Magnetism:

Electromagnet and Ferromagnetic Fluid

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Magnetism 101

Magnetic fields surround and are created by electric currents, magnetic dipoles, and changing electric fields. Magnetic phenomena were first observed at least 2500 years ago in fragments of magnetized iron ore found near the ancient city of Magnesia. These fragments were examples of what are now called permanent magnets, which were found to exert forces on each other as well as on pieces of iron that were not magnetized. What is this magnetic field? A moving charge or a current creates a magnetic field in the surrounding space, in addition to its electric field. The magnetic field exerts a force on any other moving charge or current that is present in the field (Young & Freedman).

Magnetic fields can be demonstrated in a variety of ways, but one demonstration that is a bit more exciting than the rest relies on the use of a ferromagnetic fluid, which is a fluid that will take the shape of a magnetic field. This can be further demonstrated by changing the strength of the magnetic field present and can be done so with the use of an electromagnet of varying strength.

Electromagnet

An electromagnet works under the basic principles of physics involving induced magnetic fields. A popular demonstration in physics classrooms to show these concepts involves running a bar magnet through a coil of wire that is attached to a voltmeter. The changing magnetic field produced by the magnet's movement through the coil produces an electric current in the wire, which is read by the voltmeter. This demonstration can then be reversed to create an effective electromagnet. Instead of the magnet moving through the coil of wire to create a current, a current is applied to the coil of wire to create a magnetic field (Jefferson Lab). This coil is then wrapped around an iron core to harness the magnetic field and turn the ferromagnetic core into a magnet.

One essential electromagnetic property that allows this theory to work has to do with the magnetic field of an infinite wire. When electric current is run through a wire, a magnetic field, *B*, is created that runs concentric to the wire with a magnitude:

$$B = \frac{\mu_0 I}{2\pi R},$$

where μ_0 is the permeability of free space and is equal to $\mu_0 = 4\pi \times 10^{-7} \frac{Tm}{A}$, *I* is the current in amps running through the wire, and *R* is the distance in meters measured out from the wire (Stewart & Stewart).

The magnitude of this field is compounded when the wire is then wrapped into a solenoid, and is given by the equation:

$$B = n\mu_0 I,$$

where n is the number of turns in the solenoid divided by the total length of the solenoid, and I is again the current running through the wire. As shown, the magnitude of the magnetic field present in a solenoid is dependent on the number of turns present; the more turns in the solenoid, the stronger the field is by that factor. This field is present entirely within the solenoid, leaving zero magnetic field outside the solenoid. This is what makes an electromagnet so efficient. By placing an iron core inside of a current-carrying solenoid, the magnetic field generated by the solenoid is collected by the core and can then be directed elsewhere.

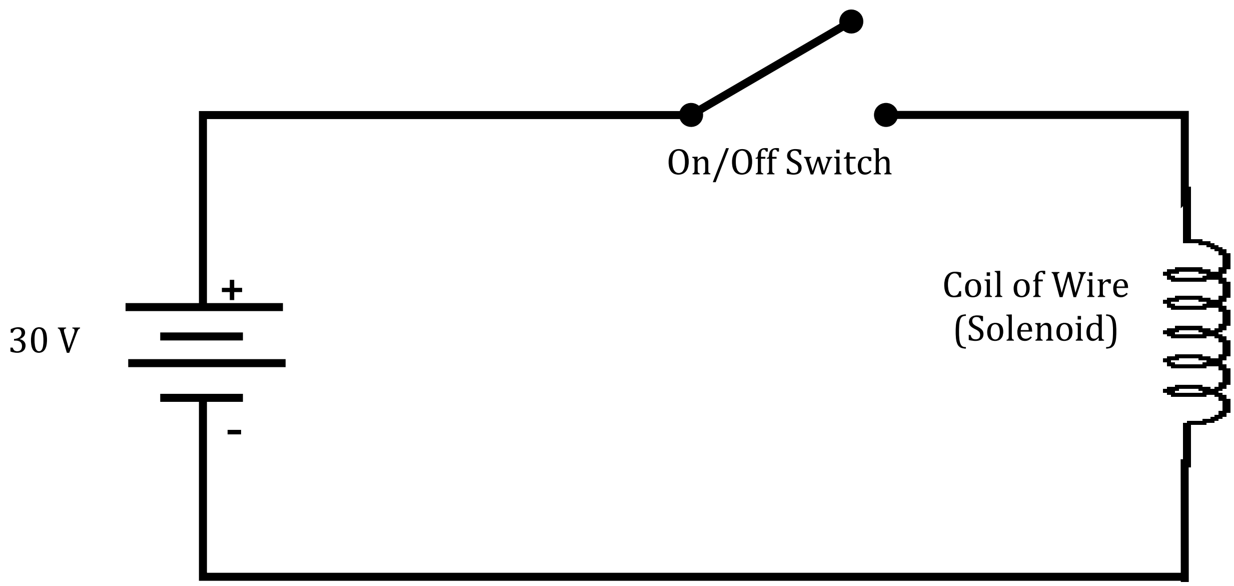
One particularly efficient design for an electromagnet is to use an iron core that is bent into a horseshoe shape. This creates a concentrated area of magnetic field generated, yielding maximum results when demonstrating the strength of the magnetic field present. Another way to strengthen the field is to increase the current running through the wire, which—among other means—can be done by increasing the voltage of the power source as long as resistance does not increase significantly within the system. In the same fashion, a system with varying resistance can create an electromagnet with varying strength, which can be extremely useful when demonstrating magnetic fields. Yet another way to increase the strength of the field (as previously hinted) is to increase the number of turns present in the solenoid. This can be difficult to do with thick wire when a very finite length of iron core is present, so it may be necessary to decrease the radius of the wire in order to increase the number of turns present. However, decreasing the radius of the wire in order to increase the number of turns may become a bit of a tradeoff, depending on the system present. A wire with a smaller radius has a higher resistance than that of a wire with greater radius, as can be inferred from the following formula,

$$R = \rho \frac{L}{A}$$

where ρ is the resistivity of the wire, L the length of the wire, A the cross-sectional area of the wire, and R the resistance of the wire, an “intrinsic feature of the material which resists current flow” (Stewart & Stewart). As the radius of the wire decreases, that area decreases as well, thus increasing the overall resistance. The greater the resistance, the less current will be able to flow through the system. However, this can be compensated for with a significant increase in turns, whatever the system will allow for.

WARNING: The increase in number of turns of wire, along with the increased resistance in combination with the high amperage of the system, will cause the system to increase in temperature, varying from relatively warm to catastrophic meltdown (i.e. wall outlet…it was Carl’s idea).

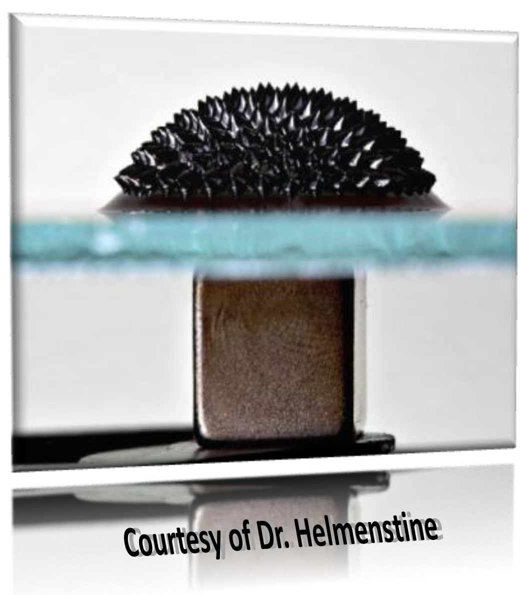
Diagram of Apparatus



Ferromagnetic Fluid

Magnetic fields propagate in all sorts of crazy directions, which can be viewed by sprinkling iron filings in the area permeated by this magnetic field. A student witnessing this demonstration will then see the field lines of the magnetic field. In the case of a bar magnet, a student will see field lines that sweep from the North to the South poles of the magnet. These field lines can also be viewed by implementing the use of a ferromagnetic fluid.

A ferromagnetic fluid is an iron-enriched fluid wherein the iron is bounded to the liquid base at the molecular level. If one were to simply stir iron filings into water and then hold a magnet to the surface of the water, the iron filings would leave solution and stick to the magnet. In the case of the ferromagnetic fluid, the "iron filings" are instead iron atoms in a chemical compound, as opposed to being suspended in a solution. When brought into close proximity of a magnet, this ferromagnetic fluid assumes the shape of the applied magnetic field, spiking up in the direction of the field lines, looking like crazy alien fluid, as seen to the right.



Making a ferromagnetic liquid involves a terribly complicated chemical process. The main goal of the procedure is to chemically compound magnetite, a ferrochloride solution, to kerosene, but the actual procedure is a bit more difficult than simply adding the two together. The following is a brief description of how ferromagnetic fluid can be made, and since it is largely a chemical process and involves very little relevant physics, the description will be kept to a minimum.

To make magnetite, solutions of ferric chloride and ferrous chloride must be mixed, yielding a muddy brown liquid. If the chemist does not have ferric chloride and ferrous chloride solutions, solutions can be made from powder forms of the chemicals (approx. 1M). The chemist should then add ammonia to the solution, and the contents will turn black and start to clump together. This is the magnetite.

The magnetite is the portion of the ferromagnetic fluid that responds to a magnetic field, but the magnetite solution would not produce an effective liquid on its own. The magnetite must therefore be bound with oleic acid, a binding agent, and infused into a solution of kerosene. Once this is complete (if done properly), the chemist will have a properly working ferromagnetic fluid, and they are ready to rock.

WARNING: The aforementioned ferromagnetic fluid can be extremely threatening, particularly to clothing, skin, mucous membranes, etc. Please use extreme caution when dealing with the fluid. Do not pour the liquid onto individuals, and whatever one may do, do not splash magnets into Petri dishes filled with the fluid. It will splash onto individuals' clothing and over tables and will be difficult to clean (once again, Michael is very apologetic on this point).

Conclusion

Overall, this project provides for a great demonstration for a physics class. Furthermore, this project was quite pedagogical in its effective—though sometimes painstaking—teaching methods of varying physical concepts. When students invest their time, resources, knowledge, blood, sweat, tears and (in particular cases) money, and become void of any social interaction, they begin to really grasp the concepts presented before them. It is one thing to learn *about* physical concepts in a classroom; it is an entirely different thing to actually *learn* the concepts in a real-life fashion. A student's interest in a subject will also peak when getting to apply the concepts they learn in class to applicable projects and situations outside of the classroom.

The authors of this report hereby suggest this project—either in its entirety or merely in its separate entities—to future students of University Physics II. Sure, the authors may have nearly killed themselves with an unsafe combination of kerosene and hot plates; they may have nearly cut their thumbs off when a hacksaw went awry. But they also shed tears of joy when their project was complete, and cried cries of relief when their belated paper was finally completed.

From this moment on, the authors of this report officially conclude this paper and bestow its contents unto you, Mr. Dr. Stewart. No, thank *you*. The pleasure's ours.

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