Electric fields and the Coulomb force apply to the interaction between stationary charges. If the charges are moving, they create magnetic fields and these magnetic fields in turn exert forces on other moving charges. In this week's lab you will observe the magnetic field created by a wire and measure the force produced by a current in one wire acting on an identical current in a second wire. Magnetic forces between wires are small, so you will need careful experimental technique to accurately measure them.

**Lab Goals:**
-- Understand the magnitude and direction of the force created when a magnetic field acts on the current in a wire.
-- Use a compass to detect the magnetic field produced by the current in a wire.
-- Practice using the right hand rule to predict the direction of magnetic forces and fields.
-- Learn how to use a current balance to make sensitive measurements of forces between wires.

**Magnetic Fields**

A charge moving in a magnetic field experiences a force in a direction perpendicular to its motion and the magnetic field, given by the cross product:

\[ \vec{F} = Q \vec{v} \times \vec{B} \]  
\[ \text{Eq. 1} \]

where \( Q \) is the charge, \( \vec{v} \) is the velocity, and \( \vec{B} \) is the magnetic field vector. For a continuous current moving along a straight wire of length \( L \), charge moving at velocity \( V \) stays in the wire for time \( \Delta t = \frac{L}{V} \). The amount of charge that passes through the wire in this time is \( Q = I \Delta t = I L / V \).

Substituting into Eq. 1, we obtain

\[ \vec{F} = I L \vec{B} \]  
\[ \text{Eq. 2} \]

So the force on the wire is proportional to the current \( I \), the length of the wire \( L \), and the strength of the magnetic field \( B \). The direction of this force is perpendicular to both the wire and the magnetic field, and can be found using the right hand rule for cross products.

We can take this behavior as the definition of magnetic field: a magnetic field of one Tesla (1 T) will push with a force of one Newton on a meter of wire carrying one Ampere of current. If the wire is perpendicular to the magnetic field, then \( F = I L B \). The earth produces a magnetic field which is about \( 5 \times 10^{-5} \) Tesla on the earth’s surface. The geographic north pole is (near) a magnetic south pole and so the north pole of a magnet is attracted to it. Thus a compass needle points from north magnetic pole toward south magnetic pole—just like magnetic field lines.

(1) Calculate the maximum force of the earth's field on a 1 m long wire with 10A.
(2) What direction should the wire be oriented to produce the largest magnetic force?
(3) Compare this to the gravitational force that acts on the mass of the wire to show why we don’t normally observe forces on typical wires with current in them.
(You can just estimate the mass of the wire to within an order of magnitude)
The origin of the magnetic field produced by a current has an elegant connection to Einstein's theory of special relativity. However, long before that was understood, a phenomenological description of the field near a current carrying wire was developed. For a long, straight wire the magnetic field is aligned with concentric rings at any radius \( r \), circulating about the wire with a strength given by

\[
B = \frac{\mu_0 I}{2\pi r} \quad \mu_0 = 4\pi \times 10^{-7} \text{ Tm/A.} \quad \text{Eq. 3}
\]

The direction of the magnetic field vector is given by a right hand rule: with the thumb of your right hand pointing along the direction of the current, the magnetic field circles the wire in the direction that your fingers curl.

4. How far from an 800 A power line is the field the same as the earth's?
5. How far from a 10 A wire is the field the same as the earth's?
6. Use the compass to observe the field near such a wire. Does it point in the direction you predict?
7. How close to a 10 A current would you have a 1 Tesla field? Can you get this close?

In passing a current through various wires, always limit the current with the bank of resistors. Be careful, the resistors can get hot! Use your foot switch to only turn the current on when you are measuring something.

**Current Balance**

The magnetic fields and the forces created by currents flowing through a typical wire in the laboratory are quite small. This does not mean that magnetic forces are always small: for example electric motors are driven by magnetic forces between wires, but this is accomplished by using many turns of wire around ferromagnetic cores in optimized geometries. Since both the fields produced and the forces felt by currents are weak, it takes a sensitive instrument to respond to reasonable currents in a single wire. In this lab we will use a current balance. It runs current through two parallel wires which repel each other. The wires move apart until the magnetic force is small enough that it is balanced by the gravitational force. The distance between the wires is precisely measured by reflecting a laser beam off a mirror and so creating a weightless pointer.

8. Which direction should the current flow in each of the two wires for the magnetic force to be repulsive? (Use the “right hand rule”)
9. Substitute Eq. 3 into Eq. 2 to derive the relation between current and force for your wires.

Now measure the amount of force created by different currents flowing through the wires. Great care must be used to set up the balance, current, and laser beams so that the system is sensitive. Keep the wires parallel and close together, but not touching. The best technique for this measurement is to place foil weights on the current balance and then increase the current until the wire returns to its initial position. The magnetic force is then exactly balancing the additional force of \( mg \) which was added. The laser beam reflected from a mirror on the balance to a far point can be used to indicate the initial position. You should choose an initial position...
with the wires quite close together (about 2 mm, but not touching) so that your current supply will be able to provide enough current to support masses at that distance. Measure the current required to balance several masses up to the largest you can balance with a current less than 10 A. Be sure your can measure the current required to balance at least 6 masses from 10mg to 50mg. It is easier to make measurements with larger masses since friction is less important here, so try starting with 30mg to learn how the system works. Be Careful! Bypassing the resistor bank will blow a fuse and looking directly into a laser is not good for your eye.

(10) On graph paper, plot the balance force vs. the square of the balance current (why?).

(11) What effect might the earth’s magnetic field be having on your data?

To remove the effect of the earth’s field, reverse the current through the whole apparatus and measure force vs. current again. Take the average of the two currents measured for each mass. Since the force due to the earth’s field should be exactly opposite in the two cases, the average should give the value without the earth’s field.

(12) Plot the balance force vs. the current squared both for the reversed current and the average.

(13) The theory of forces on wires predicts a straight line. How strongly does your data support this theory?

(14) Determine the slope of your graph, and from this calculate the distance between the centers of your wires. Compare with a directly measured value for the distance between centers.

(15) Figure out the direction of the earth’s magnetic field and use it to explain which of your two current directions required a larger current.

(16) How much current would you need for a one Newton force?

(17) Extra credit:) From your data, calculate the magnitude of the earth’s field.

Some Magnetic Field Strengths...

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