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# Simple Experiments to Help Students Understand Magnetic Phenomena

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The principles of magnetism are a common topic in most introductory physics courses, yet curricular materials exploring the behavior of permanent magnets and magnetic materials are surprisingly rare in the literature. We reviewed the literature to see how magnetism is typically covered in introductory textbooks and curricula. We found that while most texts contain a relatively complete description of magnetism and its relation to current-carrying wires, few devote much space to the development of a model that explains the magnetic phenomena students are most familiar with, e.g., the interaction between permanent magnets and ferromagnetic materials.[1] We also found that while there are a wide variety of published articles exploring the various principles of magnetic induction, only a few of these explore the basic interactions between common magnets, ferromagnetic materials, and current-carrying wires.[2,3] The activities described in this paper were designed to provide a structured series of simple experiments to help students develop a model of magnetism capable of explaining these phenomena.

The following activities were developed as part of the Explorations in Physics (EiP)[4] curriculum. Explorations in Physics is a student-centered, activity-based curriculum for college-level nonscience majors. Modeled after Workshop Physics,[5] this curriculum makes use of guided inquiry techniques, computer measurement tools, and peer learning. Since the primary focus of this curriculum is to improve students' understanding of the process of scientific inquiry, we structure these activities to guide students through the cyclic process of building and testing a coherent mental model based on simple observations.

In the classroom, these activities are organized as follows. First, students are introduced to magnets and encouraged to explore the interactions between magnets and other materials. Next, they investigate the phenomenon of magnetization using magnets and paperclips. After that, we help them develop a consistent physical model that explains the observations they have made. Then the students construct a simple compass using magnetized paperclips and discover why magnets are described using the terms *north* and *south poles*. Finally, the interaction between magnets and current-carrying wires is briefly explored.

## Magnets and Magnetic Materials

We begin with an activity inspired by the Physics by Inquiry[6] curriculum. Students are given a number of similarly shaped objects (cylinders, approximately 0.5 cm in diameter and about 3-4 cm long) made of different materials (Fig. 1).[7] The students play with these objects and, with very little intervention from the instructor, categorize them based on how they interact into three groups—*magnets*, *nonmagnet attractables* (or simply *attractables*), and *nonmagnet nonattractables* (*nonattractables*). As part of this activity, students come to realize very quickly that while two magnets can either attract or repel, a magnet and an attractable will always attract.

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We finish up this section of the course by trying to distinguish between the two ends of a bar magnet. Through class discussion, it becomes clear that we have no way of knowing which end is the "north" pole and which is the "south" pole without bringing in a magnet whose ends are already known. Taking a discovery-oriented approach, we choose one of our magnets to be the classroom "magnet standard" and use a piece of tape to mark one of the ends. Since we don't know whether this is a "north" end or a "south" end, we simply refer to the ends as "taped" and "untaped." Throughout the remainder of the class, we use this magnet as a standard by which all other magnets are compared.

**Fig. 1. Collection of materials students classify based on their magnetic interactions. We typically use an assortment of magnets, ferromagnetic materials, and nonmagnetic materials (materials with a very weak magnetic interaction). The figure shows from left to right: magnetic steel, wood, Plexiglas, copper, brass, aluminum, and a magnet.**

## Magnetization

To begin the exploration of magnetization, students play with a magnet and some paperclips. They are asked to try to lift a paperclip without using their hands and without the paperclip touching the magnet. It doesn't take long for students to figure out that a paperclip hanging from a magnet can be used to pick up another paperclip. Thus, the paperclip itself seems to be acting like a (weak) magnet. To really bring home this point, we ask students to hold onto the upper paperclip with their fingers while they slowly remove the magnet. To the surprise of many students, the bottom paperclip does not fall. So if it wasn't clear before, it is now very clear to the students that a magnet can *physically* change a nonmagnet attractable into a weak magnet.

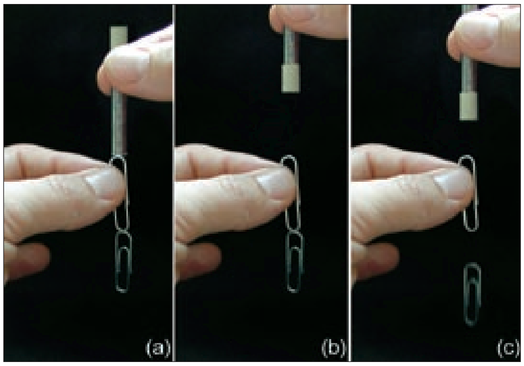


**Fig. 2. (a) Two paperclips suspended from a permanent magnet that has its taped end up. (b) The magnet has been removed and flipped over so that it is now taped end down. (c) The magnet is then slowly brought close to (but not touching) the upper paperclip and the second paperclip falls.**

We then ask students to flip the magnet over and slowly bring it back toward the top end of the upper paperclip. That is, if the upper paperclip was initially hanging from the untaped end, then they should slowly bring the taped end toward the upper paperclip. As the magnet is brought toward the upper paperclip, there comes a point when the lower paperclip spontaneously falls and that the upper paperclip can no longer be used to lift another paperclip (Fig. 2). Thus, the magnet has again had a physical effect on the paperclip. This time, it appears to have changed the paperclip from a weak magnet into a nonmagnet. In addition, this change has been brought about without any contact between the magnet and the paperclip.

At this time, it is worth pointing out to students that although a magnetized paperclip appears to be acting like a weak magnet, we have yet to verify that this is so. All we really know is that the paperclips remain attracted to each other in the absence of a magnet. This may or may not be due to one of the paperclips acting like a magnet. Since the students have already categorized magnets as objects that can attract *or repel* other magnets, it is a relatively simple task to test a magnetized paperclip to see if it has the properties of a magnet. One merely needs to demonstrate that a magnetized paperclip can exhibit both attraction and repulsion with another magnet.

To demonstrate this, we begin by floating a magnetized paperclip in a small dish of water. Although this sounds difficult, it is actually quite easy to do. The students first magnetize the paperclip by bringing it into contact with a permanent magnet. Next, they float the paperclip on the surface of a shallow dish of water. The key to successfully floating a paperclip is to grasp it by the long edges between a thumb and index finger and then slowly lower the paperclip toward the surface of the water. When the paperclip is very close to the surface of the water—once your fingers are getting wet—gently release the paperclip (Fig. 3).[8]

To verify that their floating magnetized paperclip is indeed a weak magnet, the students slowly bring up one end of a magnet toward the dish of water until they see one end of the paperclip move toward the magnet demonstrating attraction. Upon flipping the magnet around, students observe that the paperclip moves away, flips around, and moves back toward the magnet. This demonstrates that one end of the paperclip is repelled while the opposite end is attracted. By repeating this procedure and making careful observations, students can deduce that touching a taped end of a magnet to a paperclip gives rise to an untaped end on the paperclip and vice versa. This important observation is used as a key point in developing what we call the *microscopic magnet model.*

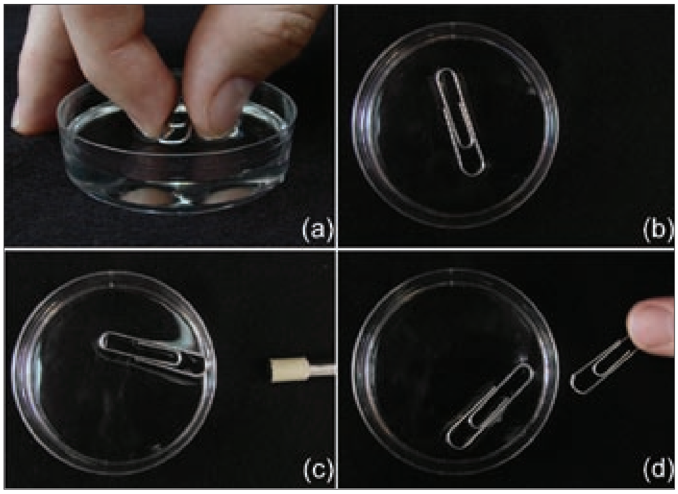

**Fig. 3. A magnetized paperclip is tested to see if it behaves like a magnet. (a) Gently dropping the paperclip onto a Petri dish of water will allow the paperclip to float. (b) The magnetized floating paperclip has aligned itself with the local magnetic field. (c) The floating paperclip interacts with a small permanent magnet that is brought nearby. (d) The floating paperclip interacts with another magnetized paperclip that is brought nearby.**

The above activity can be repeated with the permanent magnet replaced by a paperclip, magnetized by bringing it into contact with a permanent magnet. Thus, students can directly observe the interaction between two magnetized paperclips. This observation emphasizes to students that each of the paperclips has indeed become a weak magnet.

## The Microscopic Magnet Model

At this point, we would like students to develop some kind of mental model that explains what they have observed. The purpose of this activity is not to introduce a complete quantum-mechanical description of the situation. Rather, our goal is to give the students some experience constructing and scrutinizing a microscopic model based on their observations. We begin with a discussion and allow students to pose their own ideas about what might be happening. A key question to ask the students is whether or not they think the magnet is physically *creating* anything new inside the paperclip. Most students will say they don't think so. This suggests that instead the magnet might be causing some kind of "rearrangement" inside the paperclip. Now at this point it is very tempting for some students to suggest that "microscopic charges" are somehow responsible. Perhaps this is because most students have already heard that charges can move around in certain materials, namely metals. If students are then asked why certain metals are attracted to magnets while other metals are not, most will drop the idea that charges are somehow responsible. It is also possible at this point to directly explore the interaction between charges and magnets with a few simple sticky tape experiments. If the students are already familiar with sticky tape experiments, it becomes clear after a few observations that magnets act like neutral objects.

This is an ideal opportunity to remind students that we know from our own experiments that magnets can attract and repel other magnets. So instead of microscopic *charges* being affected by the magnet, perhaps it is microscopic *magnets* that are affected by the magnet. That is, maybe each atom or molecule inside the paperclip behaves like a tiny microscopic magnet. Although many students are a bit uncomfortable with this idea initially, it is worth reminding them that most of the class was perfectly happy to postulate that microscopic "charges" were somehow responsible. Thus, postulating that microscopic magnets are responsible is really not much different. Whatever the reason, the important point is to ask whether or not this idea can be used to explain the observations.

We usually begin by asking students to use the microscopic magnet model to explain the different categories of materials that have been defined earlier: magnets, nonmagnet attractables, and nonmagnet nonattractables. Most groups quickly conclude that a magnet can be described as a material in which all (or most) of the microscopic magnets are fixed, pointing in the same direction. Similarly, nonmagnets can be described as materials that have all their microscopic magnets pointing in random directions. The difference between a nonmagnet attractable and a nonmagnet nonattractable is that the nonattractable's microscopic magnets are frozen in place (like the magnet) while the attractable's microscopic magnets are free to spin around. This means that in the presence of a magnet, the microscopic magnets of the attractable will orient themselves so that there is an attractive force regardless of which end of the magnet is brought nearby. This simplistic model can be quite empowering to students since they can use it to explain some relatively sophisticated phenomena. For example, students often spontaneously use this model to explain how a paperclip can be turned into a (weak) magnet and then turned back into a nonmagnet.

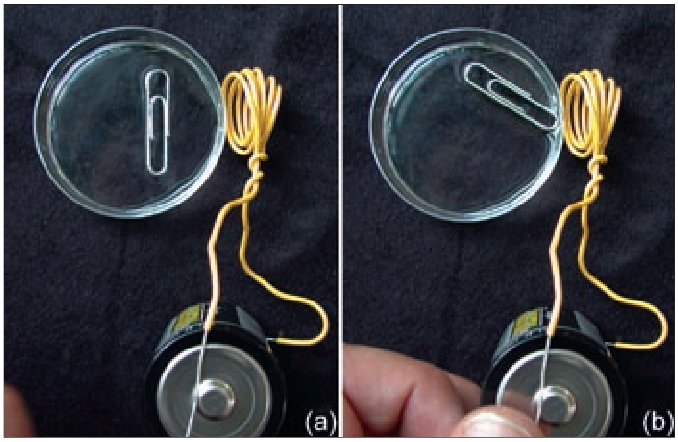


**Fig. 4. (a) A magnetized paperclip aligned with the Earth's magnetic field. The wire ends are not connected to the terminals of the battery. (b) When the coil is connected to the terminals of the battery, one end of the paperclip is attracted to the current-carrying coil of wire.**

## The "North" Pole

Another experiment the students conduct is designed to help them discover which end of their magnet (taped or untaped) corresponds to the "north pole" and which corresponds to the "south pole." We ask each group of students to prepare a floating magnetized paperclip and position them (away from metal objects) at different points in the room. Immediately the students recognize that the paperclips all align along the same direction and many make the connection that these floating magnets act like compasses.[9] Most students spontaneously conclude that the paperclips are aligned in a north-south orientation. Based on this observation, we discuss the possibility of naming the ends of our magnets based on the direction they are pointing. Of course, we also explain that it is completely arbitrary which end you call "north" and which end you call "south." However, it seemed reasonable to people hundreds of years ago to call the end that points to the north the "north-seeking pole" of the magnet, or "north pole" for short. An excellent follow-up question is to ask the students whether or not the Earth itself is acting like a magnet, and if so, which end is magnetic north and which end is magnetic south.

## Current-Carrying Wires

After performing some experiments with magnets and sticky tape to demonstrate that magnets are not affected by stationary charges any differently than nonmagnets, we experiment with current-carrying wires and magnets. Students construct their current-carrying wires by simply connecting the opposite ends of a piece of wire to the terminals of a 1.5-V "D" alkaline battery. As long as they do not hold these wires in contact with the battery for more than a few seconds, it is safe to short the battery in this way.[10]

Once again, the students float a magnetized paperclip in water. Then, using the battery and wire, they observe the interaction between the current-carrying wire and the magnet. Although the students notice the interaction right away, they find it difficult to devise rules for how the current-carrying wire and the magnet interact with each other without further instruction. Thus, we ask the students to form a single loop with the wire and investigate how this loop interacts with the floating magnet. Then, we have them try making multiple loops with their wire and try the experiment again (Fig. 4). By repeatedly experimenting with different orientations of the coil and paperclip, students can discover their own "right-hand rule" to govern the behavior of the current-carrying coil. We also ask students to try winding the current-carrying wire around the different objects shown in Fig. 1. It is immediately apparent that using a nonmagnet attractable as a core greatly improves the strength of the electromagnet. More importantly, students can explain why this is to be expected according to the microscopic magnet model.

## Reference


1. Two notable exceptions are the Physics by Inquiry curriculum (L.C. McDermott, *Physics by Inquiry*, Wiley, New York, 1996) and the Constructing Physics Understanding (CPU) curriculum (details can be found at http://cpuproject.sdsu.edu/default.html). While some of the activities and much of the inquiry-based nature of our curriculum has been heavily influenced by the Physics by Inquiry curriculum, the Explorations in Physics curriculum is intended for a general audience of college-level nonscience students, in contrast with Physics by Inquiry's specific focus on teacher preparation.
2. Charles A. Sawicki, "Inexpensive demonstration of the magnetic properties of matter," *Phys. Teach*. **36**, 553–555 (Dec. 1998).
3. F.M. Gibson and Iain MacInnes, "Symmetry in electromagnetism—A new magnetic needle," *Phys. Teach*. **38,** 316–317 (May 2000).
4. D.P. Jackson, P.W. Laws, and S.V. Franklin, *Explorations in Physics: An Activity Based Approach to Understanding the World* (Wiley, New York, 2002). Also, see http://physics.dickinson.edu/EiP.
5. P.W. Laws, *Workshop Physics Activity Guide* (Wiley, New York, 2004). Also, see http://physics.dickinson.edu/wp.
6. L.C. McDermott, *Physics by Inquiry* (Wiley, New York, 1996), pp 277-322.
7. We do not discuss the topics of paramagnetism and diamagnetism because these are typically very small effects that cannot be easily observed. Thus, by "nonmagnetic" we simply mean materials that are not noticeably attracted to a magnet.
8. If the paperclip happens to sink, it is important to dry it off completely before attempting to float it again. It is extremely difficult to make a wet paperclip float on the surface of water.
9. In order to be sure that this portion of the activity works, it is essential that the instructor perform a test (this can be done with a collection of magnetic compasses) before the class begins to ensure that the local magnetic field is not dramatically affected by nearby magnetic objects. Typically we bring together all of the compasses on a cardboard box (no metal) in the middle of the room, away from any metal furniture or room fixtures.
10. If the terminals of the battery are left shorted for a long time, more than a minute or so, the battery can become dangerously hot.


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**David P. Jackson** *received his PhD from Princeton University and is currently an associate professor and department chair at Dickinson College. He has a wide range of professional interests including magnetic fluid pattern formation and curriculum development.*

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