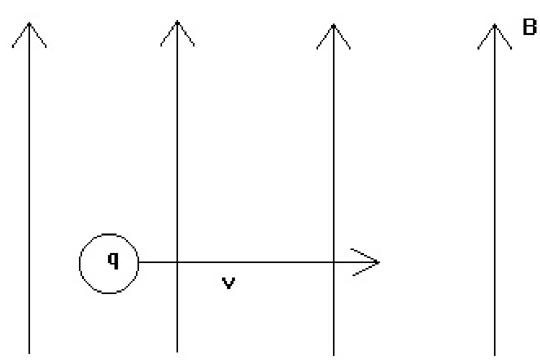
Where θ is the angle between the field lines and the velocity of the charged particle. Secondly, since it is a cross product, the force will always be perpendicular to the plane containing the velocity and the field. As the particle moves, it will be pushed at right angles to both its velocity and the field. In order to illustrate this on two dimensional pages, we should introduce some new conventions.

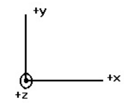
X = an arrow going into the page

• or ⊙ = an arrow coming out of the page

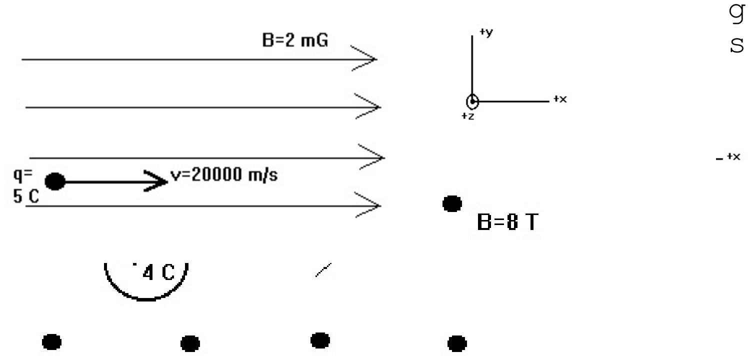
These can be remembered easily by thinking of an arrow being shot from a bow, the point coming at you is out of the page and the feathers vanishing into the page represents a vector going away from you. Besides this notation, the student should also be able to identify directions from a given coordinate system. For example, it is often the practice (on the AP test) for a given problem to come with a given coordinate system. In these cases, the answer is expected to be given by referencing the given system (on the AP test, if a student gets the problem correct, but does not answer according to the coordinates given, they are counted wrong, e.g. answering to the right instead of +x direction). With this in mind, let us do some simple examples of calculating the Lorentz force on a particle.

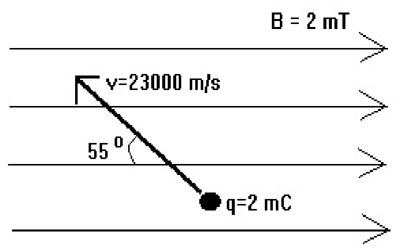
EX G.) Explain the forces acting on the particle in the magnetic field below and give your answer according to the given coordinate system.





EX H.) What is the force on the particle below? (The magnetic field is out of the page.) Answer according to the given coordinate system.

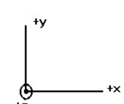




EX G.) Find the force on the particle shown below, answer according to the coordinate system given.

EX GB.) Repeat the above instructions.

The previous examples were almost trivial, but they illustrate a previously discussed important result. The value of the cross product of vxB is directly dependent on how perpendicular v and B are in direction. It is a maximum when the two are perpendicular and zero when they are parallel (according to the sine function, which is in its definition). Some books explain this in the following illustrative explaination: The Lorentz force is dependent on how many field lines the veloci ty vector crosses. For the force to exist, the velocity must cross some field line, the more it crosses, the greater the force. While not technically correct (can the astute studen t figure out why?) this explination is a helpfu l way to visualize what is happening when a charged particle moves in a magnetic field.



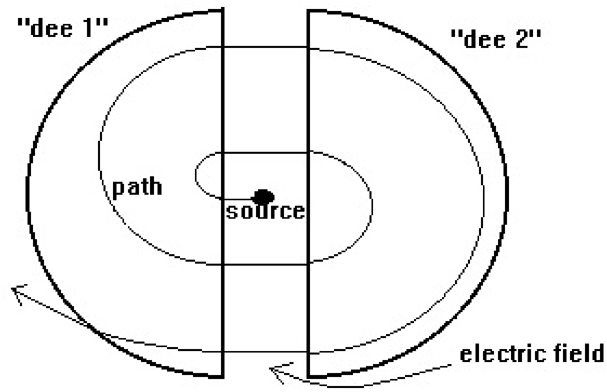
Consider the motion of a particle moving in a magnetic field so that its velocity is perpendicular to the field, as in example H. We know that it will experience a force perpendicular to the velocity, and thus it will accelerate. However, since the force will always be perpendicular to its velocity, it will never speed up or slow down. If we think about this for a moment, we can see that the particle will move in a circle.

EX I.) Derive an equation for the radius of curvature of a charged particle q with mass m, moving at speed v in a magnetic field B and determine the plane of the circle (give your answer in terms of the previously used coordinate system).

The equation derived above is a very important one, and we should take a minute to look at what factors affect the radius of the path. Notice how m and v are on top, thus more massive particles and faster moving particles will trace out larger circles (as one would expect) and particles with more charge or higher external fields will trace out smaller circles.

The Lorentz principle can be used to explain many different situations, especially in the area of particle physics. Particle physics deals with the behavior of very tiny particles, protons, neutrons, electrons and even the much smaller quarks. One common practice in particle physics is colliding particles (usually protons or electrons) and examining what arises out of the collision. Interestingly, when elementary particles collide, they often produce an array of exotic particles (kaons, muons, etc). in their debris. These exotic particles rarely last for more than a millisecond and then they decay into other particles.

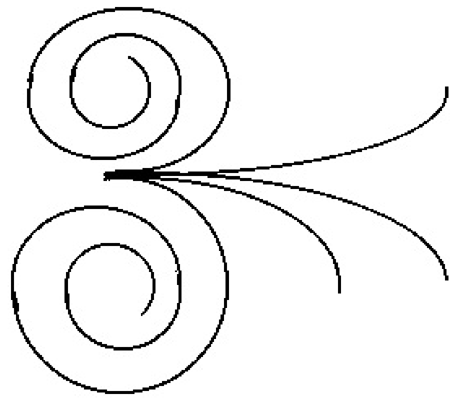
In order to collide particles, it is necessary to bring them up to very high speeds and then either smash them into a target or another fast moving particle. One of the first devices used to accelerate particles up to high speeds was called the cyclotron. It consisted of two "dee" shaped areas that contained strong magnetic fields and a region in between that contained an electric field that could be switched in direction very quickly.



The source gives out a charged particle (proton, electron) and the electric field accelerates it into dee 1. Once in the dee, it is exposed to a magnetic field (out of the page for dee 1) that bends it back into the electric field. The direction of the electric field is switched and the particle accelerates again into dee 2 when a magnetic field (also out of the page) bends it back into the accelerating area. Notice how the particle is only gaining speed in the electric field. The dees are just there to make it pass through the region over and over again (actually many, many more times than have been drawn). Eventually its speed is so great that it leaves the dees altogether and can then collide with a target. There is one main problem with these devices. If the magnetic field is constant, the radius must be very, very large if high speeds (energies) are to be obtained. Creating and maintaining a magnetic field over a large half-circular area is simply impractical. The solution is called a Synchrotron. In such a device, the radius of the spiral is kept constant by varying the magnetic field. These devices are then circular tubes instead of full area circles. Today, many particle accelerators are in operation that use this principle. For example, Fermilab in Illinois has a circumference of 6.3 km.

The next example of how the Lorentz Principle is used in particle physics has to do with interpreting the results of a particle collision. Often the collisions are staged inside a magnetic field and the paths are traced by some sort of monitoring device (historically a chamber filled with gas that would condense behind the moving particles-called a bubble chamber, but these have been replaced by a more modern computerized version called a scintilization chamber). Knowing the magnetic field, certain properties of the particles themselves can be determined by their tracks.

EX J.) Discuss the motion and nature of the particles whose tracks through a magnetic field are represented below. The field points into the page.



Notice how only one aspect can be determined and the other two must be known (of the set m,v,q). In reality, q should either be +1 or -1 (unless you are dealing with quarks or large ions) and v can be determined by the measuring device. Besides the picture, scientists examining these collisions also use the conservation of mass/energy, the conservation of charge and the conservation of momentum to precisely determine the particles involved.

One final aspect of the Lorentz Force should be mentioned. All of our previous examples have dealt with particles that are moving in the plane of the magnetic field, or exactly at right angle to the field. If the particle is not, the path will not be circular. Consider a particle that is moving out of the page at a 45^0 angle and imagine a magnetic field that has field lines parallel to the page. In such a case the particle will spiral upwards contained in a cylinder of radius $(mv\sin 45^0)/qB$. (Why?) Exactly such a principle keeps the charged particles that enter the atmosphere from space locked in what is called the Van Allen

Radiation Belt, an area of space full of spiraling charged particles.

Work in a Magnetic Field

If we consider a charged particle spiraling in a magnetic field, we might ask how much work the field is doing on the particle. This question leads us to an interesting conclusion. Since the force and the motion (whose direction is given by the direction of the velocity) are always perpendicular: <u>the magnetic field is incapable of doing work on a charged particle.</u> I encourage the student to remember this little fact and to think it over and be sure they understand why this is.

Assignment #24

1.) Two charged particles move in concentric circles in a B-field and have the same mass and velocity. If the radius of particle A's path is one half the radius of particle B's path, what relationship exists between their charges ? (B5)

2.) If a charge of 18 C moves at a speed of 9 m/sec through a magnetic field of 6 T at an angle of 35 degrees, what force does it feel ? (B11)

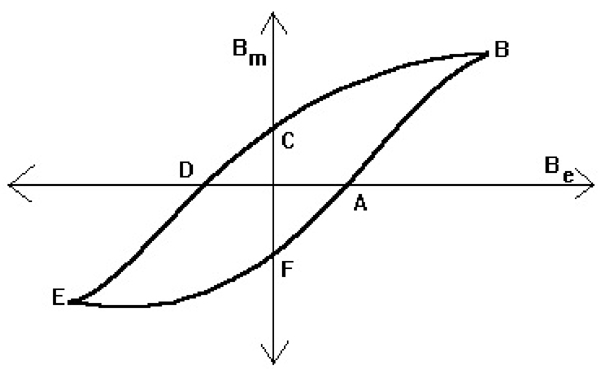
3.) On the hysteresis curve below, which section, point or points represent:

a.) The material producing no magnetic field?

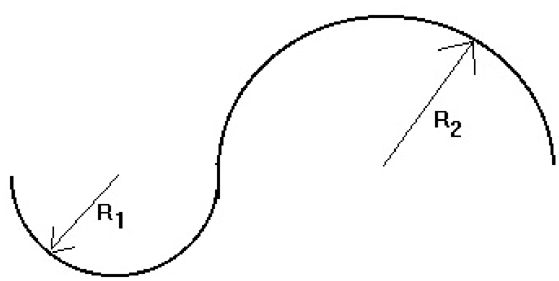
b.) The external field having no value, but the material producing a field?

c.) The material going from producing a field pointing in the negative direction to producing a field in the positive direction?

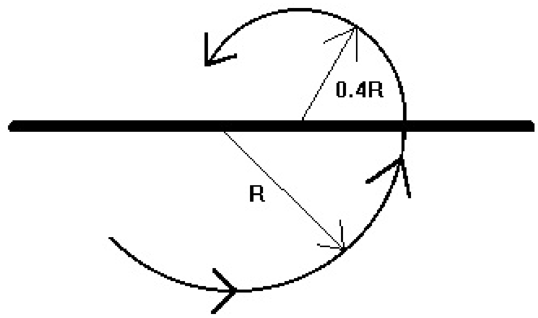
d.) The external field pointing in the negative direction while the material produces a field in the positive direction?



4.) Suppose a particle moves in a magnetic field as shown below. After the particle has completed half a circle, the field suddenly changes. It the new radius (R_2) equals $1.5R_1$, what is the new value of the field compared to the old value?



5.) A proton moves in a magnetic field as shown below. The dark section is a thin film (of negligible depth) that causes the proton to give up some of its energy. What percent of its energy was lost in the film?



6.) A proton in a magnetic field circles with a radius of 10 cm. If the proton has an energy of 150 MeV, what is the strength of the field?

7.) A proton moves in a straight line path through a region which contains both a magnetic and electric field. If the electric field points to the right, the velocity of the proton is $1.5x10^7$ m/sec upwards and the magnetic field has a magnitude of 2 T, what is (a.) the direction of the magnetic field, and (b.) the value of the electric field?

8.) An unknown particle circles in a magnetic field of 4 T with a radius of 35 cm. Determine an equation that must be satisfied regarding the particles mass, charge and energy. (i.e. an equation containing only numbers and the three allowed variables: m, q, E)

9.) Imagine that a proton is moving across a magnetic field of 3 T, making a circle of radius 10 cm at t=0. After 200 revolutions, the radius has dropped to 9 cm. What is the rate of energy loss the proton is undergoing? You may use 9.5 cm as an average radius to calculate the distance traveled and the average of the beginning and ending velocity to calculate the time.

10.) Decipher: "Exclusive dedication to necessitous chores without interlude of hedonistic diversion renders John a hebetudinous fellow." (DNCTHWG)

Activity #21 - Mapping Magnetic Fields

In this activity you will use a compass and bar magnets to map out the magnetic field around magnets. Since we have learned that a dipole will always align itself with a field, wherever we place the compass it will point along field lines.

Procedure:

1.) Place a blank sheet of paper on the table and place a single bar magnet in the center.
2.) Place the compass on the table near the magnet and put a dot at each end of the compass needle.
3.) Move the compass until the south tip of the compass points directly at the dot you made in step 2 for the north end of the compass.
4.) Dot both ends of the compass.
5.) Continue this procedure until the line you are making either goes off the page or back into the magnet.
6.) Connect all the dots with a smooth curve.
7.) Repeat this procedure about six times, or until the field pattern becomes obvious.
8.) Now repeat the entire activity with two more different combinations and positions of magnets.

Lab #17 - Strength of Magnetism

In this lab, you will measure the strength of repulsion between two magnets at different distances and attempt to determine the mathematical relationship between the magnetic force and distance.

Materials: two neodium magnets, clear plastic tube that just fits the magnets, lead weights, ruler.

This lab will be accomplished by securing the plastic tube to the table and putting one magnet at the bottom of the tube. The other magnet will then be placed in the tube so that it repels from the other magnet, being suspened. The distance between the two magnets will be measured, then weights will be added on top of the second magnet to achieve different distances between the two.

Procedure:

1.) Set up the tube securely, using ring stands and clamps and place the first magnet at the bottom.

2.) Using the most accurate and precise balance availiable, find the mass of the second magnet. Record the mass as the first trial.

3.) Place the second magnet in the tube so that it is suspended above the first.

4.) Measure and record the distance between the two magnets.

5.) Add weights on top of the second magnet, until the distance decreases. Record both the total mass and the distance.

6.) Repeat the above procedure until you have 10 data points. Try to make the interval between the distances even, not the differences between the masses.

Total Mass	Measured Distance	Force Between Mags

<u>Hints on Conclusions:</u> Your goal is to determine the relationship between the magnetic force and distance. What is that relationship? Is this what was expected? Did we study anything in a previous chapter that might have led you to believe the relationship should have been something specific? Does this relation hold for other magnets? What are the restrictions on this relationship holding for other situations? In what ways could this experiment be made more accurate? What were the factors that affected the overall accuracy of the experiment? Can you use this information to determine an equation of a kind similar to NULG or Coulomb's law? Why or why not? There is one constant that you know should be present in a magnetic equation, can you use it to determine an appropriate equation?

Activity #22 - Strength of Magnetic Fields

In this activity, you will use a computer interface to measure the strength and variations in magnetic fields.