Title:	**Magnetic Force on a Current-Carrying Wire**
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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 magnetic field on a current-carrying wire. 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 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. Optional extension activities include exploring the effect of the angle between the current and the field and mapping the magnetic field in space. The lab also revisits Newton's 3rd Law.

Time Required:	Two 44-minute periods
NY Standards Met: **AP Physics Learning Objective:**	S4.1 Students can observe and describe transmission of various forms of energy. S5.1 Students can explain and predict different patterns of motion of object (e.g., linear and uniform circular motion, velocity and acceleration, momentum and inertia).

	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.
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Behavioral Objectives:

Upon completion of this lab activity a student should be able to:

- describe the relationship between current in a wire and the induced magnetic field.

- qualitatively discuss both the magnitude of the magnetic force on the wire and its direction.

Class Time Required:

Two 44-minute class periods. Extra time required for extension activities, depending on how much analysis is done in class.

Teacher Preparation Time:

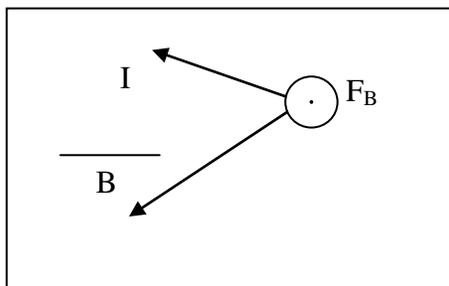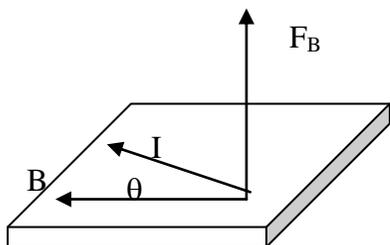10 minutes to set out materials.

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

- 0.5Ω resistor, 10W (optional)

- 3 horseshoe magnets clamped together with the poles aligned and field direction marked

- Triple beam balance

- 0 - 5A ammeter or multimeter (optional)

- straight bus wire (uninsulated copper wire with solder finish), 6" (#16)

- graph paper or graphical analysis software

- compass

- protractor for extension activity

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 $\vec{F}_B = I\vec{l} \times \vec{B} = IlB \sin\theta$ 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 = the force exerted on the wire by the magnetic field in Newtons, and θ = 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 conventional current direction and field vector tail to tail. Make your right hand into a gun. Your pointer finger is the current, your other fingers are the magnetic field vector. Your thumb, which should be 90° to your pointer finger, shows the direction of the force.

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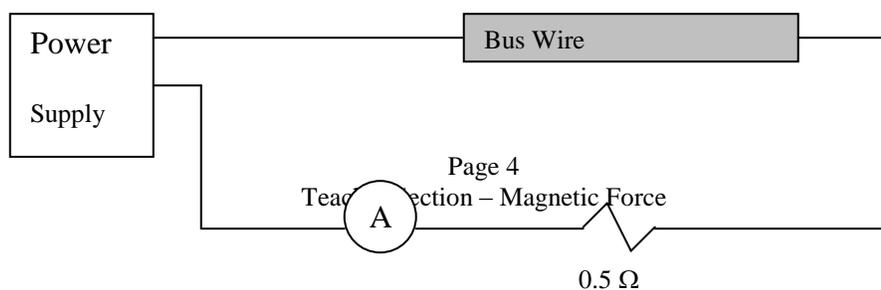
In the lab, the angle θ between the current and the field will always be 90°. The lab can serve as a jumping off point for exploring the right hand rule in more detail for those classes that will be going into greater depth. For classes (Regents and Honors) where the right-hand rule is no longer required,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

requiring further depth of study for angles other than 90°.   In Extension Activity I, the effect of changing the angle is explored.

Note to Teachers:
- 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 reverse 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.

- A nice demonstration to start out with and help students make the connections to Newton's 3rd Law is to:
  1. Place the magnets directly on the table, with the "U" facing outward toward them. Hold the dowels in your fingers so the bus wire is hanging down parallel to the ground but away from the magnets. Turn on the power supply to get a current. Nothing happens.
  2. Turn off the power and move the bus wire just in front of the magnets. Turn on the power and voila, the bus wire will move toward or away from the magnets, depending on the direction of the current. There is a force on the wire.
  3. Put the magnets on the balance with the dowels now clipped to the ring stand so the wire remains fixed in place. Now it is the magnets that move, illustrating Newton's 3rd Law.

- The student section of the lab is split into two distinct sections. The first includes the instruction sheets. They can be handed out one per lab group. The second section is the student data sheets that each student would use to record data and answer to questions.

- If your power supply does not display the current it outputs, you may want to include the 0.5 ohm resistor and 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.

Power Supply

Bus Wire

Page 4
Teac___ ection – Magnetic Force

A

0.5 Ω

Activity III: Changing the length of the wire between the Fahnestock clips is awkward and works best if two people work together. One person adjusts the clamps holding the dowels to the crossbar while the other person simultaneously squeezes the Fahnestock clips to allow the wire to slide and adjust.

Extension Activity: The idea is that they can move the wire upwards starting from far inside the U of the magnets and eventually well 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.

Answers to Questions: *send email to cipt_contact@cornell.edu to request answers.*

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.

Materials:
- 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 from local hardware store
- Stranded hook-up wire (#18), insulated, 2 pieces approximately 2.5 feet long each
- Banana plugs and alligator clips
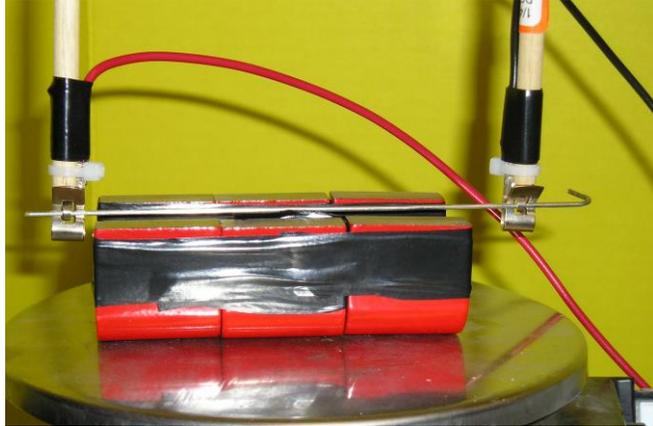- Plastic tie wraps (local hardware store)
- Superglue

Construction Directions:
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

References:

Walker, James S. Physics. 2nd ed. Upper Saddle River: Pearson Education, Inc, 2004.

Equipment List

Item Number	Quantity	Item
1	1	DC regulated power supply (0-3 A, 0-5 V)
2	1	Magnet (3 individual horseshoes stuck together)
3	1	Cross bar
4	1	Straight copper bus wire
5	3	Clamps
6	2	12" wooden dowels with conducting, non-magnetic clips and banana plug leads attached
7	1	Triple beam balance
8	1	Ring stand

MAGNETIC FORCE ON A CURRENT-CARRYING WIRE

Introduction:

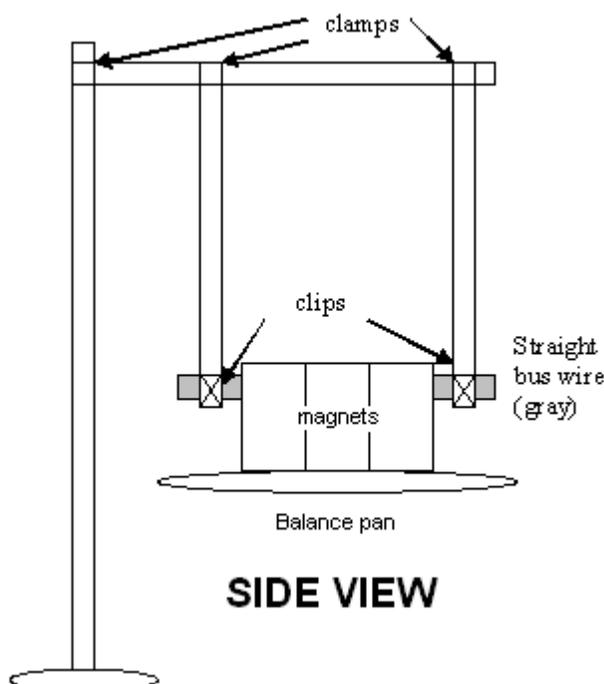When placed in an external magnetic field, a wire that carries a current experiences a force due to the magnetic field. We will be exploring the direction of the magnetic force, its magnitude, and parameters that affect the force.

Materials:

- DC Power supply, 5V adjustable, 3A max

- Triple beam balance

- 12" Dowels with conducting, non-magnetic clips

- Compass

- Ring stand with 3 clamps and cross bar

- 3 insulated wires and 2 alligator clip

- straight bus wire, 6"

- 3 horseshoe magnets clamped together with the poles aligned

Instructions:

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 or slightly above the "U" of the magnets i.e., between the two magnetic poles where the field is the strongest. 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.

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?*

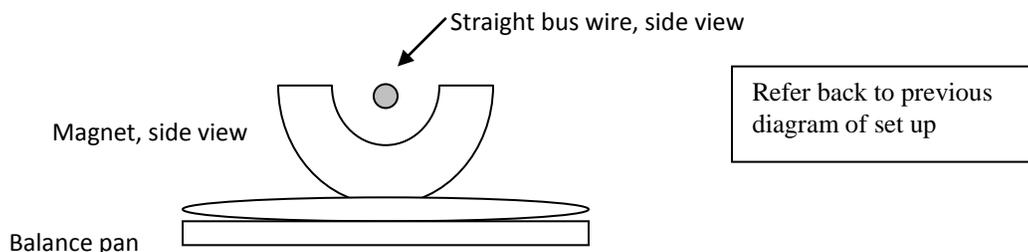Determine the mass of the magnets and record on the student data sheet.
Making sure the control on the power supply is turned to a minimum, turn on the power supply. Increase the current to a fixed value that you will use throughout these explorations, at no more than 3A. (As you slowly turn the dial, 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.)

Answer the questions on the student data sheet for Activity I.

Determining the direction of the magnetic field: A compass points in the direction of the field (out of the north pole and into the south pole of your magnet). 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! It might have been reversed.

Activity II: *If you place a straight current-carrying wire in an external magnetic field, what is the relationship between the magnitude of the current in the wire 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. If necessary, adjust the dowels so that the horizontal bus wire that will carry current is the total length of the magnets. The wire should be positioned where the magnetic field is strongest just at or below the top surface of the magnets. Do not change the height of the wire for the rest of the experiment.

Straight bus wire, side view

Magnet, side view

Refer back to previous diagram of set up

Balance pan

Keeping the length and position of the wire constant, adjust the current in 0.5A increments. Take measurements of the change in the apparent mass of the magnets for each current tested. Use this apparent change in mass to determine the force on the wire.
Record your results in the data table on the student data sheet.

In your data table you should record:
   Magnitude of the current in the 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
Be sure to indicate <u>units</u> in the data table.
Answer the questions in the student data sheet.

<u>Activity III:</u> *Design and carry out an experiment to explore the relationship between the magnetic <u>force</u> on a current-carrying wire in a magnetic field and the <u>length</u> of the current-carrying wire in the magnetic field. Include a brief procedure, a data table, an appropriate graph of your data and an analysis and conclusion.   In your analysis, be sure to address the questions on the student data sheet.*

<u>Extension Activity:</u> *Using the current-carrying wire to probe the field, <u>map the magnetic field</u>. Design a procedure to determine how the strength of the magnetic field changes as a function of distance, starting from inside the "U" of the magnets and ending at some distance above the magnets. Show your data in a table and show a map of the field.*

MAGNETIC FORCE ON A CURRENT-CARRYING WIRE

Student Data Sheet

Name_____   Date _____

Activity I: **Go to the instruction sheet and follow the instructions for Activity I. Record answers and data below:**

Mass of magnets_____ (Be sure to indicate units)

1. What happens to the apparent mass of the magnets when there is current in the wire? _____

    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.

Draw and label an arrow with the symbol "B" to indicate the direction of the magnetic field in your diagram.

$\odot$	A circle with a dot represents a vector coming out of the page.
$\otimes$	A circle with an "x" represents a vector moving into the page

If you're not sure how to find the direction of the magnetic field, refer back to the instruction sheet.

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 <u>magnitude</u> of the angles between the magnetic force vector and the other two vectors? _____

6. Are the 3-dimensional relationships between the direction 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:

Go back to the instruction sheet and follow the instruction. If you place a straight current-carrying wire in an external magnetic field, what is the relationship between the magnitude of the <u>current</u> in the wire and the magnetic <u>force</u> it experiences?

Record your data below:
Be sure to indicate <u>units</u> in the data table!

Mass of magnets with no current _____
Length of wire carrying current in the magnetic field_____

Current	Magnets' Apparent mass	Apparent change in mass	Apparent change in weight

8. How does the apparent change in the weight of the magnets relate to the force on the wire?

9. What pattern do you see in the data?

10. Make a graph of Magnetic Force on the wire versus Current in the wire, draw a best-fit line for your data and attach to your lab.

11. What can you say about the mathematical relationship between the force and the current (directly proportional, indirectly proportional…)?

Activity III: Design and carry out an experiment to explore the relationship between the magnetic <u>force</u> on a current-carrying wire in a magnetic field and the <u>length</u> of the wire. Include a brief procedure, a data table, an appropriate graph of your data and an analysis and conclusion. In your analysis, compare your results with the expected results, addressing each of the points below:

12. Find the equation in your textbook that describes the magnetic force on a straight current-carrying wire in a magnetic field and write it out and define each of the symbols and their MKS units:

13. According to this equation, what is the relationship between the magnitude of the conventional current and the magnetic force on the wire? (directly proportional, indirectly proportional…?)

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

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

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

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

18. From each of your two graphs, calculate the magnetic field strength at the position of the wire.
    • 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?

Go back to the instruction sheet and complete the extension activities assigned by your teacher.