In the last of three units on electromagnetic theory you will see the first example of a unified field theory. We begin our study with a look into pure magnetic effects. We shall end with a brief historical outline of how electricity and magnetism were merged into a single set of four equations that completely describe all electromagnetic events. Before taking a test on unit 303 you should know the material outlined below:

I. Sources of Magnetism

A. Bar Magnets

B. Electrical Current Sources

1. Straight Currents

2. Solenoids

II. Magnetic Forces

A. Charged Particles with pure Magnetic Fields

B. Charged Particles with Crossed Electric and Magnetic Fields

C. Parallel Currents

III. History of Electromagnetic Field Theory

A. Gauss's Law of Electricity & Gauss's Law of Magnetism

B. Oerstead and Ampere

C. Michael Faraday

D. James C. Maxwell

This unit should take about 7 days to complete. Day 1 will cover all of I.A&B. Day 2 will cover II.A. Day 3 will cover II.B. Day 4 will explore II.C. Day 5 will survey the contributions of people listed in III. Day 6 is a practice test and Day 7 will be test 303.

Warning! Students should begin to expect more spatial and verbal questions with this unit. The following directions are defined for the spatial directions: (1) up the page ↑, (2) down the page ↓, (3) to the right →, (4) to the left ←, (5) out of the page ⊙ and (6) into the page ⊗.

You have already seen how electric fields were used to explain *action at a distance* for charged and neutral objects. You also had lab exercises for mapping electric fields. Since magnetism is another *action at a distance* effect one should naturally wonder about the characteristics of magnetic fields. In this lesson we look at two possible sources of magnetic fields. We begin with a quick comparison of electric and magnetic fields.

Electric Fields

- The symbol for the electric field is **E**.
- Electric field units are volt/meter or Newton/Coulomb.
- Electric fields are created by charges at rest.
- Electric fields begin on positive charges and end on negative charges.

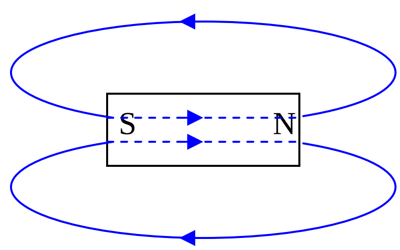
Magnetic Fields

- The magnetic field symbol is **B**.
- Magnetic field units are Teslas, T or 1 N/ (C· m/s).
- Magnetic fields are generated by charges in motion.
- Magnetic fields have no beginning or end; magnetic monopoles don't exist!

You should notice that the extra "m/s" in the magnetic unit suggests relative motion is needed since these are the units of velocity. Charges must be moving towards or away from you in order for you to see a magnetic field. If you run along with moving charges at their same speed and in their same direction you will see the magnetic field disappear and a newly developed electric field taking place! Consider a train hauling a coal car full of electrons. You stand waiting for the train to pass in order to cross the tracks. From your point of view the moving electrons will generate a magnetic field. From the perspective of the locomotive and any passenger on the train, there is no magnetic field. Yet the passengers will detect the hair-raising presence of an electric field.

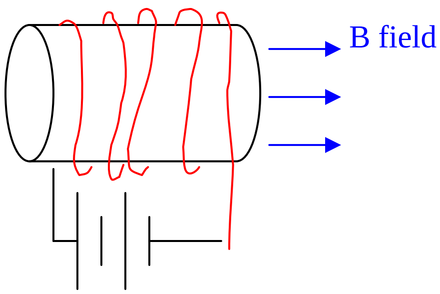
Another oddity about magnetic fields is that there are no places for field lines to end or begin. All magnetic field lines are closed, continuous loops that are circular, elliptical, etc. If you break a magnet in half, you will not get a north pole and a south pole but rather two smaller magnets. Until we can find a particle that is a pure north magnetic charge or pure south magnetic charge, B fields will have no end or beginning.

Bar Magnets & Solenoids



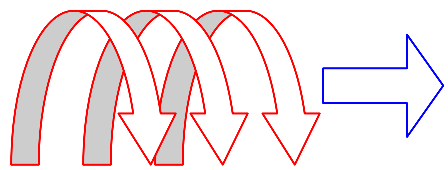
Magnetic fields of bar magnets exit the bar at the north pole of the magnet and enter the bar at the south pole. This is also true for horse-shoe shaped magnets. The lines go from south pole to north pole within the interior of the magnet. Two representative field lines are shown in the figure to the right. The charges in motion within are bar magnet happen to be the orbital electrons of particular nuclei. There are only about 4 metals that allow orbital electrons of neighboring atoms to align. Iron, nickel and cobalt are in the group with iron being the most common. These types of metals are also known as ferromagnetic metals. You are responsible for knowing which way the magnetic field points around a bar magnet.

If wire is turned in such a way as to form a cylindrical coil and then current is passed through the coil you can create a magnetic field similar to that shown in the above figure. This is known as an electromagnet. By reversing the direction of the current in a solenoid you can flip the direction of the magnetic field. In order to determine the direction of a magnetic field within a solenoid one must employ the use of the *right-hand curl* rule. You curl your fingers of your right-hand around the solenoid in the direction of the current flow. Pointing your thumb along the axis of the solenoid will determine the direction of the magnetic field within the solenoid. See both figures below for examples.



Magnetic field points from left to right inside of the coiled wire above. This is because the current flows up the back side and down the front side of the coil.

Right Hand Curl Rule



Thumb points this way. ↑

↑ Fingers curl this way.

Always use your right hand for conventional current flow.
See figure 21-37 of text.

You are responsible for finding the direction of the magnetic field at either end of a solenoid when given the direction of current flow or vice-verse. The magnitude of the magnetic field within the solenoid depends on the current and the number of turns that are wrapped around the cylinder. You can also increase the intensity of the magnetic field strength by placing an iron core within the cylinder. The weak magnetic field due to the electromagnet will align the electron orbits of the iron core. The strength of a tightly wound, air core coil is shown above. The constant for magnetism, μ_o, plays much the same role in magnetism as does the ε_o in electricity. You will not have any calculations using the above equation in this course. The formula is shown for the sake of the curious.

$B = \mu_o n I$
where $\mu_o = 4\pi E\text{-}7$ Tm/A
and n is turns per unit length

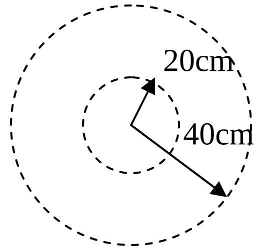
Magnetic Field Due to a Very Long, Straight Current

In the beginning of the 19th century it was thought that electricity and magnetism were two entirely independent concepts in science. In 1820 electricity and magnetism became connected for evermore. Hans C. Oerstead noticed that an electric current flowing through a wire would cause the needle of a magnetic compass to deflect. Moving electrical currents will create a magnetic "tunnel" about the path of the current.

Since electrical currents produce tubular magnetic fields then one should be expected to know how to find the magnetic field strength (B) at any point as well as the direction of the field at any point. The strength of the B field depends on the equation shown in the box to the right. The funny constant, μ_o, again appears in the formula. In this case it is more convenient to combine mu naught with the 2π into a single value of 2 E-7 T-m/A.

$B = \mu_o I / (2\pi r) = (2E\text{-}7)\ I/r$
Where r is ⊥ distance from I
to designated point in problem.

Example #1 (End view of current)

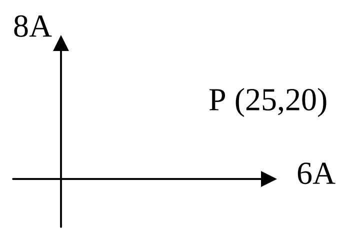


A 6 A current flows out of the page toward you. What is the magnetic field strength at a distance of 20 cm from the current? What is the magnetic field strength 40 cm from the current?

The magnetic field at r=20cm is B = 2E-7Tm/A(6A/0.2m) or 6 μT. At twice the distance, 40 cm from the current, the field strength is only half as strong. You can use the formula again or merely divide the previous answer by 2 to arrive at a field strength of B = 3 μT.

But magnetic fields are vector quantities so we also need a direction. Which way do the magnetic field lines point? In the above example the lines are flowing either clockwise (cw) or counterclockwise (ccw). In order to determine the direction of the field lines you use the right-hand curl rule. In this case, however, the current is straight and the field lines curve. Using your right hand align your thumb with the current flowing out of the page and notice that your fingers tend to curl counter-clockwise. At the 12 o'clock positions on the above circles the magnetic fields are pointing to the left. At the 9 o'clock positions the fields point down. At 6 o'clock positions the field lines point to the right and so forth. See figures 21.27 & 21.28 for more direction examples.

Example #2 (Side view of currents)



A 6 a current flows from left to right as shown in the figure to the right. An 8 A current is almost touching the 6 A current at the origin and flowing up the page. Find the magnetic field strength at point P which is at (25cm, 20cm) from intersection of the currents.

1. At P there is a 6μT field coming out of the page due to 6A current.
2. At P there is a 6.4 μT field going into the page due to 8 A current.
3. The two vectors are anti-parallel so you subtract in order to find the net B field. The total magnetic field at point B is 0.4 μT into the page or 400 nT into the page.

Both currents and particle beams will create "magnetic tubes" as they move through space. The right-hand curl rule is used to describe the direction that the magnetic tubes curl about the path of the charged particle. In the next lesson we see how the magnetic field due to the motion of a single particle can affect its own motion.

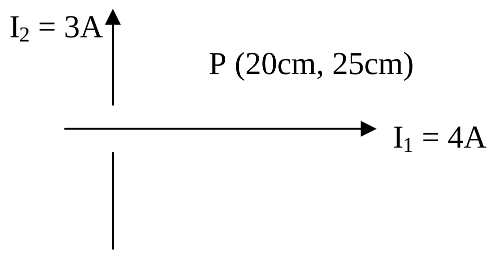
Homework

Use the last boxed equation to get the magnitude of the magnetic field vector. Use your *right hand curl rule* to get the direction. Then all you have to do is add the vectors. For end-view problems the direction of the B field is $\perp$ to the radius from current to P and in the plane of the paper. See next page for problems.

Finding Magnetic Field Strength

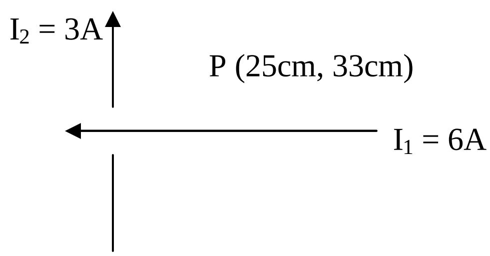
Use B = 2E-7 (I/r) to find the magnetic field at a radial distance from a long straight current. Also, use the **right-hand curl** rule for <u>sources of B</u>.

1. The horizontal current is 4 A and the vertical current is 3 A in the directions shown below.



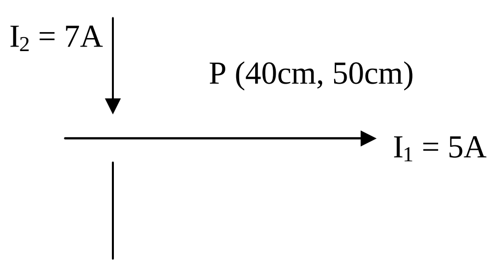
Find the net B at point P.

2. The horizontal current is 6 A and the vertical current is 3 A in the directions shown below.



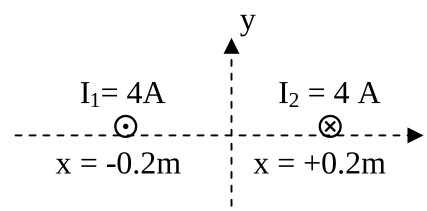
Find the net B at point P.

3. The horizontal current is 5 A and the vertical current is 7 A in the directions shown below.



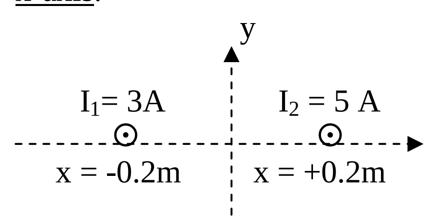
Find the net B at point P.

4. In the figure below currents are show flowing into or out of the page <u>on the x-axis</u>.



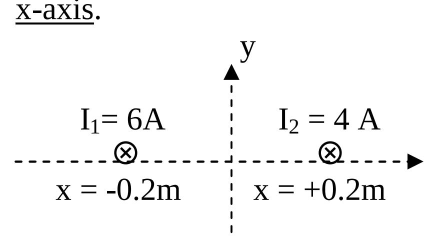
Find the net magnetic field at the origin.
Find the net magnetic field at x=+30cm.

5. In the figure below currents are show flowing into or out of the page <u>on the x-axis</u>.



Find the net magnetic field at the origin.
Find the net magnetic field at x=+30cm.

6. In the figure below currents are show flowing into or out of the page <u>on the x-axis</u>.



Find the net magnetic field at the origin.
Where would B=0 T on the x-axis?

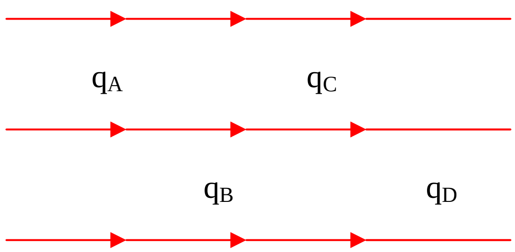
<u>Answers</u>

1. 0.2 μT out 2. 6.0 μT in
3. 5.5 μT out
4. 8.0 μT up; 6.4 μT down
5. 2 μT down; 11.2 μT up
6. 2 μT down; at x = +0.04m

Lesson 3-18 Magnetic Forces on Point Charges

<u>Charge in a Pure, Uniform Electric Field</u>

Consider four, positively charged particles in a pure **E** field as shown in the below.



The above charges have the following initial conditions:

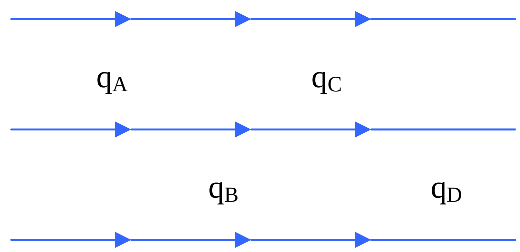
a) q_A is at rest.
b) q_B is initially moving to the right.
c) q_C is initially moving up the page.
d) q_D is initially moving up and to the right at some angle from the vertical.

The resulting descriptions of motion that will be observed are outlined below.

a) The first charge will accelerate from rest to the right. You can use the kinematics equations with initial velocities of zero.
b) The second charge will also accelerate to the right but the initial velocity terms in the kinematics will no longer be zero.
c) The third charge will move along a parabolic path. For constant speed in the "Y" direction use $d = v_Y t$. For constant acceleration in the "X" direction use the kinematics as described in part (a).
d) The fourth charge will move along a parabolic path. For constant speed in the "Y" direction use $d = v_Y t$. For constant acceleration in the "X" direction use the kinematics as described in part (b).

<u>Charge in a Pure, Uniform Magnetic Field</u>

Consider four, positively charged particles in a pure **B** field as shown in the below.



The above charges have the following initial conditions:

a) q_A is at rest.
b) q_B is initially moving to the right.
c) q_C is initially moving up the page.
d) q_D is initially moving up and to the right at some angle from the vertical.

The resulting descriptions of motion that will be observed are outlined below.

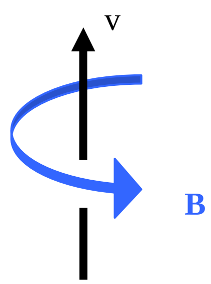
a) Nothing happens and the charge will remain at rest in the **B** field. Boring!
b) The charge will continue to move to the right at a constant speed according to $d = vt$. Boring, part II!
c) The charge will move in a circular motion wrapping around the magnetic field lines. To determine which way the charge circulates use your **right** hand. Point your index finger in the direction of the charge's motion. Point your middle finger in the direction of the magnetic field. Your thumb will point to the direction of the center of the curve as long as it is perpendicular to the direction of index and middle finger directions.
d) Since the velocity has perpendicular and parallel parts the resulting motion is a combination of (b) and (c)- a coiled or helical path will result.

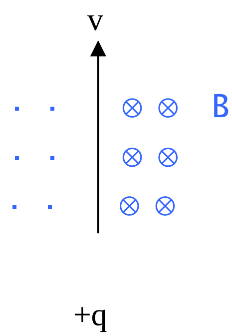
We see that not only does an electric charge have to move as suggested by the units on the last page but now it must move perpendicular to the **B** field lines. Why? Also recognize the resulting path is circular rather than parabolic.

Why Does a Charge Curve When Crossing **B** Field Lines?

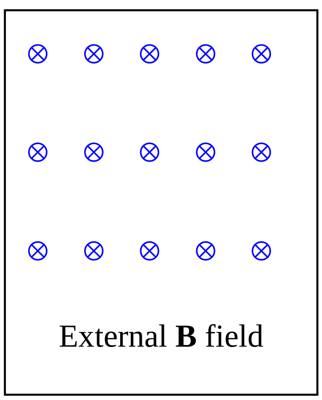
The answer is the key to understanding over half of this unit. As a charged particle moves through space it must drag its **E** field lines along. The motion of the **E** field lines being pulled through space causes the lines to wrap around the path. The resulting wrapped lines are what we perceive as magnetism.

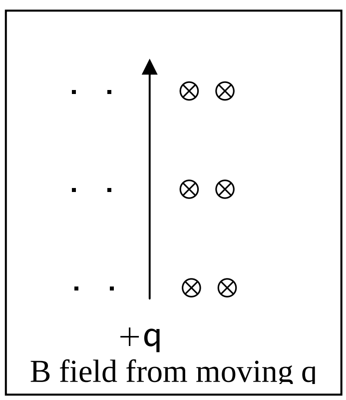
As a charged particle moves through space it will create a tubular, magnetic vortex that curls around its path. Picture the charge leaving a magnetic tunnel in its wake. Both two and three-dimensional representations are shown below. Note that direction of the magnetic curl is reversed for negative charge.

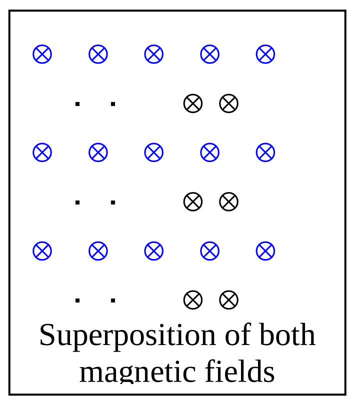




Consider a charged particle moving across a magnetic field from some other source. As the charge moves there is an action-reaction between the magnetic tube of the moving charge and the external magnetic field. Suppose that there is a magnetic field pointing into the page as shown in the left-hand figure below. Now imagine a proton attempting to move up the page through that field. The proton's tubular field would have the form shown in the second figure below. A combination of the two fields is shown below right.







The combined magnetic fields will weaken on the left side of the path since the two fields are anti-parallel. The two fields strengthen on the right side of the path since the fields are parallel. The greater magnetic pressure from the right side of the path will curve the charge to the left. As the path curves the fields continue to add on the outside and partially cancel on the inside. It is the superposition of the external magnetic field and the charged particle's field that makes any charge curve when crossing another **B** field.

The moral of the story is that when charged particles attempt to cross magnetic field lines their paths will bend into circular or semi-circular shapes. The direction of the curve is found using the second right-hand rule. But how big is the curve?

Magnetic Force

The strength of the magnetic force is found using the cross product. In this course we will focus entirely upon directions that are purely perpendicular for the problems solving exercise. The force equation is shown to the right. The subscript for perpendicular direction will be assumed and dropped for the remainder of this lesson.

$\mathbf{F}_B = q\mathbf{v} \times \mathbf{B} = q(v_\perp)B$ where $v_\perp$ is the part of velocity $\perp$ to B.

Homework

For each of the following problems the particles are assumed to be moving $\perp$ to the magnetic field. You can use the other right-hand rule for determining the direction of velocity, B and force. The equations shown below will be helpful:

Magnetic Force

$F_B = q\, v_\perp B$
$F_C = m(v_\perp^2) / R$

By combining the centripetal and the magnetic force we arrive at an equation for the radius of curvature of the path:

$$R = m\, v_\perp / (qB)$$

Equations of Motion

The particle will move along the path at constant speed so d=vt is correct to use here.

1. For a semi-circular path : $\pi R = v\, t$
2. For a circular path: $2\pi R = v\, \tau$

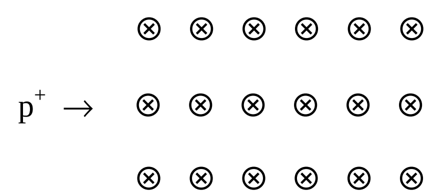
The acceleration of the particle can be found using either of the following:

1. $a = F/m$
2. $a = v_\perp^2 / R$

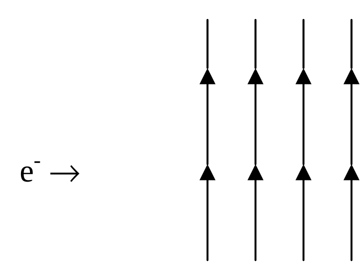
If a charged particle is injected into a uniform magnetic field from the outside it will generally follow a semi-circular path. If the charged particle is created in a magnetic field then it will most likely follow a circular path unless friction creates an inward spiral. We won't go there for this course! The following constants will be helpful:

$m_e = 9.11$ E – 31 Kg $\quad$ $m_p = 1.67$ E -27 Kg $\quad$ $|e| = 1.6$ E – 19 C

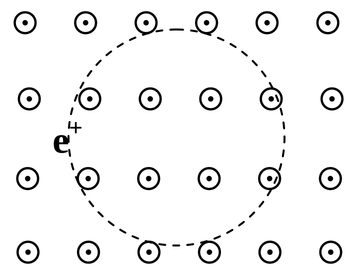
1. A proton moves at 3E+7m/s from left to right across the page into a 50 mT magnetic field as shown in the figure to the right. Determine the magnetic force on the proton, the radius of curvature and the time for the proton to move along the semi-circular path. Which way does the path curve?



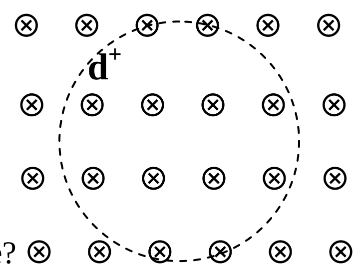
2. An electron is moving at 5E+7 m/s from right to left across the page. It enters a 9mT magnetic field that points up the page. Which way does the semi-circular path curve? What is the radius of curvature? What is the acceleration of the electron? How long is it in the magnetic field before exiting?



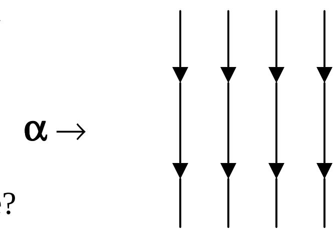
3. A positron is a positively charged electron. A positron is created in a 800μT magnetic field that points out of the page. The radius of curvature for the circular path is 75 cm. What is the speed of the particle? How long does it take to complete one revolution (i.e. period)? What is the acceleration of the particle? Which Way does the positron orbit as seen from above the page? Ignore relativistic effects.



4. A deuteron particle has the same charge as a proton but about twice the mass. A deuteron is trapped in a circular orbit in a 90 mT magnetic field at 2 E+7 m/s. What is the radius of curvature? How long will it take to complete one orbit? What is the net force acting on the deuteron? Which way does the particle orbit as seen from above?



5. An alpha particle has twice the charge of a proton and about four times the mass. An alpha particle is moving at 4E+7 m/s when it enters a 500mT magnetic field. If the particle completes a semi-circular path before leaving the field how long is the particle in the field? Which way does it curve? What is the radius of curvature?



<u>Answers</u>

1. 2.4E-13 N ; 6.26 m; 656 nanoseconds; up the page

2. into the page; 31.6 mm; 7.9E+16 m/s^2; 2 nanoseconds

3. 1.05E+8 m/s; 45 nanoseconds; 1.48 E16 m/s^2; clockwise

4. 4.64 m; 1.46 microseconds; 2.88E-13 N; counterclockwise

5. R = 1.67 m so 131 nanoseconds; into the page

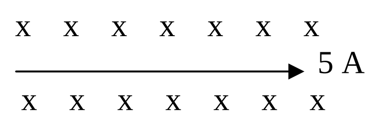
Lesson 3-19 Magnetic Forces on Current Segments

When an electric current flows through a wire there is the result of moving electric charge. If you place a wire of length L in a magnetic field B and pass a current I through the wire there will be a magnetic force provided that all of current or part of current flows perpendicular to the magnetic field. The resulting force is shown in the box to the right. In this course emphasis will be on currents that are already perpendicular to the magnetic field. The direction of the magnetic force is found using the other right hand rule. Place your index finger in the direction of the current flow. Point your middle finger in the direction of the magnetic field and your thumb will be along the direction of the magnetic force.

$\mathbf{F}_B = \mathbf{I}_\perp L \times \mathbf{B}$ or $ILB\sin\theta$

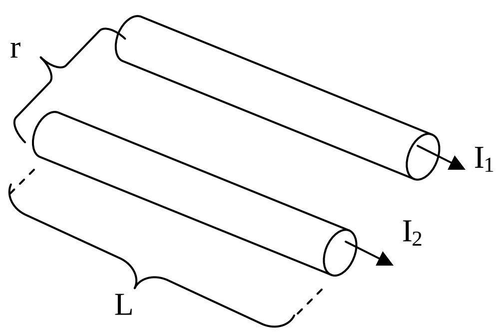
Example #1

A 5 A current flows along a 4m length of wire that is perpendicular to a 300 mT magnetic field. Find the magnitude and direction of the force on the wire as shown in the figure to the right. From the diagram and using the second right-hand rule the force on the wire is "up the page". Using the boxed equation above the force is seen to be 6N.



Forces on Parallel Currents

When two parallel currents are near each other there will be a magnetic force between the wires. One wire acts as the source of the magnetic field that the other wire is attempting to flow through. Consider two wires that are parallel over a distance of L and have their centers separated by a distance of "r" as shown in the figure below. The currents are I_1 and I_2 respectively.



- I_1 produces a magnetic field that penetrates I_2 with a magnitude of $B_1 = \mu_o I_1/(2\pi r)$.
- I_2 experiences a force of $I_2 L B_1$.
- The net force between parallel currents will be the combination of the two equations;
  $F_B = \mu_o I_1 I_2 L / (2\pi r)$
- Parallel currents will attract and antiparallel currents will repel.

There are two different explanations for why parallel currents attract. If you draw the individual magnetic fields from the two currents you will notice that the fields cancel in between the currents. Outside of the currents the fields add. The external magnetic pressure being greater will force the wires together. Reversing the currents will make the field between the currents stronger thus forcing the wires apart. A second method of explanation is using the right-hand curl rule for one wire followed by the other right-hand rule on the other wire. Try it and see.

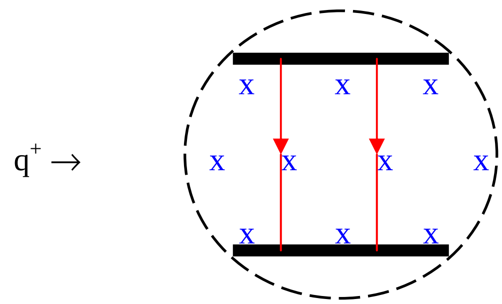
Homework: page 664-667 Problems Chapter 21:29, 31, 37 ($F_S = kx$), 57, 60

Lesson 3-20 Mass Spectrometers

A mass spectrometer is a device that is used to determine the mass of an unknown particle. These devices are employed at the molecular, atomic and sub-atomic level. There are three parts to the mass spectrometer. The three stages are described below.

Particle Accelerator	Velocity Selector	Mass Spectrometer
▪ Uses electric fields to move many particles to about the same speed.	▪ Uses crossed E & B fields to pass particles of a single speed.	▪ Uses pure B field to resolve beam into different masses.
▪ $-q\Delta V = ½ mv_f^2 – ½ mv_o^2$	▪ $v = E / B$	▪ $m = qBr/ v$

The velocity selector works off the principle that the electric field acts with the same force on all particles independent of how fast they move. The magnetic field on the other hand is velocity dependent. The idea is to shoot a charged particle through crossed electric and magnetic fields. See the diagram to the right.



The end of the coil is shown as a black circle with a current flowing in a clockwise manner. The clockwise current produces a magnetic field into the page shown in blue. Also shown in black are parallel plates with voltage differences so that the resulting electric field lines are shown in red.

As a positively charged particle passes from left to right through the crossed fields the electric force is down while the magnetic force is up (or vice-versa for negative charge).

$$\sum F_Y : F_B – F_E = qvB – qE = ma$$

A particle moving too fast will experience a larger magnetic force and be pulled up out of the beam. A particle moving too slowly will experience a weak magnetic force causing the electric field to pull the particle downward out of the beam. There is exactly one speed however, that will perfectly balance the upward magnetic force and the downward electric force. Particles at this speed will pass through the selector without deflection. To determine the speed that gets though without deflection merely set the acceleration in the y direction equal to zero and solve for v.

$$\boxed{v_{Eq} = E / B}$$

By adjusting either the voltage across the parallel plates to change E or the current passing through the coil to change B you can dial up any desired speed for particles before they enter the pure magnetic field of the mass spectrometer. By knowing the radius, length and number of turns in the coil a reading from an ammeter is needed to calculate B. By knowing the gap distance between parallel plates a reading from a voltmeter is all that is necessary to get E. Since the q's cancel out in the derivation of the equilibrium speed the velocity selector will not discriminate between doubly or singly charged particles. Be sure that you can do the following: Given the direction of E, B, F_E or F_B for a charged particle moving in a known direction in a velocity selector you should be able to determine the direction of the other vectors.

Homework: page 663-664 Problems Chapter 21: 11, 13, 14, 15, 16, 19, 22, 23, 25

Lesson 3-21 Electromagnetism

From Oersted's discovery in 1820 until 1865 electricity and magnetism went from being two different topics to a single topic of great importance. An outline of the developments is given in this lesson. You are not responsible for solving any problems with the following equations since they all have calculus symbols in them. But you will be held accountable for matching the equations to their physical implications as well as the names of their associated authors.

Gauss's Laws

Gauss's Law of Electricity describes all of the events of unit 11a for electrostatics when combined with a few definitions. The equation is shown in the box to the right. Cause is on the left and effect is on the right of the boxed equation. Some of the physical interpretations are listed below:

$$q = \varepsilon_o \oint \mathbf{E} \cdot \mathbf{dA}$$

- Charges at rest produce electric fields. Do you see $q \rightarrow E$ in the box?
- Electric field lines begin on positive charges and end on negative charges.
- $E = kq/r^2$ or $E = (1/4\pi\varepsilon_o)\, q/r^2$ comes directly from here.

Gauss's Law of Magnetism describes how particles at rest can create magnetic fields. Recall that there are no such things as magnetic monopoles. Because of this fact this equation has a zero at the beginning. Again, cause is listed at the beginning of the equation and effect at the end of the equation.

$$0 = \oint \mathbf{B} \cdot \mathbf{dA}$$

- There are no magnetic particles to produce magnetic fields. $0 \rightarrow B$
- Magnetic field lines have no beginning or end and must be closed loops since there are no particles in the universe to start or stop the lines.

Ampere's Law

After Oersted made his discovery Ampere placed the relation in to equation form. This equation was completed by 1830. Source is shown on the left with effect on the right of the boxed equation. Combining this equation with a few other definitions leads to all of the magnetism concepts in this unit before this lesson.

$$\mu_o I = \oint \mathbf{B} \cdot \mathbf{dL}$$

- Electric charges in motion produce magnetic fields. Do you see $I \rightarrow B$?
-

Faraday's Law

This law was simultaneously discovered by Michael Faraday of England and Joseph Henry of USA. It is named after Faraday however, because he was the first to publish and also perhaps because he was already a well known chemist. From the previous boxed equation one notices that there is an magnetic source to electric fields. It is only natural to ask if the reverse is also true. Are there any electric sources to magnetic events? What Faraday discovered is that a magnetic field that changes either strength or orientation with time will generate an electric field. Have you ever noticed how the light bulbs in a house will once again brighten immediately after somebody knocks down a power line? This is an example of Faraday's equation in action. The collapsing magnetic field induces a second electric field that can generate a powerful surge and brighten the bulbs.

$$-\frac{d\Phi_B}{dt} = \oint \mathbf{E} \cdot \mathbf{dL}$$

- A changing magnetic field can produce an electric field. (1835)

Maxwell's Equations

Now we see that moving electric charges produce magnetic fields according to Ampere's Law. By 1835 it is also recognized that changing magnetic fields can produce electric fields. Eventually a Scotsman named James C. Maxwell begins to ask the following question. If changing magnetic fields create electric fields then why not have changing electric fields produce a magnetic fields also? If Maxwell is correct then there is a second term needed in Ampere's Law because there is another way to make magnetic fields. So Maxwell adds a second term to Ampere's equation around 1865. The four equations listed below are known as Maxwell's Equations.

Maxwell's Equations of Electromagnetism

$$q = \varepsilon_o \oint \mathbf{E} \cdot \mathbf{dA} \qquad \mu_o I + \mu_o \varepsilon_o d\Phi_E/dt = \oint \mathbf{B} \cdot \mathbf{dL}$$

$$0 = \oint \mathbf{B} \cdot \mathbf{dA} \qquad -\frac{d\Phi_B}{dt} = \oint \mathbf{E} \cdot \mathbf{dL}$$

Why is it that Maxwell did the least amount of work in contribution to the above equation yet gets the entire set named after him? Reconsider the set with his only part colored in red. It is because of his concept of what would be the consequences of his addition.

Consider if you start with changing magnetic fields generating electric fields. Now if magnetic fields are always changing then their generated electric fields are always changing. But changing electric fields produce changing magnetic fields. Causing one to oscillate produces the other type of field. Once you get the oscillations started they can perpetuate themselves through space. Maxwell recognized that you could have electromagnetic waves. They were originally called Maxwellian waves. Maxwell even calculated the speed of the waves. He theorized that the waves would move at the value a shown in the box to the right. This speed happens to be the speed of light!

$$v = 1/\sqrt{\mu_o \varepsilon_o}$$

Maxwells's final piece of the puzzle accomplishes the following three things.

- ✓ Gives us a theory that unites electricity, magnetism and optics into a single set of equations. This is a unified theory.
- ✓ Gives us the answer to the question is light made of particles or waves? After 1865 there was no doubt that light had a wave nature rather than a particle nature.
- ✓ Until this point in time only physical measurements of the speed of light had been made. Nobody before Maxwell had a theory as to why light traveled so fast.

I regret that we have no more time to spend on magnetism and must quickly brush over the ideas of Faraday and even Maxwell. But apparently all of this talk about waves indicates that we should look into some wave concepts. In unit 304 we begin with a study of mechanical waves and sound.

Be able to match the physical interpretations of the equations with their physical consequences. Also be aware of which person is associated with which equation. This part will be matching so you do not need to memorize the equations.

Lesson 3-22 Practice Test

In order to review for your test you may wish to work the following questions and problems from the text book at the end of Chapter 21.

<u>Conceptual Questions</u>
pp. 660-662

Question #'s 4, **5**, **6**, 7(reverse direction and change magnitude), 8, 11(up and left), **13** (N is right), **15** (→), **16**, **17**.

<u>Practice Problems</u>
pp. 662-668

Problem #'s 11, 13, 19, 56, 58, 60, 63, 77.

<u>Historical Test Items</u>: Students should be familiar with the contributions of Franklin, Gauss, Oersted, Ampere, Coulomb, Faraday, Maxwell, Milliken, J.J. Thomson for the purposes of matching names with accomplishments.

Just in case you missed it, J.J. Thomson measured the charge to mass ratio (q/m) for an electron using the first, crude mass spectrometer. But he had two unknowns and only one equation (1897). About 9 years later (1906ish) Milliken measure the charge of the electron with an oil drop experiment, thus giving us a second equation for the charge of the electron independently of its mass.

Also be prepared to match the physical interpretations of Maxwell's equations to the equations. I will provide the equations so that you do not have to memorize calculus symbols that you do not yet understand. I may consider providing the equations and asking you to label the individual names of each formula and then explain why they are all named for somebody else in an essay.