

Magnetism as a Size Dependent Property: A Cognitive Sequence for Learning about Magnetism as an Introduction to Nanoscale Science for Middle and High School Students

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Abstract: In this study, we use evidence from students in grades 10-12 ($N = 148$) to document the ways in which children learn about and model their conceptual understanding of magnetism. Our model-based design capitalizes on phenomena that are engaging to students, to describe the behavior of magnetic materials across scale, from the familiar to the nanoscale. Data are drawn from written responses to pre- and post-questionnaires, embedded assessments, activity journal pages, and informal interviews, to describe a progression of students' mental models of magnetism. Our goal is to integrate multiple related concepts to describe possible pathways for learning. An implication of this work is that it may be used to inform level appropriate strategies for both instruction and assessment for the study of magnetism across scale.

Introduction

Magnetism is long standing staple of science curricula from grades K-12 and beyond. It is a phenomenon that fascinates and interests students of all ages. Yet we know surprisingly little about people's conceptions of magnetism (Hickey & Schibeci, 1999; Maloney, 1985), nor have conceptions of magnetic phenomena been investigated as intensively as other physical phenomena such as electricity, force and heat (Borges & Gilbert, 1998; Erikson, 1994; Hickey & Schibeci, 1999).

Researchers have previously documented students' conceptions related to magnetism such as (a) models of magnetism (Borges & Gilbert, 1998; Constantinou, Raftopoulos, & Spanoudis, 2001; Erikson 1994); (b) the confusion between magnetism and charge (Borges & Gilbert, 1998; Hickey & Schibeci, 1999; Maloney, 1985); (c) action at a distance (Bar, Zinn, & Rubin, 1997); and (d) the concept of field (Bradamante & Viennot, 2007; Guisasola, Almudi, & Zubimendi, 2004; Guth & Pegg, 1994). Less study has been devoted to the exploration of how students' conceptions about magnetism progress or to document the transitional nature of students' conceptions and mental abstractions as they learn. Nor have students' conceptions of magnetism across scale been investigated. Learning about nanomagnetism, for example, provides a means of not only introducing concepts of nanoscale science to children, but it is a vehicle to reinforce and apply science concepts already existing in the curriculum.

The concepts of magnetism pose a challenge for learners; they require higher levels of cognition and mental imagery than more concrete and tangible concepts (Barrow, 1987; Borges & Gilbert, 1998; Guisasola, et al., 2004). The idea of an object causing a force to be exerted on another without touching, or reasons why an object could be attracted toward either end of a magnet are counterintuitive for children (Constantinou, et al., 2001). Children commonly believe that magnets are electrically charged, and that electrostatic and magnetic interactions are the same (Borges & Gilbert, 1998; Haupt, 1952; Maloney, 1985). Many students may also believe that the magnetic field has a finite boundary (Bar, et al., 1997), or that the field lines are a concrete entity (Guisasola, et al., 2004; Guth & Pegg, 1994). Understanding these concepts requires the ability to construct mental models of abstract concepts, such as spatial orientation, noncontact forces and the particle nature of matter.

The goal of our research is to describe the increasingly sophisticated ways in which students construct mental models about magnetism. We will show how a limited number of key benchmark concepts, through guided inquiry, mental imagery, and metacognitive reflection, can enable students to develop a deeper and more intuitive understanding of magnetism and magnetic phenomena, both in the realm of the familiar, as well as at the nanoscale.

Theoretical Framework

This work is based on a developmental view of learning "developing relations among a (relatively few) set of core concepts throughout schooling" (Catley, Lehrer & Reiser, 2005, p. 8). These concepts provide targets for learning, accessible to younger students yet still a challenge for in-depth understanding at later grades (Lehrer & Schauble, 2004). Wiggins & McTighe (2006) characterize these core concepts as linchpin ideas - those concepts within a content domain that have enduring value throughout and at multiple levels with the domain providing conceptual anchors for construction of knowledge and a basis for assessment.

We also draw from the literature on mental models and model-based learning. As a representation of something in the absence of the real thing (Greca & Moriera, 1997) mental models provide a lens through which levels of understanding and cognitive sophistication, relative to a target concept, may be approximated. Model-based learning presumes that through the process of generating, critiquing and revising our mental models we can approach a more coherent and normative understanding (Clement & Steinberg, 2002; Coll, France, & Taylor, 2005; Lehrer & Schauble, 2006; White & Frederiksen, 1998). Models are the dominant form of explanation in science and learning science is to make, revise and justify self-constructed models, not simply to use models posed by others and taken for granted (Lehrer, 2009).

Mental models provide the learner a means to organize concepts in a way to help understand the world or to explain it to others (Harrison & Treagust, 1996). In order to construct a coherent conceptual understanding of scientific principles, learners must be able to formalize, assess and reflect upon, and justify their understanding of scientific concepts as they develop them (Cavicchi, 1997; Clement, 1989; Clement & Steinberg, 2002). In the process of constructing a mental model the learner reduces a phenomenon to the elements most meaningful, selecting “only some parts of the entity and relations between them” to create a personally meaningful representation (Gilbert & Boulter, 1995).

The use of mental models generated and revised by the student while learning and revealed through multiple inscriptions (Latour, 1990) will provide a lens through which both the researcher and learner will be able to access the evolutionary nature and coherence of that cognitive process. The invention and revision of models, as an expression of a form of knowing is characteristic to the natural sciences and “are the defining features of scientific thinking” (Lehrer & Schauble, 2006). Yet, it has been shown that changes in mental models and conceptions do not occur quickly and often require repeated challenges, metacognitive reflection, and multiple mixed models along the way (Nussbaum & Novick, 1982).

One of the impediments to understanding magnetism, especially magnetism at the nanoscale, is the concept of the atom and the particle nature of matter. At the nanoscale the effect that thermal energy has on particle motion is manifested in the behavior of the material. The behavior of these materials is not only relevant to the realm nanoscale science, but serves as a tool for connecting to and learning about the nature of magnetism in general.

Children are aware of the terms atom and molecule and references to both of them as “particles” and yet still believe that matter is continuous or that substances contain molecules rather than substances are composed of molecules (Harrison & Treagust, 2002). A scientific understanding magnetism requires an understanding of the particle nature of matter and the implications of thermal energy and applied forces on the appropriate hierarchy of single or aggregate groups of particles (e.g. atom, domain, magnet).

The overarching goal of this research is to provide an in-depth look at the progression and coherence of students’ mental models in learning about magnetism. An important part of our work is the belief that nanoscience and nanotechnology offer an exciting impetus for learning, empowering student learning in the context of new and exciting concepts of emerging discovery. Furthermore, the introduction of nanoscience into the existing curriculum helps to provide a big picture view of science and conceptual coherence of scientific concepts for students. The specific goals for this study will be to answer the following questions.

- 1) What is the nature and range of sophistication of grade 10/12 students’ initial models of magnetism and magnetic interactions?
- 2) What common patterns emerge as students critique and revise their mental models of magnetism during the learning process?
- 3) What themes among students’ developing mental models provide coherent explanatory power across scale?

Method

This study was guided by an orientation in interpretive research (Creswell, 2009), to document the generation and iterative revision of students’ mental models of magnetism. We used a quasi-experimental design to compare the construction and progression of mental models of selected concepts of magnetism. Emphasis was placed on students’ construction and revision of models, coordinated across multiple magnetic phenomena and scale. Iterative cycles of investigation, reflection and revision were used to provide students the opportunity to revise their models for coherence and explanatory power. The two teachers participating in this study each taught their own magnetism unit, following the lesson format provided by the researchers and, with minor modifications, used the same assessment instruments.

Participants

The grade 10-12 high school students ($N = 148$) in this study comprised a non-random sample, solicited from two high schools with which researchers had previously worked as constituents in a nanoscience teacher professional development program. The classes were all high school physics classes; the majority (approximately 95%) of the students in the classes were in the 11th grade (see Table 1).

Table 1: Student Groups Comprising the Sample

Sample	Description of students	N	Intervention	Code
1	High school physics (17-18 years)	66	Yes	MC
2	High school physics (17-18 years)	72	Yes	PL

Intervention

The series of lessons for the intervention will follow a cycle of model-based inquiry in which students will make predictions, conduct investigations, interpret results and apply their revised mental models to new situations. During the cycle of lessons, students will be provided multiple opportunities to reflect on and revise their mental models, and to defend or revise them in light of new and possibly conflicting evidence. The series of lessons which will be employed were designed by the researcher and are based on those concepts believed to be most salient to students constructing a coherent understanding of magnetism and the behavior of magnetic materials across scale.

Data Sources

The data collected consisted of student responses to pre- and posttest tests, inscriptions from embedded assessments, activity journal pages, collaborative group artifacts and informal interviews. Our goal was not the assessment of effectiveness of an intervention. Rather, we aimed to document the status and growth of students' mental models and explanations of magnetic phenomena through the normal course of classroom instruction by the classroom teacher. Our lessons and assessments for this study consisted of items in the areas of: the concept of magnet; magnetic interactions, magnetic versus electrostatic interactions, magnetic fields, domains, magnetizing and demagnetizing, and magnetism at the nanoscale. The assessment items were paper and pencil open ended response and graphic format.

Data Analysis

Written responses were transcribed into a spreadsheet for comparison and analysis. Drawing and graphics were coded to fit students' conceptions into categories representing levels of sophistication based on the depth of understanding exhibited relative to target concepts.

Findings and Discussion

We describe our findings for the following categories: (a) magnetic materials and interactions; (b) magnetic field; (c) models of magnetization and magnetic domains; and (d) magnetism at the nanoscale.

Magnetic Materials and Interactions

Students initially conducted an inquiry designed to elicit their models of magnetic interactions and then made a drawing of their own design to interpret their findings. Interactions were typically classified as attractive, but not necessarily repulsive, in various combinations of weak or strong (see Figure 1). Some students focused on the nature of interactions, others by the materials involved.

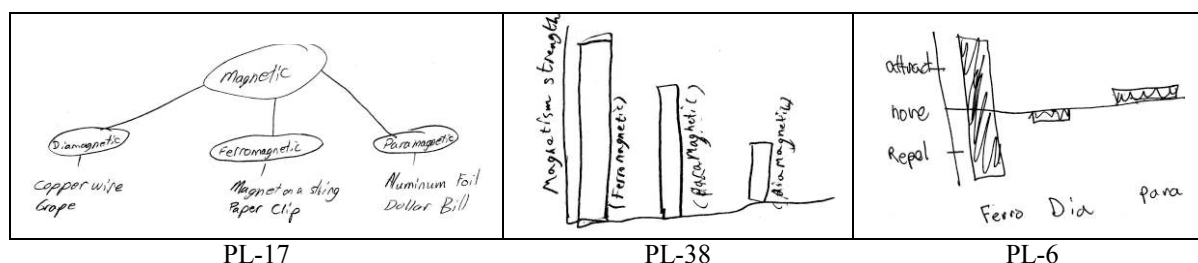


Figure 1. Classification of Magnetic Interactions

While some students' drawings depict more than one level of interpretation, many lacked the degree of sophistication that would indicate a broad understanding of concepts. Few students included repulsion for example in their model, despite having used two magnets and despite observing the diamagnetic behavior of a grape. Very few students included the possibility that there could be no magnetic interaction even though some of the materials used were not magnetic (plastic ruler, paper, wood), and students frequently did not make a distinction between strong versus weak interactions. Some students' models indicated common non-normative beliefs, for example that all metals will be attracted to a magnet. Table 2 lists categories of responses that might be used to differentiate levels of students' conceptions of magnetic interactions based on their observations with these materials.

Table 2: Concepts of Magnetic Interactions

Level	Key features of drawings
More sophisticated	Includes magnetic and non-magnetic, attraction and repulsion, strong and weak, includes magnet-magnet interactions; defines types of magnetism
	Includes magnetic and non-magnetic, strong and weak, types of magnetism
Less sophisticated	Little or no predictive value; reflects only materials used

The purpose of this initial lesson was to help students develop an awareness of degrees of magnetic attraction and/or repulsion, how these interactions are observed, and what common materials exhibit these properties. Students revisited categories of magnetic materials, the degree of response and the ability of some materials to remain magnetized or not, in subsequent lessons.

Magnetic Fields

The detection of magnetic fields was an integral part of our lessons, both for investigation and as a tool for detection. The drawing of an iron filing diagram identified a change in the space surrounding a magnet and provided an overall concept of the both the geometry of the field and areas of more and less density. Students also discovered during this activity the three dimensional nature of the field. Mapping the field with a compass provided students access to the directional orientation of the field and identified the compass as a field “detector” for subsequent inquiries, the magnetization and cutting of a wire and magnet consisting of iron filings in a straw.

The pre- and posttest assessments asked students to draw or write all of the “characteristics” that they think might help to explain how magnets work (see Figure 2).

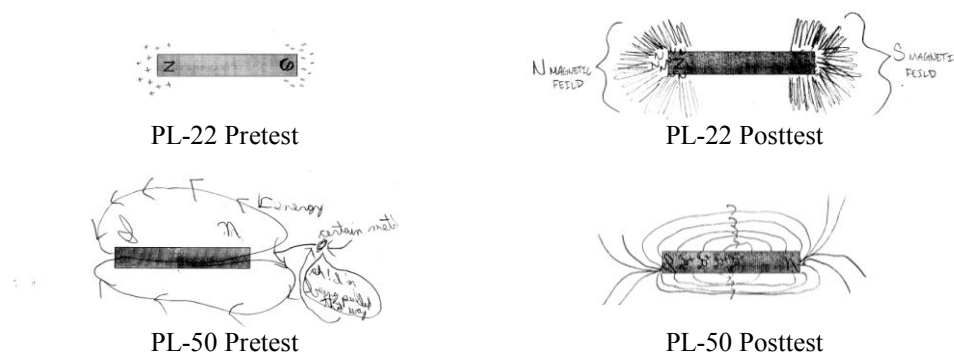


Figure 2. Pre- and Posttest Drawing of “Characteristics” of a Magnet.

In previous iterations we framed this question more to elicit conceptions specific to magnetic fields. However, we found that leaving the item more open for interpretation produced a broader range of responses. Additionally, we found that the degree to which students might elaborate on their conception of the field helped provide a means for categorizing understanding. The most sophisticated models included enough field lines to convey a greater density at the poles, the symmetric nature of the field, identification of poles and an indication of direction. The role of the field in the alignment of the domains of a ferromagnetic object is a key concept that recurred in subsequent lessons.

Magnetization and Magnetic Domains

We approached the concept of domains with a stepwise progression of investigations to help students construct, and provide us access to, increasingly sophisticated mental models. At the end of the first investigation, categories of

magnetism, we asked students to speculate how a magnetized nail might differ from a non-magnetized nail if they were able to “see inside.” These models provide a means of eliciting students’ mental models of how magnetized and non-magnetized materials might differ (see Figure 3).

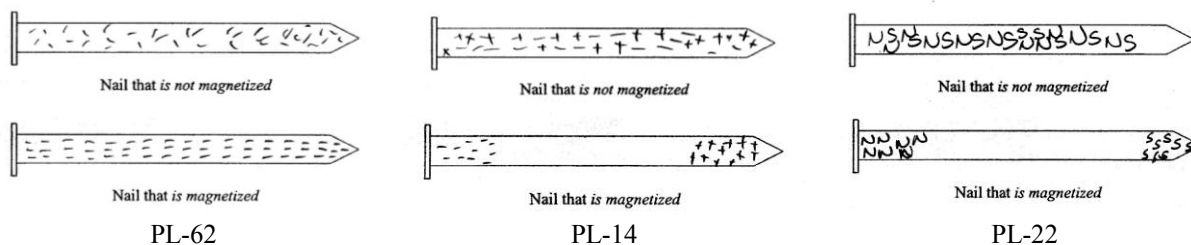


Figure 3. Pre-instruction Models of Magnetized and Non-magnetized Nails

These models provided a beginning for the development of the concept of domains, fundamental in providing the conceptual framework to understand how a nail, for example, can be attracted to either end of a magnet, why an object can be magnetized, or why nanoscale materials do not stay magnetized. At key times throughout the lessons, students referred to their initial models, confronting and revising them based on new evidence and their changing conceptions. Posttest responses for the same students are shown in Figure 4.

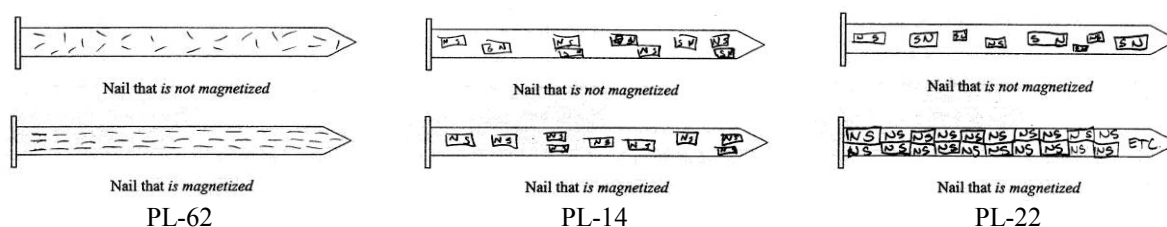


Figure 4. Post-instruction Models of Magnetized and Non-magnetized Nails

These inscriptions demonstrate that while PL-22 and PL-14 had begun to incorporate the concept of domains into their conceptual framework, PL-62’s mental model had not changed. PL-22’s model would also indicate that the entire nail was comprised of domains, while PL-14’s model gives the impression of domains embedded in another material.

One of the several ways in which we made the concept of domain accessible to students was through a “straw magnet.” Student made their own magnet by filling a soda straw with iron filings and then magnetizing and de-magnetizing their magnet, observing the change in field with a compass. While students generally began to associate being magnetized with a state of conditional alignment, we found that many still held on to their concept of charge (see figure 5).

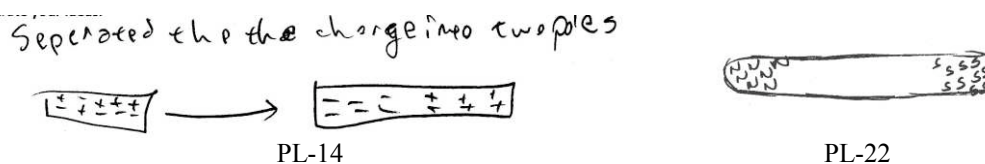


Figure 5. Magnetizing a Straw Magnet

The two inscriptions in Figure 5 are good examples of models between the pre- and post-instructional models in Figures 3 and 4. Both of these models show an increased sophistication from the initial model, yet are refined further during the remainder of the lessons as the inscriptions in Figure 4 demonstrate.

After the straw magnet lesson, students from one group create a drawing for what they believed would happen when a nail is approached by either end of a magnet (see Figure 6). The other group responded to a similar question with a written response (see Table 3).



Figure 6. How a Nail is Attracted to Either Side of a Magnet (MC-21).

The drawings by student MC-21 are a reasonable model of the alignment and reverse alignment of the domains in the nail, subject to the field of the magnet. This student aligns the domains in the nail relative to the magnet and indicates the action of the field.

Table 3: How a Paper Clip is Attracted to Either Side of a Magnet

Level	Key concepts
More sophisticated	The magnet magnetizes the paper clip, which means it causes the domains within it to be lined up. The paper clip can be attracted to both ends of the magnet because both ends will line up the domains. Therefore, one end of the magnet will line up the domains in one direction and the other end will line them up in the other direction. (MC-66).
Less sophisticated	The domains of the paper clip will shift according to what side of the magnet is presented allowing it to pick up the paper clip (MC-67).

The more sophisticated of the responses alluded to the alignment of domains, yet none of the students in our sample referred to the concept the field in the action; the level of sophistication appeared to stall with the magnet causing the effect. This is however neither surprising nor discouraging, given the limited time frame for instruction and the abstract nature of the interaction.

Magnetism at the Nanoscale

The magnetic properties of nanoscale materials is grounded in two key concepts (1) the dominance of the behavior of a particle by the larger number of atoms on the surface of the particle relative to atoms in the interior compared to microscale and macroscale objects, and (2) thermal effects which exceed the tendency for nanoscale domains to remain aligned in the absence of a magnetic field. The investigation and explanation of the behavior exhibited by a magnetic fluid (ferrofluid) ties together all of the concepts presented in the preceding lessons. Figure 7 shows two student inscriptions, representative of two levels of sophistication, applying observations from the nanoscale material investigation with the concepts they learned.



Figure 7. Response of a Magnetic Fluid to a Magnet.

Inscription PL-1 correctly shows the gathering of the magnetic fluid near the pole of the magnet underneath, but lacks the conceptual detail of the field lines and the corresponding “lining up” of the magnetic particles. The second inscription shows correctly oriented field lines with the magnetic particles conforming to a pattern similar to what students had observed with iron filings.

Students were also asked to explain why nanomagnetic particles do not remain magnetized when larger samples of the same materials do. The rationale behind the question is to elicit students’ ability to translate their mental models of magnetization, field, domains, and the effect of thermal energy and particle size, to the behavior of the magnetic fluid (See table 4). We found that, even at the end of the series of lessons, there remained a continued perception of electrostatic charge being a factor in the magnetic behavior of the nanoscale particles among some students’ conceptions. The two following responses illustrate, “There is too much surface to keep the charges magnetized and therefore tend to lose charge quickly” (MC-52); “The charges have a bunch of space to move around and don’t want to stay in one spot to stay magnetized” (MC-6).

Table 4: Why Nanosize Particles Do Not Stay Magnetized

Level	Examples of student responses
Most sophisticated	These nanoscale particles are constantly moving around, causing the domains to become unaligned at any moment. If the domains are unaligned, the particle cannot stay magnetized (MC-4).
Less sophisticated	They don’t have enough atoms on the inside to make up domains to stay lined up to keep magnetized (MC-15).

While the responses in Table 4 hint at aspects of thermal energy and the impact of surface, relative to volume, students may remain “captured” by their intuitive knowledge (Cheng & Brown, 2007), reverting back to that intuition rather than using a still undeveloped but more sophisticated model.

Conclusion

This research represents a pilot study. Our goal was to begin to document a range and progression of sophistication of students’ mental models of magnetism, revealed through multiple and frequent inscriptions. We believe that through model-based learning, mentoring students to construct, metacognitively reflect on, and reform their mental models, learners will approach a more coherent and normative understanding of concepts of science. This study serves as a starting point for further research that aims to develop cognitively grounded and research-based cohesive physical science curricula organized around key theoretical principles.

While we are encouraged by our results, we also recognize that learning about the nature of magnetic interactions presents many cognitive challenges. In the case of domains, for example, we found that students associate an element of alignment to a magnetized object, but that their understanding of that alignment might just as likely reside at the atomic level, involve an electrical polarization, or may consist of an alignment which, while similar to the concept of domains, appears more to be an artifact of composition. Students created multiple inscriptions based on the concept of domains, yet appear to not have significantly grasped the concept that each domain is in effect its own little magnet with its own magnetic field.

The nature of nanomagnetic materials poses challenges in learning, both in terms of magnetic fields and domains, but with the added layer of complexity of the particle nature of matter and kinetic molecular theory. We found, for example, that some students believe that atoms in a nanometer size piece of iron are smaller and closer together than in a larger piece. That notwithstanding, the impact of thermal vibrations on the alignment of the atoms in a single (nanoscale) domain was accurately described by a large portion of students. A kinesthetic activity in which students in a group each modeled an atom proved a tangible way to compare surface to volume and the effect of thermal vibrations.

Similar to the findings of Cheng and Brown (2007), we also found that students reverted to prior models in the absence of newer more fruitful ones and the tendency to rely too heavily on concrete interpretations of models used for explanatory purposes. Effects of thermal energy or mechanical shock, or dropping a nail to demagnetize it, are often believed by students to physically translate the atoms in the material, rather than to disorient their magnetic alignment. The distinction is confounded, however, with the observation of a magnetic fluid in which the domain particles actually do translate in the absence of a field.

We believe that the study of magnetism provides a meaningful framework and engaging segue for the introduction of nanoscience and of the size dependent nature of materials at the nanoscale. Further study of the ways in which students conceptualize magnetic phenomena across scale, and the cognitive pathways by which those conceptions are able to progress toward greater levels of sophistication will not only provide a descriptive account of learning, but may also inform instruction. In addition, we believe that evidence suggests that magnetism is a meaningful and authentic way in which nanoscience can be introduced to serve existing standards and curricula.

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