Magnets: Fun with New Materials

Recent developments in magnet manufacturing has led to economical access to Neodymium magnets. These materials exert such strong magnetic forces and have very large Coercivity values that many experiments and demonstrations are now practical to carry out in high school classrooms.

ATTRACTIVE COINS:

Money is always fun to play with. Recent design changes in our coins are interesting from both a chemistry and a physics point of view.
Thanks to Lew Brubacher's article[1] in the September '04 Crucible, we know that the Canadian penny has changed over time.

Pre 1997	98% Copper 1.75% Zinc 0.25% etc.
1997-2002	Zinc core plated with copper
2003- 2004	94% steel 1.5% nickel plated with 4.5% Copper

Demonstration 1:

After establishing that iron and nickel metals are magnetic and copper is not, pour out a handful of pennies of assorted dates onto a table top. State that you find new shiny pennies especially attractive, then sweep a strong ferrite magnet over the pile. The 2003 and later pennies will jump up and stick to the magnet.
"Attractive indeed!

Activity 1:

The differences in composition of the pennies have resulted in clear differences in mass. If you have a centigram (or better a milligram) electronic balance, have your grade 9 students graph the mass of pennies vs. their year of issue. Graphs clearly show the mass changes as well as enough "scatter" to discuss precision and accuracy with the class. (The older the coin, the more wear will have occurred. With a milligram balance, this bias may show up in the data.)

Nickels are also nice. Up to 1979, the Canadian nickel was made of.... Nickel.
After that, the alloy had so much less nickel it was no longer magnetic. So you can sort the coins with a magnet. Except that the newer nickels are now made with a steel core and are once again magnetic. Thus, using a magnet to find the "collectables" in a pile of nickels is not as effortless as it once was.

[1] Dr. L. Brubacher, Fun With Pennies, Crucible, Vol. 36, No. 1, September 2004

 Doug De La Matter

Demonstration 2:

The pre-79 nickels are a indeed physics collector's item. Since they are almost pure nickel, the coin exhibits a Curie temperature of near 358 ^{o}C.
Fix a ferrite magnet to a retort stand with a test tube clamp so that one pole of the magnet faces down. Hang a chain of pre-1979 Canadian nickel coins from the face of the magnet. Heat the lowest coin delicately with a butane or propane torch. It will start to move and will soon drop off... the Curie Temp of Iron is 700C so you don't want to ruin your magnet demonstrating the loss of magnetic properties in the nickel.

Safety note: Be sure to have a heat resistant container underneath to catch the hot coin! The metal coin can bounce and roll. Warn students not to touch it until it has cooled to room temperature! Use another magnet to pick it up. (Once the metal cools below the Curie temperature it regains its ferromagnetic properties.)

If you want to do a higher budget experiment, the Canadian dollar coin (the Loonie) is made of a nickel core, plated with a Copper-Tin mixture, so a Loonie of any year will behave like the old nickels. HOWEVER, you end up with a larger piece of very hot metal dropping off the magnet and because you are heating longer to get the whole coin up to temperature, the magnet is heated more as well.
In all cases, care must be taken to avoid heating the <u>magnet</u> above its Curie temperature. Ferrite magnets are fairly robust, but can still be weakened substantially if the Curie temperature is exceeded.
Neodymium magnets have a relatively low Curie temperature and should not be used for this demonstration.

Students often think that the earth's iron core acts as a giant permanent magnet. However, the temperature of volcanic lava is much hotter than the Curie temp of Iron (700^{o}C) so we know that the iron core is much too hot to show ferromagnetic properties. [The earth reaches 700^{o}C at a depth of 20 km.]
The geologic magnetic field is a result of electromagnetism, not ferromagnetism.

MAGNETIC BUMPER BOATS

Why do iron and a few other metals show magnetic properties?
The classic explanation is that the atoms have electron arrangements that give each atom a net magnetic polarity. Those atoms influence each other and form small magnetic domains. The atoms in each domain are aligned to make a tiny magnet. Neodymium magnets are so strong, that we can demonstrate this effect with what I call Bumper Boats. Take a small Nd magnet (I use 3/8" x 1/8" dia.) and push it into softened wax of a T-light candle. Float a set of them on water to make a model of a soft iron bar. Mark the same pole end of each candle with a hot crayon.

Demonstration 3:

(a) Two ferrites align the candles into a "magnet"

Add water to a container and place the candles with embedded magnets on the water so that the surface of the pool is almost covered with the floating candles. Align two ferrite magnets (2" x 1" x 1/2") so that their faces attract. Place one at each end of the pool and observe the behavior of the magnetic candles.
The candles will line up in rows to form a large domain. It will be evident that the candles close to each ferrite magnet turn slightly to show the direction of the magnetic field near the face of the magnet.

(b) Reverse the ferrites so the candles realign.

A soft iron bar can exert a strong magnetic field if all of the atoms are aligned together, but soft iron has a low Coercivity. It cannot resist an opposing magnetic field that tends to realign the polarity of the domains. In this model, the small magnets will shift around if we flip the external magnetic field.

Often the best way to do this with an iron bar is to stroke the bar with a magnet. We can shift the external magnets to accomplish this. In the model as in real life, the alignment is rarely perfect.

(c) Coercivity demonstration.

Move a ferrite magnet over the dish, disrupting the candle-magnets.
This shows why you should NOT push two soft-iron magnets together. You will feel the mutual repulsion, but the magnets will be weakened considerably as some of the domains inside each are shifted out of alignment.

(d) Thermal Motion and the Curie Temperature

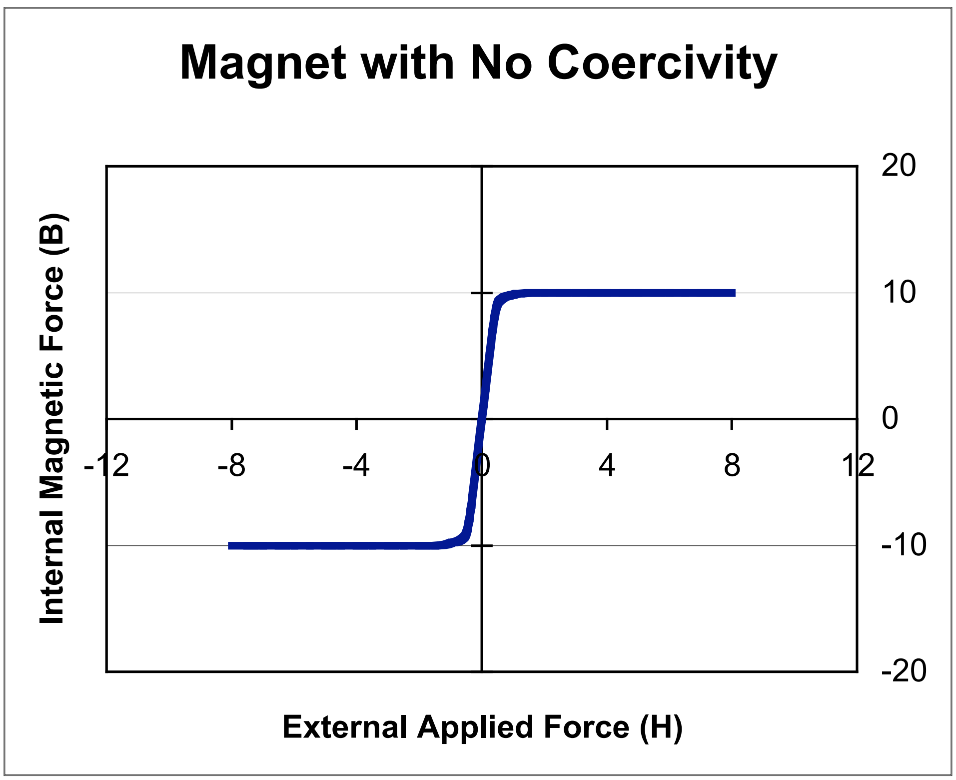
Simulate heating of an iron bar by shaking the container with the external ferrite magnets removed. The motion of the candles in the water imitates the effect of internal motion of atoms and local domains in the iron. Above the Curie temperature, a bar will no longer respond as a magnet. When the soft iron cools, the jumbled domains will form smaller less organized domains and the "bar magnet" will exert a very weak residual magnetic force

(e) Imaging Magnetostriction.

It is not true that transformers hum because they cannot remember the words!

Realign the candle magnets with the larger ferrites so that one domain is formed in the container. Now, rotate the ferrite magnets around the container to reverse the polarity of the magnet represented by the candles. Imagine that each candle is actually oval shaped. As the external magnets rotate around the pool, the flotilla of oval candles would have their long axes aligned first along the length of the dish, and then across the width. The “bar” would appear to get shorter and wider. then as the candle magnets realigned in the opposite direction the “bar” would grow longer again.
The soft iron cores in AC transformers reverse their magnetic field at a rate of 60 Hz. Each cycle causes the core change size briefly. If a core is in contact with the casing, a 60 Hz hum is heard.
A perfect transformer core would have a Hysteresis graph that would look like this:

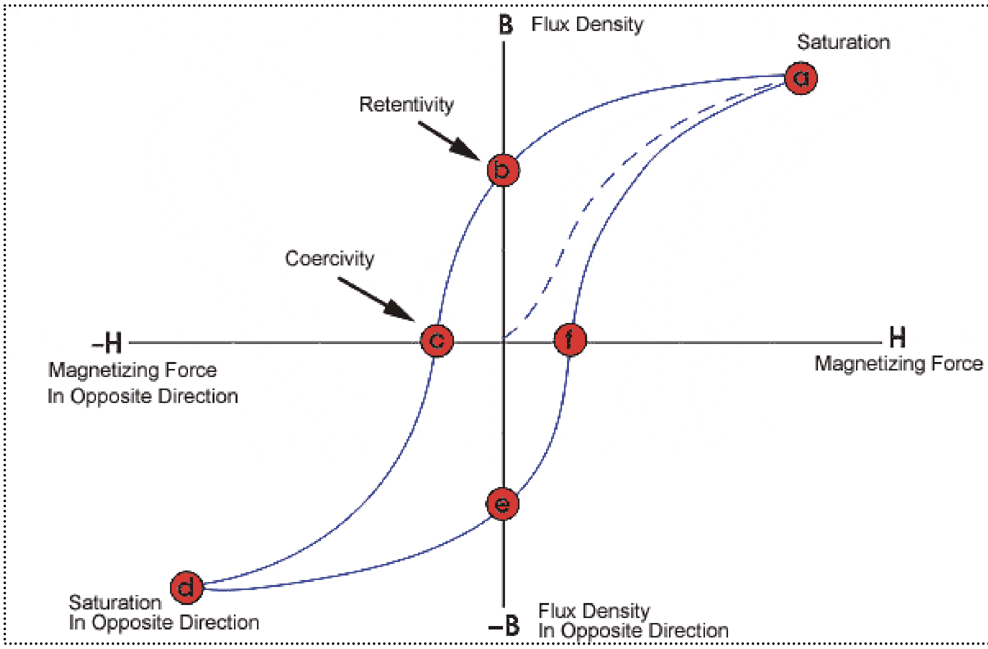
Graph A



Real materials do not change the direction of their magnetic fields instantaneously. The above material has Remanance (Retentivity); the magnetic field from the material stays at +10 until it is flipped. But it has NO Coercivity, that is, it takes no work at all to flip the field to the opposite direction.
The amount of force it takes to drive the magnetism of the object from the saturation level to zero is called the Coercivity of the material.

A “real” material would demonstrate properties shown on graph **B** below.
This is called a “hysteresis loop”.

Graph B



(courtesy of Univ. of Iowa, NDT Resource Center INTRODUCTION TO MAGNETIC IMAGING[2])

The candle pool is a good model to demonstrate these concepts.
If we use a second set of candles with stronger magnets in them, the magnetic field from those candles would be stronger after we took away the external magnets. This magnet would have a higher REMANENCE.

IF we replaced the water with little beads, the candles could still rotate, but it would take much more force to reposition all the candles. This model would show a higher COERCIVITY.
From the table below, it is evident that soft iron would follow most closely the behavior in Graph A. Neodymium would follow Graph B with points [c] and [f] much more widely separated than the other magnet types.

[2] http://www.ndt-ed.org/EducationResources/CommunityCollege/MagParticle/Physics/Magnetism.htm

Magnet Type	**Remanence** (Tesla)	**Coercivity** (Tesla)	**Max. Energy Product** (kJ/m^3)
Ferrite	0.2 – 0.4	0.3	10-50
Alnico	0.6 – 1.2	0.1	60-70
Samarium Cobalt	0.8 – 1.2	1	400
Neodymium	1.0 – 1.5	10	400
Soft Iron	0.13	0.0001	1.3×10^{-4}
Hard Iron	0.10	0.005	6×10^{-3}
Earth's Magnetic Field	0.00001		-

TYPES OF MAGNETISM

There are 5 recognized forms of magnetic materials

TYPE	RESPONSE TO MAGNET	EXAMPLE
Diamagnetic	Repelled	Water
Paramagnetic	Attracted weakly	Aluminum, Oxygen
Ferromagnetic	Attracted strongly	Iron metal
Antiferromagnetic	Attraction increases with temperature	Hematite (Fe_2O_3)
Ferrimagnetic	Strong attraction	Contains Ferric or Manganese ions eg. Magnetite (Fe_3O_4)

Diamagnetic materials have all electrons paired in orbitals. The magnetic moments of paired electrons cancel out. Thus, no atoms in the material have a net magnetic moment. When placed in a magnetic field, electron orbitals realign and the material responds by resisting that realignment. This resistance results in a force that moves the material away from the magnet.
When the external magnetic field is removed, the material returns to its normal state. Most elements in the periodic table are diamagnetic. Bismuth, Diamond and Copper have notable diamagnetic properties. WATER is also diamagnetic

Diamagnetic materials are always repelled from a magnet.

Paramagnetic materials have a few unpaired electrons per molecule and show a small attraction to a magnet as electron orbitals shift in response to the external magnetic field. However, they do not keep this response when the external field is removed. Since the alignment of the unpaired electrons is disturbed by random thermal motion within the material, even ferromagnetic materials will behave as paramagnetic compounds when heated above a certain temperature characteristic of each material. This is known as the Curie temperature.
Platinum and Aluminum are paramagnetic and Oxygen is slightly so.

Paramagnetic materials are weakly attracted to a magnet but do not attract other materials to themselves.

Ferromagnetic materials have enough unpaired electrons to react to an external magnetic field, but they are able to retain their magnetic properties once the field is removed. Above the Curie temperature, thermal motion randomizes the alignments of the internal domains and the material behaves as if it were paramagnetic.
eg. Iron Metal
Ferromagnetic materials can become magnetic in a magnetic field and that magnetism stays in the material after the external field is removed.

Antiferromagnetic materials are usually minerals with large concentrations of atoms that have several unpaired electrons. However, the crystal structure of the mineral is such that the magnetic moments of those atoms are aligned in random or in opposing directions. The magnetic properties depend on the geometry of the crystal structure and on whether the sample is a single crystal or a collection of many crystals. They will be attracted by a magnetic field and the attraction often increases with increasing temperature until the Neel temperature is reached. (The term “Neel temperature” is used for antiferromagnetic materials and is equivalent to the Curie temperature .)
Hematite Fe_2O_3

Ferrimagnetic materials are special compounds that contain a large proportion of Ferric (Fe^{3+}) or Manganese (Mn^{2+}) ions. These ions have unpaired electrons in all five 3d orbitals and so have the largest magnetic moments of the common transition metal elements. In these compounds, the direction of the magnetic moments are fixed by the crystal structure, but the domains are not all equal in size, and a permanent magnetic moment results.
Magnetite Fe_3O_4

Fun with Lenz's Law

Lenz's Law states:

> *"The current induced in a conductor by a moving magnet is such that the magnetic field resulting from the current will have a polarity that opposes the motion of the magnet."*

If the current is induced in the body of a conductor, such as a piece of metal, it is referred to as an Eddy Current.

The effects are small in laboratory scale materials, but Neodymium magnets are so strong for their mass(and so cheap) that we can see dramatic effects easily.

Demonstration 4

Drop a cylindrical Nd magnet through a 2 m lengths of various tubes. The diameter of each tube should be just slightly larger than the magnet.
A plastic tube shows us the effect of gravity.
Copper tubes show different magnetic susceptibilities. As the magnet falls, a current is induced in the pipe by the moving magnet. This current opposes the motion and slows the fall of the magnet.
Aluminum tubes show the most dramatic effect.

Place identical magnets inside a plastic sleeves. Drop one down a normal copper pipe and the other down a pipe that has a slot cut down the length of it. The space interferes with the formation of eddy currents and the magnet falls faster than in the normal pipe. If an uncovered magnet is dropped down the slotted pipe, the metal magnet can contact the two sides of the slot and complete the circuit. An uncovered magnet falls more slowly than a covered magnet.

The four pipes can be arranged easily in a wooden stand so that students can release the magnets simultaneously and see (and hear) them drop out the bottom of the apparatus.

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Although "small" in the laboratory, these effects are very important factors in industry. The opposition offered by an eddy current applies whether it is induced by a moving magnet, or by another electric circuit. In transformers, eddy currents can cause the loss of useful energy as electric power is stepped up or down in voltage. Long transmission lines have experienced induced current surges caused by changes in the earth's magnetic field when it is being distorted by intense solar flares. Power blackouts have resulted as control equipment became overloaded.

Demonstration 5: Aluminum Pan and Pendulum

If a cylindrical magnet is suspended on a long piece of dental floss or other non-twisted fibre, about 1 or 2 mm above the flat bottom of an aluminum pan, the pendulum exhibits very interesting behavior. The swing is damped dramatically if the magnet swings close enough to the aluminum metal.
Suspend the magnet with the polar axis horizontal.
Swing the pendulum (a) with the polar axis in the direction of the swing and
(b) with the axis perpendicular to the direction of swing.
Now swing the pendulum at 45 degrees to the direction of the magnet's polar axis. The swing will "polarize", gradually starting to swing in the easiest direction.

The magnetic damping effect is used in some types of brakes and on the arms of pan balances. Braking without physical contact!

Try swinging the pendulum over a copper penny (non-magnetic). and over some aluminum foil folded to about 10 thicknesses. You can actually start the pendulum in motion by "pulling" the magnet with the aluminum.

Fun with ELECTROMAGNETISM:

Most of us have "viewing tables" with various embedded coils waiting in dusty cupboards. I think they can lead to some interesting activities if we start off slowly and work through the theory with students.

Demonstration 6

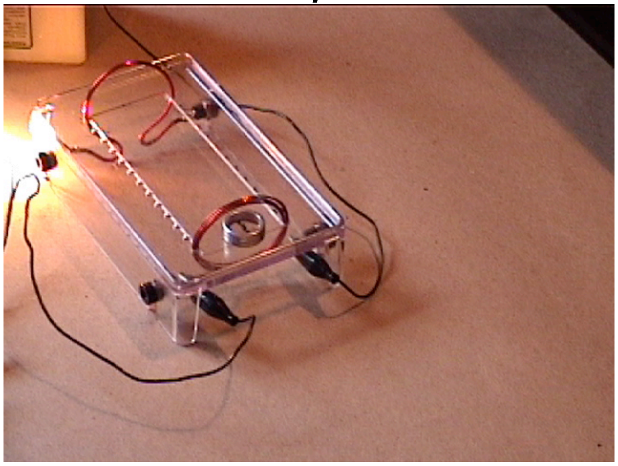
The circuit that I use begins with a Lead-Acid motorcycle battery. These batteries are small, lightweight, yet can supply a large current at 12V. I include a 12V headlight bulb and socket as a load (the high-beam filament passes the most current) and a door-bell push-button switch to allow power to be pulsed in the circuit. Long leads can be made from audio speaker wire and alligator clips.

Safety Tips: 12V is usually safe to work with if skin is dry. However, students should always use appropriate techniques for avoiding shock. Students should only handle one wire at a time. Since a short circuit can overheat wires quickly, leading to possible burns or a fire, First Aid materials and a fire extinguisher should always be on hand.
The battery should remain disconnected until the circuit has been fully assembled. There is a chance of Hydrogen gas accumulation inside any lead-acid battery. To avoid the chance of explosion, the last connection in the circuit should always be made at a distance from the battery.

Inexpensive see-through compasses can be used to map the magnetic field around the coil but note that on the overhead projector, N & S look almost the same, so YOU can see the direction of the polar field, but your audience cannot.

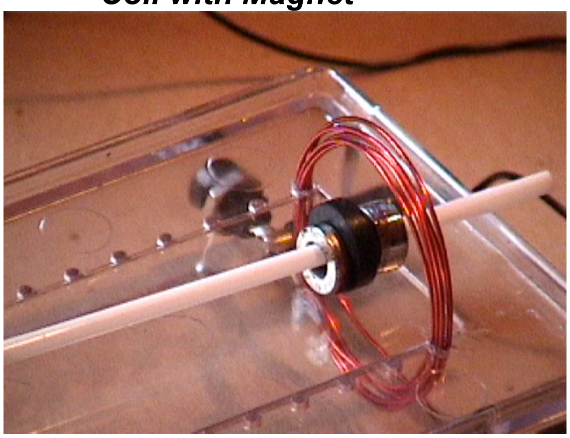
This picture shows the basic set-up for a multi-wire demonstration coil

Coil with Compass



The following picture shows a ring magnet supported by a straw so that it is in the centre of the coil. The straw is held up by two rubber plumber's washers. The magnetic effects are too small to affect the magnet while the load is in the circuit. Remove the light bulb from the circuit and use the push button to pulse high current through the coil.

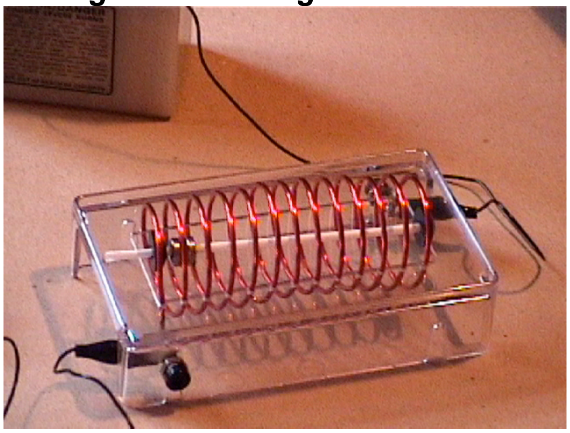
Coil with Magnet



Depending on the polarity and position of the magnet relative to the coil, it will slide either forward out of the coil, or be pulled back into the centre of the coil.

Repeat this set-up with a long demonstration coil as in the picture below:

Long Coil and Magnet on Straw



Students can see the effects of position and polarity on the motion of the magnet as the current is pulsed through the coil. Pulses should not last more than 1 second to avoid overheating the leads.

Student Activity:
Using a hollow cylinder Nd magnet (1/2"L x 1/4"OD x 1/8"ID), push the straw through the centre for visibility and guidance. Students should wrap 2 m of thin wire into a coil around the outside of a small (13x100 mm) test tube and tape the wire in place on the tube.
Put the magnet inside the tube, position it carefully using the straw and connect the coil to the no-load power circuit. When the switch is pushed, the magnet can be launched out of the end of the tube. (The magnet travels less than 1/2 metre.)

I suggest that this is a great cumulative activity for students. They must identify the correct polarity of their magnet-straw projectile and identify the polarity of the coil when hooked up to the battery circuit. Coil-winding skills are important and the success of the cannon can be measured by the distance the magnet is launched.
For convenience *as well as safety*, the magnet should be launched into a clear plastic tube. The distance of travel can then be easily measured and the projectile will not fall to the floor, avoiding loss or damage. Most home supply places sell clear plastic sleeves to fit over fluorescent light tubes. They are an inexpensive addition to the apparatus.

Several related concepts can be tested:

1. Will 2 magnets be better than one? The magnetic field is stronger, but now the projectile weighs twice as much!

2. A copper, aluminum or iron core can be placed inside the magnet using small nails. The wide head forms a “magnet cap” that can focus the magnetic field. Are these cores effective? How could they set up a control with the same mass? (Use a wood core and make projectiles of equal mass).

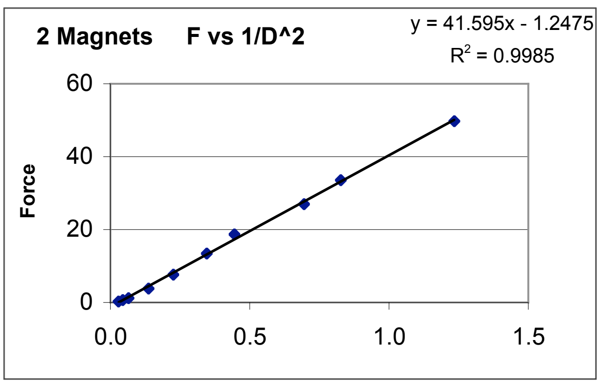
3. To get strong uniform magnetic fields for the above trials, use a hollow transformer coil. A 500 winding coil gives excellent results.

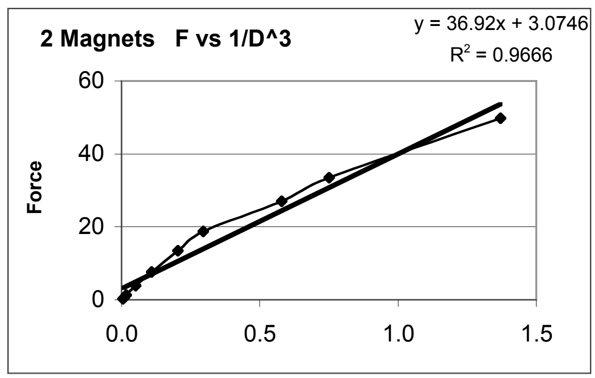
WARNING: Be careful. There are enough little variables here that YOU may end up playing with the apparatus for too much of your valuable time. Let the students discover the details as you watch each group prepare and execute their launch sequences.

Measuring Magnetic Force

If you have a good centigram or milligram electronic scale, you can do a great little student project measuring the variation of magnetic force with distance.

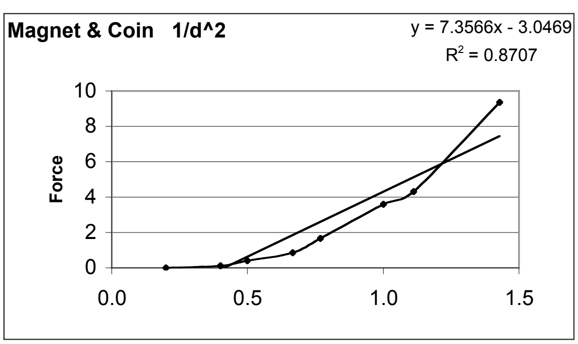
Fill a PET water bottle with enough water to weigh just under the maximum weight that your scale measures. Tape a magnet to the cap of the bottle and place it on the scale. Zero the scale, then lower another magnet down toward the cap of the bottle. Record the distance and the lifting force (shown as a negative weight reading) as the mobile magnet approaches the fixed one.
Since the text tells them so, the kids will "know" before they start that the variation of magnetic field with distance is a $1/r^2$ behavior.
Great!

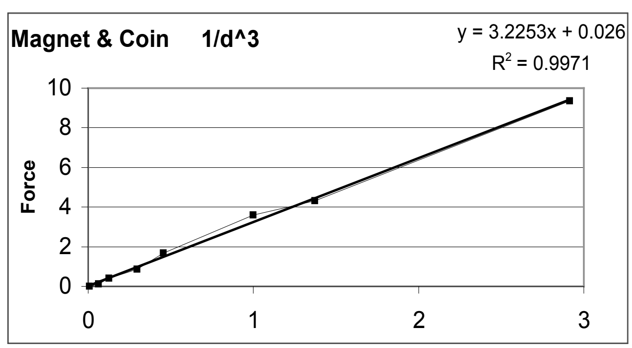




Now repeat the experiment with a coin taped to the cap (just unscrew the cap with the magnet and screw on another one with the coin attached).

This time a different behavior is seen





Mathematically, this is similar to a point charge attracting an electric dipole. Intuitively we can see that with the 2 magnets, the N pole on each magnet attracts the S pole on the other one. With the coin, the poles are induced, so a much weaker attraction exists and the force is reduced much more as we move away from the attracting magnet.

There are many variations available:

Stationary Magnet	**Mobile Magnet**
N pole facing up	S pole facing down
Polar axis horizontal	Polar axis vertical
Polar axis horizontal	Polar axis horizontal
Polar axis horizontal	Current carrying coil with magnetic axis horizontal
Polar axis vertical	Current carrying coil with magnetic axis vertical

Recall that the definition of the unit of magnetic field strength is:

1 Tesla = 1 Newton.second/Coulomb.metre
= 1 Newton/ Ampere.metre

Can your students confirm the unit experimentally?

All of this fun flows from the availability of strong, cheap ferrite magnets and strong, small, cheap neodymium magnets. I hope that I have stimulated your interest in using these fascinating objects in your classroom.

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USEFUL LINKS:

1. For an extremely rich source of ideas and accessible explanations see:
The Magnetman Rick Hoadley
http://my.execpc.com/~rhoadley/magindex.htm

2. For an excellent, more advanced discussion of Magnetism, connect to the University of Iowa, NDT Resource Center at:http://www.ndt-ed.org/EducationResources/CommunityCollege/MagParticle/Physics/Magnetism.htm

3. An engineering look at Magnetics can be found in an excellent resource manual available at www.dextermag.com

4. Reasonably priced magnets and other equipment can be found at Indigo Instruments
http://www.indigoinstruments.com/magnets/rare_earth