CNS Institute for Physics Teachers

Title:	**Magnetic Force on a Current-Carrying Wire**
Version:	November 5, 2006
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Appropriate Level:	Regents, Honors, AP Physics
Abstract:	This series of activities is designed to allow the student to explore the effect of an external field on a current-carrying wire in that field. It is expected that students would have some prior experience with magnetism but that they would not have studied this particular topic before the lab. Students determine the direction of the magnetic force on the wire, allowing them an opportunity to experience the right-hand rule. For Regents level students, the concept of the direction of a force vector being in an unexpected direction can be explored without going into the right-hand rule. For AP Physics students, mastering the right-hand rule is essential. The lab will give the students a very visual experience of the theory. Students also determine the relationship between the length of the current-carrying wire in the magnetic field and magnetic force and between the current in the wire and the magnetic force. Students gain valuable experience in gathering data, calculations, graphing and graphical interpretation. An optional extension activity in mapping the field is included.
Time Required:	Two 44-minute periods
NY Standards Met:	M1.1, M1.2, M3.1, S2.4, S3.1, S3.3, S4.1, S5.1
AP Physics Learning Objective:	Students should: Understand the force exerted on a current-carrying wire so they can calculate the direction and magnitude of the magnetic force on a straight segment of current-carrying wire in a uniform magnetic field Understand how to analyze data, analyze errors and communicate results.
Special Notes:	Magnetic Force is kit available from the CIPT Equipment Lending Library, www.cns.cornell.edu/cipt.

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Objectives:

- To learn about the effect of a magnetic field on a current-carrying wire. To explore both the magnitude of the magnetic force on the wire and its direction.
- To gain experience in graphing and interpretation of data.

Class Time Required:

Two 44-minute class periods

Teacher Preparation Time Required:

10 minutes to set out materials. To save time for students on setting up the equipment, it is suggested that the teacher set up the equipment and circuits ahead of time, allowing students to focus on the specific goals of the lab. This would require an additional set up time of approximately 15 minutes.

Materials Needed:

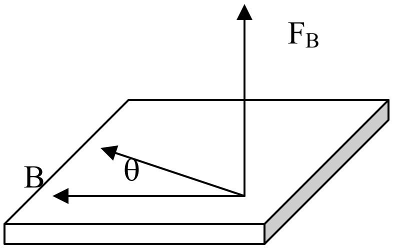
- DC Power supply, 5V adjustable, 3A max
- 12” wooden dowels with conducting, non-magnetic clips
- Ring stand with 3 clamps and cross bar
- 3 insulated hook-up wires with banana plug ends and 2 alligator clips
- 0.5-ohm resistor, 10W
- 3 horseshoe magnets clamped together with the poles aligned and field direction marked
- Triple beam balance
- 0 - 5 A ammeter (or multimeter)
- straight bus wire (uninsulated copper wire with solder finish), 6” (#16)
- graph paper or graphical analysis software
- compass

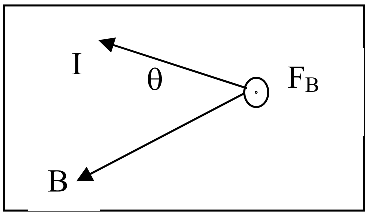
Assumed Prior Knowledge of Students:

Students should be familiar with simple circuits and have been introduced to magnetism. This lab is meant as a first exploration of the magnetic force on a current-carrying wire in an external magnetic field.

Background Information for Teachers:

Current-carrying wires in external magnetic fields experience a force that is given by the equation $\vec{F}_B = I\vec{l}x\vec{B} = IlB\sin\theta$ where I=conventional (positive) current in a long straight wire in amperes, l = length of the wire in meters, B = magnetic field strength in Teslas, F_B is the force in Newtons, exerted on the wire by the magnetic field, and θ is the angle between the direction of the current and the magnetic field vector. The current direction and magnetic field vector define a plane. The force vector is perpendicular to that plane and therefore always perpendicular to both the current and the field. The direction of the force vector (out of or into the plane) is given by the right hand rule. [Place the current direction and field vector tail to tail. Place the wrist of your right hand where the two tails meet with your fingers aligned with the direction of the current and your thumb at 90 degrees to your pointer finger. Sweep or bend your fingers toward the field vector. If you cannot do this, turn your hand over 180 degrees so that you can. Your thumb is pointing in the direction of the magnetic force vector]





Overhead view, looking down on the plane defined by I and B. In this two-dimensional drawing, the force vector comes out of the page and is indicated by a circle with a dot in the center (as if you are seeing the arrowhead coming towards you. If the I and B vectors were reversed in order, the force vector would be going into the page and would be represented by a circle with an x inside, as if you were seeing the arrow tail as it moved away from

In the lab, the angle θ will always be 90°. The lab can serve as a jumping off point for exploring the right hand rule in more detail for those classes that will be going into greater depth. For classes (Regents and Honors) where the right-hand rule is no longer required, the lab will introduce the idea of the direction of the magnetic force without requiring further depth of study for angles other than 90°.

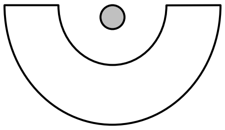
<u>Note to Teachers:</u>

Because the apparatus is sensitive to magnetic materials and external currents in the area, it is recommended that the wooden dowels be used to assure that the metallic clamps are sufficiently far away from the magnets to not alter the data significantly. It is also critical that the clips used to hold the uninsulated bus wire be non-magnetic or it will be attracted to the magnets and unable to stay in the center of the magnet horseshoe. The triple beam balances work better than digital balances since they do not introduce additional electrical circuits and they read to a sufficient number of significant figures for the students to see a change in the apparent weight of the magnets when the current is in the wire.

You can mark the poles of the magnets for the students or have them determine the poles with a compass. But a word of caution, the magnetic field is strong enough to alter the orientation of the compass needle! After determining the direction of the magnetic poles, students should take the compass away from the magnets and compare to known north to see which way the compass needle really points! Then they will know which way the poles are in their magnets. This may be an extra confusion that you may want to avoid by marking the poles for the students ahead of time, using this same caution. Students will still need to know which way the magnetic field vector points relative to the two poles.

Answers to questions and additional tips:

1. The apparent mass of the magnets will change, increasing or decreasing depending on the direction of the current in the wire and direction of the magnetic field. Using the right-hand rule, you can determine the direction of the force on the current-carrying wire due to the magnetic field. See introductory notes above or a physics text.

   For example, if the conventional (positive) current in the bus wire (shown in gray in this diagram) is running out of the page, and the magnetic field is going from the left pole to the right pole of the magnet (shown as a horseshoe shape), then the force on the current-carrying wire due to the magnetic field is straight up on the page. Since the wire is fixed in place by the clips and can not move, the students will see the equal and opposite force acting on the magnets straight down and the magnets will thus appear to gain in mass. If the magnetic field were oriented right to left with the same current in the wire, they would see the magnets appear to lose mass.

   Likewise, if the current in the wire were going into the page in the diagram above, and the magnetic field were oriented left to right, they would see the magnets appear to lose mass. Finally, if the current in the wire were going into the page and the magnetic field were oriented right to left, they would see the magnets appear to gain mass due to the downward force on the magnets.

   The direction of the force on the wire is 180 degrees opposite to that on the magnets. The force is only present when there is current in the wire.

2. and 3. Diagram: The magnetic field vector is drawn from the north pole to the south pole. The Force vector should be 90 degrees to both the field vector and the direction of the current. Student work can be checked for proper orientation using the right hand rule (see above introduction to theory.) The right hand rule gives the direction of the force on the current-carrying wire.

4. With reversing the current, if they previously saw the apparent mass of the magnets increase, they should now see them decrease (and vice versa).

5. The magnitude of the angle should not have changed. The force vector is always perpendicular to both the magnetic field vector and the direction of the conventional current.

6. The three dimensional relationship has not changed.

7. Students will attempt to derive the right hand rule in some form. While it may not come out perfectly, especially since we have not explored other angles between the current direction and the magnetic field, their attempts at coming up with a rule will provide a hypothesis that can be tested and/or can be used as a starting off point for discussion of the accepted theory.

8. As the length of the wire carrying current increases, the apparent change in weight should also increase proportionally.

9. Directly proportional. For helping students interpret their graphs, you can remind them of how to determine mathematical relationships drawn from graphs of experimental data: * If two parameters are directly proportional to one another, i.e., if one parameter is doubled (without changing any other variables), the other is also doubled, then you should see a linear, positively sloped graph. For example, in F=ma, force is directly proportional to acceleration. If you double F, then acceleration will also double. A graph of F vs. a would be linear with a positive, constant slope representing the mass. Or we could say the acceleration is equal to the applied force times some constant (which is the mass).

   Similarly, at small angles, for a simple pendulum, $T=2\pi\sqrt{L/g}$. If you were to change the length and measure the period, a graph of T vs. L would not be linear, but T^2 vs. L would be linear. $T^{2\ \text{is}}$ directly proportional to the length. Or we could say the period squared is equal to L times some constant (which is $4\pi^2/g$).

10. $\vec{F}_B = I\vec{l}x\vec{B} = IlB\sin\theta$

    I=conventional current in amperes

    l = length of the wire in meters

    B = magnetic field strength in Teslas

    F_B is the force in Newtons exerted on the wire by the magnetic field

    θ is the angle between the length and the magnetic field vectors (The length vector is in the same direction as the conventional current)

11. directly proportional

12. directly proportional

13. 90 degrees to both current direction and field direction according to the right hand rule

14. slope represents BI, magnetic field strength times the current

15. slope represents Bl, magnetic field strength times the length of the wire carry the current

Extension activity:

The idea is that they can move the wire upwards starting from inside the U of the magnets and eventually above the U of the magnets. For each incremental move, they would take data on the change in apparent mass of the magnets. This can be used to determine the force at the different locations, thus mapping the strength of the field which is directly proportional to the force.

To make your own equipment:

Most of the equipment is easily found in most physics labs. The triple beam balances are usually found in Earth science labs.

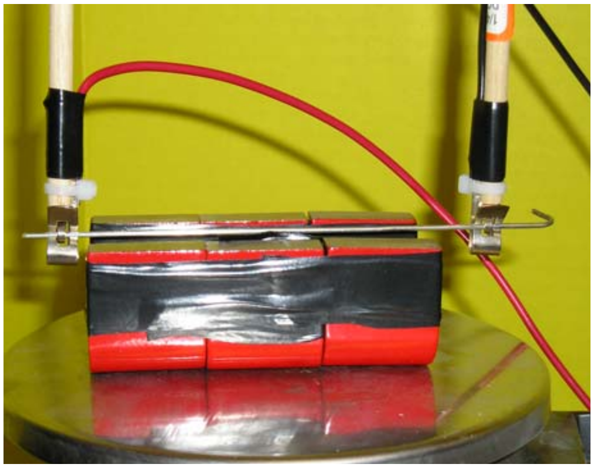
Specialty Parts:

- Magnets: Eclipse Part # S813 - Simonds International ; Fitchburg, MA 02140 phone: 800-343-1616 fax: 800-541-6224
- Fahnestock Clips, nonmagnetic, 25/32" long x 5/16" wide - H.H. Smith 533
- Dowels, 1/4" diameter, 12' long - local hardware store
- Stranded hook-up wire (#18), insulated, 2 pieces approximately 2.5 feet long each
- Banana plugs and alligator clips
- Plastic tie wraps (local hardware store)

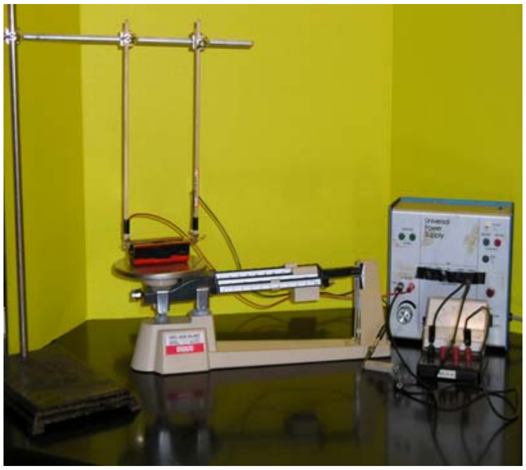
Instructions:

Three magnets will be held together in the same orientation. This requires holding them together firmly and taping. Several turns of black electrical tape works well, first taping two together and then adding the third. This is most easily done with two people since the magnets will want to reverse orientation to each other.

To make the dowels and clips: split the end of the dowel a short way from the bottom. Insert a Fahnestock clip into the slit and glue with super glue, clamping with a plastic tie wrap to hold it firmly in place. The hook-up wire can then be soldered to one edge of the clip. Finally, the whole connection can be taped with electrical tape to secure it. You need two dowel/clips for each set-up. Use one black and one red insulated wire for each set-up. By holding the clips to the inside of the dowels (i.e., with the solder joints to the wires facing each other) students can easily measure the length between the solder joints as the length of the current-carrying wire.



Close-up of the clip arrangement on the wooden dowels, with magnets



The complete lab set up

Magnetic Force on a Current-Carrying Wire

Introduction:

When placed in an external magnetic field, a wire that carries a current experiences a force due to the magnetic field. We will be exploring the direction of the magnetic force, its magnitude, and parameters that affect the force.

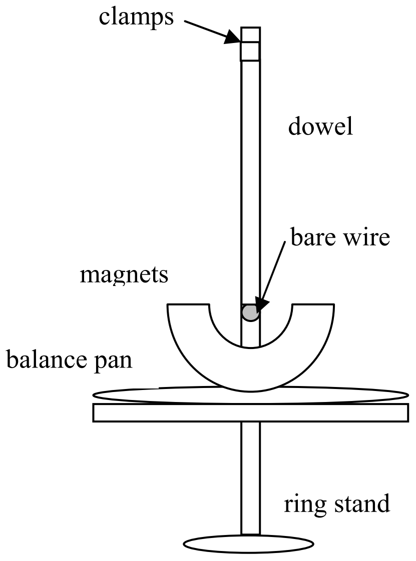
Materials:

- DC Power supply, 5V adjustable, 3A max
- Triple beam balance
- 12” Dowels with conducting, non-magnetic clips
- 0-5 A ammeter (or multimeter)
- Ring stand with 3 clamps and cross bar
- 3 insulated wires and 2 alligator clip
- compass
- straight bare (uninsulated) wire, 6”
- 0.5-ohm resistor, 10W
- 3 horseshoe magnets clamped together (poles aligned)

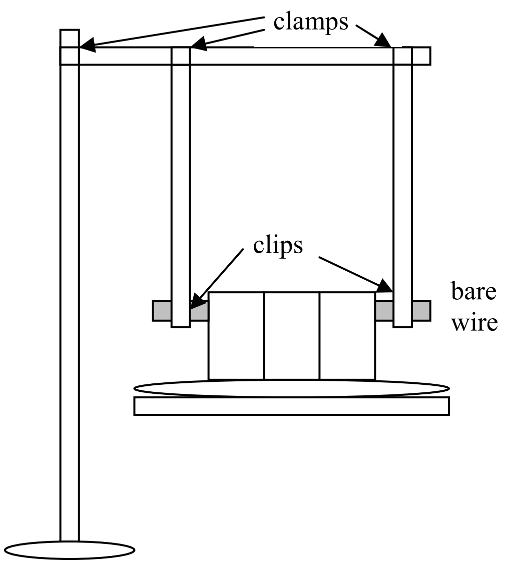
Directions:

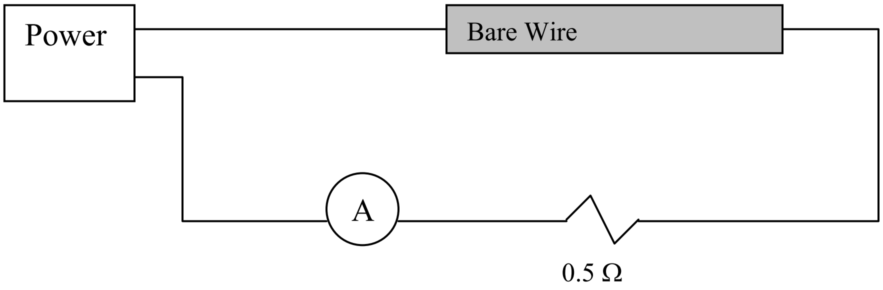
Place the magnets on the scale in the middle of the balance pan. Clamp the dowels onto the cross bar so they hang vertically downward with the clips lowered just into the “U” of the magnets. The clips should be far enough apart from each other so they are just on either side of the magnets. Connect the straight wire between the two clips. Using the 5V, 3A DC output on the power supply, make a complete series circuit including the straight wire, the resistor and the ammeter in your circuit. The resistor will allow you to set the current and the ammeter will allow you to keep track of the current.

FRONT VIEW



SIDE VIEW





Activity I:
How does the direction of the magnetic force on a current-carrying wire relate to the direction of the magnetic field and the direction of the electrical current?

Determine the mass of the magnets. __________________ (Be sure to include units.)

Making sure the control on the power supply is turned to a minimum, turn on the power supply. Increase the current to a fixed value that you will use throughout these explorations, at no more than 3 A. (As you slowly turn the dial, check the ammeter. If the needle is trying to go in the negative direction, STOP. Reverse the leads on the power supply so the current is going the other way and the ammeter needle moves freely.)

1. What happens to the apparent mass of the magnets?

   ____

   There is apparently a new force on the magnets. In what direction is that force?

   ____

   By Newton's 3rd Law, what direction is the reaction force on the current carrying wire? ____

   This is the magnetic force, F_B, on the current-carrying wire. Is this force present when there is no current? ____

   Turn off the power supply.

   In the diagram below, the horizontal line represents the straight bus wire in the magnetic field. Given the positive and negative power supply connections, draw and label an arrow in your diagram to indicate the direction of the conventional current in the wire.

⊙ A circle with a dot represents a vector coming out of the page.
⊗ A circle with an "x" represents a vector moving into the page.

Draw and label an arrow with the symbol “B” to indicate the direction of the magnetic field in your diagram. (Use a compass to determine the direction of the magnetic field just inside the “U” of the magnets. But a word of caution, the magnetic field is strong enough to alter your compass! Take the compass away from the magnets and compare to known north to see which way the compass needle really points!)

Now draw and label a third arrow, F_B to indicate the direction of the magnetic force on the wire.

2. What is the angle between the magnetic force vector and the direction of the current?
   ____

3. What is the angle between the magnetic force vector and the magnetic field vector?
   ____

Does the direction of the force depend on the direction of the conventional current?

To determine this you will need to reverse the connection on the power supply. If you are using an ammeter with a needle, you will need to reverse the ammeter (since the needle can only go in one direction.)

4. What happens to the apparent mass of the magnets with the current in the wire reversed? ____

   What direction is the force on the magnet? ____________________________

   By Newton’s 3rd Law, what direction is the magnetic force (the reaction force) on the straight wire? ____

   Draw another diagram of the wire indicating the direction of the conventional current, the direction of the magnetic field, and the direction of the magnetic force on the current-carrying wire.

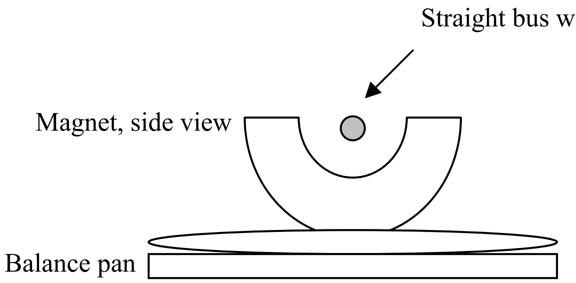
5. What happened to the magnitude of the angles between the magnetic force vector and the other two vectors? ____________________________________

6. Are the 3-dimensional relationships between the directions of the three vectors the same? ____

7. Given the direction of the conventional current and the magnetic field vector, can you come up with a rule for determining the direction of the force on the straight current-carrying wire:

Activity II:
What is the relationship between the length of the straight current-carrying wire in the magnetic field and the magnetic force it experiences?

Reconnect the ammeter and set the power supply connections so you will get a positive current that the ammeter can read. Adjust the dowels so that the horizontal bus wire that will carry current is the total length of the magnets. The magnetic field is strongest just below the top surface of the magnets (just inside the "U"). Position the dowels so the straight wire hangs at this point. Then do not change the height of the wire for the rest of the experiment.



Refer back to previous diagram of set up

You can change the length of the wire that carries current by adjusting the position of the clips. It is easiest if you loosen the clamps holding the dowels to the cross bar first so they can slide along the cross bar. Then change the position of the clips on the wire. Finally retighten the dowels to stabilize the system. Keeping the current constant, take measurements of the change in the apparent mass of the magnets for various lengths of current-carrying wire in the magnetic field, keeping the current constant (no more than 3A). Use this apparent change in mass to determine the force on the wire.

In your data table, have columns for

Length of the current carrying wire in the magnetic field (your independent variable)
Mass of the magnets (with no current in the wire)
Apparent mass of the magnets with current in the wire
Apparent change in the mass of the magnets
Apparent change in the weight of the magnets (this is also equal in magnitude to the magnetic force on the current-carrying wire)

Be sure to indicate <u>units</u> in the data table!

Length	Mass	Apparent mass	App Δ in mass	App Δ in weight

8. What pattern do you see in the data?

   Graph Magnetic Force versus Length and attach to your lab.

9. What can you say about the mathematical relationship between the two (directly proportional, indirectly proportional…)?

Activity III:
Design and carry out an experiment to explore the relationship between the magnetic force on a current-carrying wire in a magnetic field and the magnitude of the current in the wire. Include a brief procedure, a data table, an appropriate graph of your data and an analysis and conclusion.

Compare your results with the expected results:
When you have completed the three activities, find the equation in your textbook that describes the magnetic force on a straight current-carrying wire in a magnetic field and write it here:

10. Define each of the symbols used in the equation and indicate their MKS units.

11. According to this equation, what is the relationship between the conventional current and the magnetic force? (directly proportional, indirectly proportional…?)

12. What is the relationship between the length of the current-carrying wire in an external magnetic field and the magnetic force on the wire?

13. According to your text, how is the direction of the magnetic force related to the conventional current direction and to the magnetic field direction?

14. In the Force versus length graph, what does the slope represent?

15. In the Force versus current graph, what does the slope represent?

16. From your two graphs, calculate the magnetic field strength just inside the "U" of the magnets where the wire resided.
    - Show your work.
    - Be sure to include units.
    - Calculate the % difference in the two results for the field strength.

    If your data did not support the relationship shown in the accepted equation, where do you think the errors or differences in your experiment arose?

Extension Activity:
Using the current-carrying wire to probe the field, map the magnetic field.
Can you determine, for example, how the magnetic field strength changes above the magnets and inside the "U" of the magnets?