TRACING A PROSPECTIVE LEARNING PROGRESSION FOR MAGNETISM WITH IMPLICATIONS AT THE NANOSCALE

Knowledge that each of us has constructed is structured. It consists of units of information linked together in multiple ways and to varied degrees in an overarching framework which allow us link together concepts for a broader understanding and to make sense of new situations and unfamiliar stimuli. Assessing and understanding the framework of students’ knowledge provides a challenge for the educator, but also provides a foundation for teaching and learning. We will use artifacts from students engaged in learning about magnetism to describe a conceptual progression for learning about magnetism and magnetic phenomena, with the added goal of applying these concepts to the behavior of materials at the nanoscale. The goal of this pilot study is to portray student learning of those concepts of magnetism that support understanding of magnetism in the context of nanoscale science in order to describe a coherent progression of student conceptions, in addition to beginning to construct a framework of assessment of those conceptions. Data is drawn from written responses to pre- and post-questionnaires, field notes from classroom observations of students engaged in guided inquiry, and students’ models and graphical representations to describe growth as well as gaps in learners’ cognition and conceptual understanding. Using core concepts that we believe to be essential to the understanding of magnetism, we will trace out a preliminary learning progression leading to the properties and behavior of magnetic materials at the nanoscale, capitalizing on phenomena that are not only engaging and motivating to students, but directly related to a conceptual understanding of magnetism of materials of all scales. We believe this work may be used to inform level-appropriate strategies for both instruction and assessment for the study of magnetism at multiple levels.

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Magnetism, Nanoscience and Science Education

Magnetism is as mysterious to learners of all ages as it is appealing, and rare would be the child who has not had at least some level of experience playing with magnets. National standards documents itemize at least some concepts about magnets and magnetism for student learning, beginning with K-2 and continuing through high school (AAAS, 2001; NRC, 2001). Surprisingly, however, few school age children have a scientifically based understanding of the concept of magnetism or how magnets work, regardless of the grade level and school instruction. Despite the familiarity and study, the mechanism and forces by which magnets function are seldom understood outside the science community. Researchers know surprisingly less about conceptions of magnetism (Hickey & Schibeci, 1999), nor have
conceptions of magnetic phenomena been investigated as intensively as other physical phenomena, such as electricity and heat (Borges & Gilbert, 1998; Erikson, 1994).

While there is research regarding certain aspects of students learning about magnetism and the misconceptions and gaps in understanding they may have at specific grade levels (Borges & Gilbert, 1998; Constantinos, Raftopoulos & Spanoudis, 2001; Guisasola, Almudi & Zubimendi, 2004; Guth, 1995; Guth & Pegg, 1994; Johnson, 1999; Maloney, 1985; Meyer & Carlisle, 1996), little appears to have been done to study the longitudinal progression of how students learn about magnetism and magnetic phenomena. Emphasizing the need for students to understand magnetism on a practical level, Driver, Squires, Rushworth & Wood-Robinson (1994) concluded, “approaches which draw on everyday experience and focus on the uses of magnets would be advisable” (p. 127). A practical and coherent conceptual understanding of magnetism and magnetic fields may also provide a framework to understand less tangible concepts such as gravitation and electric fields.

Our research is intended to describe a framework within which central conceptual pathways for learning about magnetism can be used to understand student learning and cognition, as well as to inform instruction. This work reports the ongoing iterative development of a learning progression for magnetism, to culminate with the ways in which the magnetic behavior of materials is manifested at the nanoscale. Additionally, we seek to describe potential ways in which students’ understanding of magnetism can become more developmentally sophisticated, and to develop a cartography charting of core concepts and learning performances through varying grade levels. Such a portrait of learning may then be used to guide teachers in appropriately assessing students in their construction of knowledge about magnetism and in offering alternative strategies. We will use preliminary evidence from children engaged in learning about magnetism to describe a learning progression about magnetism and magnetic phenomena. Ultimately, studies such as this will help to extend traditional instruction to include innovative and cutting-edge science exemplified by the introduction of nanoscience into the K-12 curriculum.

**Conceptual challenges for learning magnetism**

Aspects of magnetism have been shown to be difficult for children to understand (Barrow, 1987; Borges & Gilbert, 1998). The idea of an object acting on another without touching is counterintuitive for young children; likewise it is difficult for children to understand that a magnet can both attract and repel other objects (Constantinou, et al., 2001). Magnetism, magnetic fields and the nature of magnetic materials also require a mental spatial orientation and the ability to construct mental models of abstract concepts including kinetic molecular theory and the particle nature of matter.

Humans understand a phenomenon by constructing a working model of their interpretation of the phenomenon and reasoning through their manipulating the model (Borges and Gilbert, 1998). Researchers believe that the process of building and reflecting upon mental models has a close resemblance to everyday reasoning (Clement, 1991). 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 model initially produced may aim toward descriptive and mechanistic representations to describe structure
or function. The aspects of focus within a mental model are likely to be influenced by purpose, need, and prior knowledge and experiences that the learner may have.

There are a number of challenges in learning magnetism. Student learning and conceptions have been studied from the elementary grades through college (Barrow, 1987; Borges & Gilbert, 1998; Brademante & Viennot, 2007; Constantinou, et al., 2001; Erikson, 1994; Guisasola, et al., 2004; Guth & Pegg, 1994; Saglam & Millar, 2006). Borges and Gilbert found that among secondary, university and graduate students, the majority of these students retained naive and scientifically flawed concepts about magnetism, even after long periods of study.

In nanoscience education, magnetism is linked to the constructs of size dependent properties and the particle kinetic molecular nature of matter. At the nanoscale, the magnetic behavior of the material is dependent upon, in addition to the chemical nature of the composition, the size of the particle, effects of thermal energy and the interplay of forces, which at larger scales, are insignificant. All of these pose challenges in their own right for learners because each requires a higher level of cognition and abstract mental imagery than more concrete and tangible concepts (Borges & Gilbert, 1998; Guisasola, et al., 2004; Smith, Wiser, Anderson & Krajcik, 2004).

In general, science education research on students’ learning and conceptions of magnetism has focused on three aspects of magnetism: (a) magnetism and charge; (b) models of magnetism, and (c) magnetic fields. In the following sections, we summarize this research. Additionally, a summary chart of this research can be found in Appendix A.

Magnetism and Charge

Probably, the most common conception about magnets that has emerged from research, with which learners across all ages and levels of education struggle, is congruence of magnetic activity with charge – the belief that some regions of the magnet are positive and others are negative. The beliefs that the poles of a magnet are electrically charged, and that magnetization involves the transfer of charge, have been revealed from studies of learners across multiple ages and educational levels (Borges & Gilbert, 1998; Hickey & Schibeci, 1999; Maloney, 1985; Saglam & Millar, 2006).

Maloney (1985) found among high school students the belief that magnetism and charge are one and the same thing. Students believed that one pole of a magnet is positively charged and the other is negative, or that an object with a static charge will be attracted to a magnet. In a study of grade 6 students, Barrow (1987) found that students believed that magnetism resulted from the distribution of electrons in one object and protons in another, making electrostatic and magnetic interactions synonymous. Students also often view magnetization as the flow of charges (Borges & Gilbert, 1998).

In a study by Guisasola, et al. (2004), researchers examined students’ conceptions regarding how a magnet could attract an object like a paper clip. In both written response and interview, responses such as the following excerpt were common, alluding to the role of charge in the model of magnetism (Guisasola, 2004, p. 451):

A paper-clip is a metal, and metals have free electrons in their structure. The field generated by the magnet polarizes the magnet and attracts or repels electrons, depending on the pole of the magnet that we use. This way, we shall have the
positive pole of the magnet with the negative zone of the clip, or vice versa, that will attract. (3rd year physical science student)

This 3rd year physics science students’ conception follows the idea of an electrical polarization. The same explanation emerged in the study by Borges and Gilbert (1998) who found that both students and teachers used an electrical polarization explanation, signifying that magnets act upon other objects, polarizing them in an electrical sense. Similarly, Hickey and Schibeci (1999) found that in pre-service and in-service elementary teachers’ accounts of magnetic attraction and repulsion, the majority clearly supported a polar charge model, although through different mechanisms by which charge is accumulated and transferred. However, these researchers pointed to the possibility that use of the term “charge” may in some cases refer to symbolism often found in textbooks, wherein the plus and minus signs are used as a means of differentiation between poles rather than to imply electrical charge.

Models of Magnetism

Researchers have delineated models of magnetism over a range of age groups and experience levels. In a study by Erickson (1994) of students’ conceptions of magnetism in grades 4, 7 and 10, three models emerged. Common among the younger students was the ‘pulling model,’ primarily providing only a description of observation, and associated mainly with the effect of magnets on other bodies without consideration of mechanism or causality. The ‘emanating model’ is explained in terms of the magnet emanating rays of energy toward attracted objects. The ‘enclosing model’ is characterized by rays coming out of the magnet, spreading over the area to create region of influence, analogous to the effect of gravity. These models are analogous to those found by Meyer (1991) with students from grades 4 and 7 in a study in which students were given a similar task.

The work of Meyer (1991) also revealed a difference in approach between age levels. Younger students were indifferent as to which side of the magnet they used in repeated trials, whereas older students were more diligent, recognizing that opposite sides represent different poles. In a similar activity, Meyer (1991) found that while younger students treated both sides of the magnet the same, following the enclosing model, some of them used the term magnetic field, taking language that they may have heard in the media, read about in school, or learned from family or peers. Other differences were noted as well, such as they was students “measured” the distance between the magnets and objects interacting with them. These distinctions demonstrate the effect of how prior knowledge of the learner influences learning, emphasizing all the more the importance of being able to ascertain as accurately as possible, what it is that students know coming to instruction.

Meyer (1991) examined her data for implicit theories which the students were believed to have used in their investigation. The ‘strongest magnet,’ from student investigations is the one that (p. 236).

- pulls a magnetic object from the greatest distance
- has the largest magnetic field
- moves or lifts the greatest number of objects
- pulls more objects through a non-magnetic barrier
- holds more magnetic objects in a chain
- pulls magnetic objects from a weaker magnet
- has the greatest measurable pull (with a spring balance)
Hickey and Schibeci (1999) also found, in their study involving pre-service and in-service primary teachers, models of magnetism confused with gravity, the beliefs that all metals are magnetic and that magnetism is an inherent property of a material and does not need to be created, and the theory that magnets have to overcome influences of air in order for an object to be attracted.

Mental models of the nature of magnetism have been categorized by Borges and Gilbert (1998) from a sample including secondary students, technical students, physics teachers and engineers. The models elaborated form a conceptual progression from a “pulling model” at the most basic level, through models of magnetism as a cloud, electricity, electrical polarization, and finally as a field. While repeated exposure to learning about magnetic phenomena was shown to drive conceptions toward a more scientific view, it is also evident that throughout all levels of education and experience, naïve models are resistant to change.

In terms of a progression of levels of conceptual sophistication, some of these studies may indicate that at different grade levels, the ways in which students approach the task of classification, the level of their ability to differentiate meaningful differences, and the manner in which they analyze their findings co-vary with age and experience with the concepts involved. Yet, there exist conceptions of magnetism which persist throughout all levels of science education that are incongruous with the most basic scientific validity.

**Magnetic Fields**

The concept of the magnetic field has emerged as a means of understanding the nature of magnetic effects and interactions. As a means of describing physical quantities in time and space, the field is a unifying concept in the explanation of magnetism. It is an abstract concept that took 150 years to formally emerge. Students have difficulty with constructing mental models of magnetic fields and understanding the concept of force at a distance and often attribute a real existence to field lines and their action on other objects. Students often believe that a medium is required for a transmission of the action of a magnet, that the field affects a change in the space surrounding it which mediates the interaction, that the field has a finite boundary (Bar, Zinn & Rubin, 1997), and “think that the magnet cannot function without gravity” (Bradamante, Michilini & Stefanel, 2006, p. 375).

As the following examples from Guisasola, et al. (2004, p. 452) indicate, university students throughout their span of study in science and engineering held unscientific accounts of the nature of the magnetic field: “Because a magnet has a termination where field lines converge and a source where they are produced, and they create the magnetic field.” “Because field lines go into and out of the poles of a magnet; these field lines have the direction of B and they act on elements that have free electrons.” “It lets the flux go through, and the field lines that go through it pull it. If we had put the south next to the clip instead of the north, the field lines would have repelled it instead of attracting it.”

In a study involving post-secondary students, Guth & Pegg (1994) found that conceptions of the commonly demonstrated field lines using iron filings vary greatly in beliefs of how and why the lines originate. These students most often believed field lines to be concrete replicable entities. Three levels of understanding regarding students’ reasoning about field lines emerged from this work. In the most concrete sense students viewed field as a finite number of lines separated by space and filings being attracted to the lines, thus forming a pattern by “gathering along the lines” (p. 142). In the next
level, students modeled the filings in the pattern as tiny compasses, the filings becoming magnetized in the field and then aligning themselves along discrete field lines.

In the third level students applied a more formal mode of reasoning as to why the lines formed, based the recognition that (1) the filings become magnetized and (2) the filings affect each other by their own magnetic fields. In the more expert view then, these two ideas are required to explain the formation of the pattern of filings around the magnet without conceding that a finite number of lines exist. In this view, each point in the space around a magnet is unique and subject to both a magnitude of attraction and direction of orientation.

**Magnetism at the Nanoscale**

The emergence of nanoscience education also offers the exciting opportunity for children to not only examine the phenomenon of magnetism in a new dimension, but to use the unique behavior of nanomagnetic materials to connect an array of concepts of magnetism across all scales. Nanoscience is characterized as the study and manipulation of materials, and fabrication of structures and devices having at least one dimension in the range from 1 nanometer to 100 nanometers. The rapidly developing niches for the use of nanoscale magnetic particles, and materials containing them, offer an open opportunity to not only introduce nanoscience into the curriculum, but to incorporate the unique behavior of nanomagnetic particles into the study of magnetism, capitalizing on phenomena that are not only engaging and motivating to students, but directly related to a conceptual understanding of magnetism of materials of all scales.

Magnetism at the nanoscale, and the behavior of nanoscale magnetic particles in a ferrofluid, pose a unique application of how forces and properties which are dominant at larger scales often concede their dominance at the nanoscale. At the nanoscale ferromagnetic particles consist of a single domain and, as a consequence of the size of the particle (the surface are to volume ratio, and the increased importance of thermal energy for a small particle) they behave paramagnetically, rather than ferromagnetically. At the macroscale, a magnetized “particle” the dimensions of a bar magnet will likely stay magnetized. At the nanoscale it will not. The behavior of these materials not only illustrates a relevance to the realm nanoscale science, but serves as a tool for teaching magnetism as a bulk property, as well.

One of the impediments to understanding magnetism, especially magnetism at the nanoscale, is the concept of the atom and the particle nature of matter. The very nature of magnetism originates with the atom; atoms within ferromagnetic materials align into groups called domains. At the nanoscale the effect that thermal energy has on particle motion is manifested in the behavior of the material. Thus, there are different hierarchies of “particles” and the ability to differentiate such interlinked concepts poses challenges to understanding. Novick and Nussbaum (1981) brought attention to students’ particle conceptions of matter and found that cognitive challenges are often not overcome even by many older students.

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 and the mechanism of magnetic interactions at any scale require an understanding of the particle nature of matter and the implications of thermal energy on the particles. This is especially true with nanomagnetic materials where, because of the consequences of size, behavior is more attributable to particle that bulk.
Learning Progressions

With few exceptions research in children learning about magnetism has tended to focus on single concepts, effectively and accurately reported students’ conceptions, but within a rather narrow range of concepts, as outlined above. Little has been done to investigate across ages, students’ linking conceptions of how magnetization occurs, the mechanism of the alignments of domains and the types of magnetism exhibited by various materials, or to describe a coherent progression by which children can link these concepts together. While this prior work has gone far to build a research base of understanding and to inform instruction, there has been little done to investigate children’s beliefs and conceptual development of magnetism across multiple grades, or from a longitudinal perspective. The synthesis of a cross-age account of students’ conceptual grasp and development of the concepts of magnetism, in the form of a learning progression, will help to define congruent and interrelated concepts and how they might build together for a coherent understanding.

As we began to examine sequential ways in which concepts important to the understanding of magnetism could be related, research in learning progressions provided a framework. (Alonzo & Steedle, 2008; Catley, Lehrer & Reiser, 2004; Smith, Anderson, Wiser & Krajcik, 2004; Yunker, 2008). Research into children’s developmental learning of a concept, spanning multiple grade levels is still largely nonexistent (National Assessment Governing Board, 2006). Additionally, depending on the construct, there may be more or less evidence about how the ideas at a given level of understanding “hang together,” but even so, past research has focused more on single ideas and concepts, rather than relationships between them (Alonzo & Steedle, 2008).

A learning progression begins with the synthesis and definition of a construct and the elaboration of those key concepts which shall serve to provide a developmental framework surrounding the construct – the “big ideas.” Big ideas refers to key concepts and organizing principles that are at the core of a discipline. Wiggins & McTighe (1998, 2006) characterize a big idea as a linchpin – an idea within a content domain that has an enduring value throughout and at multiple levels with the domain. More than a fact or skill, a big idea provides more than a conceptual anchor for students’ construction of knowledge. Big ideas provide a focus, both to prioritize concepts and to provide a basis for teaching, student learning and assessment (Wiggins & McTighe, 2006).

As developmental schemata of domain specific content knowledge, cognitive skill and conceptual understanding, mature learning progressions are grounded in research in learning and are informed by empirical evidence of student performance in classrooms. Built around central disciplinary concepts, the ways in which students learn these concepts, the alternative conceptions students may have, and how these conceptions can be overcome, a learning progression becomes a portrait of learning as well as a model for instruction linked to standards of performance and assessment of student progress (Kennedy & Wilson, 2007; Smith, et al., 2006).

Standards documents or research from cognitive science may be used to define and clarify exactly what it is that students should be required to know about the construct. At one end, learning progressions are anchored by these expectations, clarifications of what it is that students should be expected to know, or be able to perform, within the context of the domain, relative to the student ability, grade level and context. These upper performance levels, the
goals of the design of instruction, define the top level of the learning progression and can be referred to as upper anchors (Mohan, Chen & Anderson, 2008).

At the novice level of the progression, anchors are defined by students’ existing knowledge. Lower anchors may be elicited though empirical research on students’ existing content knowledge and conceptual development. Alternately, if empirical data is unavailable, review of the research literature on students’ understanding of the identified construct, including misconceptions and alternative understandings, may be used to support the development and progress of full understanding. Anderson (2008) writes of the process in the development of her longitudinal learning progression of carbon cycling,

We initially developed an Upper Anchor framework organized around model-based accounts of carbon cycling, based on current national standards and research. The Upper Anchor represented what we saw as a conceptually coherent understanding about carbon-transforming processes achievable by high school students. The Lower Anchor was based on our experience and reading of research about the reasoning of elementary school students (p. 21).

Inasmuch as our learning progression for magnetism is grounded in what we believe are the concepts key to understanding magnetism at the nanoscale, we have taken a backwards design approach (Wiggins & McTighe, 2006) to specify our upper anchors, grounded in the conceptual understanding which we believe is key for understanding magnetism across all scales as well as at the nanoscale.

The subjectivity of grain size also plays a role in the elicitation of relevant levels in a progression. For example, Catley, et al. (2004) and Smith, et al. (2004) produced multi-year progressions for the learning and understanding of evolution and the nature of matter, respectively. Regardless of the duration of the learning progression, the development of initial and final anchors and the validation of the progressive levels in between require not only expert knowledge within a content domain, but needs support of research on learning as well.

The definition and separation of levels between what students may be expected to understand between the theoretical ‘expert’ level and less sophisticated levels, may begin from a hypothetical position, but through iterative development should become more an evidence-driven process. In the development of a learning progression on the rock cycle, for example, Yunker (2008) used semi-structured informal interviews with participants of a progression of educational levels (6th graders, pre-service teachers, graduate students and professors) to elicit relative levels of understanding of the concept. In the process, she revealed as well, gaps in understanding and misconceptions, even at the upper educational levels. Other methods that have been employed have included using manipulatives during semi-structured interview, such as a size and scale card sort (Delgado, Stevens, & Shinn, 2008), or interacting with children in an informal learning environment like a field trip (Plummer, 2008) and video analysis of children’s activities and group discussions.

Once upper and lower anchors and appropriate levels of conceptual sophistication differentiating them are projected, students’ conceptual levels are empirically tested with, for example, formal and embedded assessments, as well as interview, focused on validating the “fit” of the progression’s prediction, as well as to elicit alternative ways in which students confront the situations. From this, a preliminary learning progression, describing students’ conceptual pathways can be formulated and field tested.
One challenge in this process is the use of language; another is the issue of consistency (Alonzo & Steedle, 2008). In the case of language, meanings of a word often change with age. The word force, for example means something different to children when the concept of motion is associated with it. Terminology also varies with perspective and context. The chemical symbol Na, for example, may mean a shiny soft metal that bursts into flame when it is dropped into water in one context; it may just as well represent an atom with eleven electrons and low ionization potential in another (Bodner, 2008). The same words, terms or symbols often have entirely different meaning, which poses not only problem in communication, but leads to errors in assessment and student frustrations. Consistency of representation also changes with age and personal experience, for example the way we look at an object or consider its function. Younger students may take a more intuitive experiential look at a situation, for example in the modeling of a magnetic field, whereas older students may associate specific rules of action with specific situations, but fail to see similarities where they occur.

Our goal, to better inform our learning progression for magnetism, as well as to provide a guide for assessing performances of students, will be to construct well defined maps to differentiate relative levels of conceptual congruence and sophistication. Such progress maps (Wilson & Sloane, 2000) will correspond to each conceptual big idea. Tools like the progress map are to assessment what big ideas are to learning. They provide a focus and definition for learning and assessment and, when shared with the student, allow the student to reflect on his or her own conceptual standing.

Method

The initial goal of our research was to try to define students’ experiential definitions and conceptions of magnets and magnetic phenomena, across grade levels from 8 through 16. Additional data obtained from physics graduate students enabled us to extend our analysis into those grades for a portion of our conceptual progression. The second goal was to generate and pilot assessments as part of teachers’ teaching units on magnetism to try to document the progression of students’ conceptions throughout the course of instruction.

The data obtained from the samples in this study are student artifacts in the form of written responses to questions and embedded assessments, diagrams and drawings, and pre- and posttests. While two groups of students comprising the sample consisted of classes engaged in learning about magnetism, we are not assessing the impact or effectiveness of an intervention. Student learning about magnetism in these classes was as a part of normal classroom instruction. Rather, we aim to document the status and growth of students’ conceptions through the normal course of classroom instruction by the classroom teacher.

The results come from survey data and student artifacts collected from lessons taught in a normal high school setting by the classroom teacher that were part of a series of lessons in magnetism at the nanoscale. The lessons used for this study consisted of student inquiry in the areas of

- The nature and dimensions of magnetic interaction
- The distinctions between magnetic and electrostatic attraction
- The concept of the magnetic field
- The process of magnetic induction
- The implication of magnetic domains
- The effect of size on magnetism at the nanoscale
Participants and Data Collection

This study of children learning about magnetism employed a convenient sample consisting of students from middle school through high school. In addition, for one survey question, we also used a convenient sample of physics graduate students. As our research continues to develop, data from elementary grade students will be incorporated. Data obtained thus far include written responses to pre- and post-questionnaires, field notes from classroom observations of students engaged in guided inquiry, informal interviews, and embedded informal assessments including students’ construction of models and graphical representations. Data for the one survey question asked of the graduate physics students were obtained by means of an on-line questionnaire. A summary of the student samples and the nature of the concepts assessed are provided in Table 1.

Table 1
Student Groups Comprising the Sample

<table>
<thead>
<tr>
<th>Sample</th>
<th>Description of students</th>
<th>n</th>
<th>Intervention</th>
<th>Code</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>US high school physics (17-18 years)</td>
<td>10</td>
<td>Yes</td>
<td>BL</td>
</tr>
<tr>
<td>2</td>
<td>US high school physics (17-18 years)</td>
<td>66</td>
<td>Yes</td>
<td>MC</td>
</tr>
<tr>
<td>3</td>
<td>US high school physics (17-18 years)</td>
<td>72</td>
<td>Yes</td>
<td>PL</td>
</tr>
<tr>
<td>4</td>
<td>Graduate students in physics</td>
<td>27</td>
<td>No</td>
<td>GR</td>
</tr>
<tr>
<td>5</td>
<td>Finnish lower secondary science (14-15 years)</td>
<td>18</td>
<td>No</td>
<td>LF</td>
</tr>
<tr>
<td>6</td>
<td>Finnish upper secondary chemistry (17-18 years)</td>
<td>21</td>
<td>No</td>
<td>UF</td>
</tr>
</tbody>
</table>

Three of the data sources (Samples 1, 2 and 3) were convenient classroom samples in which both teachers had previously participated in a professional development program involving lessons in nanoscience, which included a series of lessons for magnetism at the nanoscale. These teachers invited researchers to participate in the design and tailoring of lessons and assessments and to mentor them in the teaching of concepts of magnetism as a typical and normal unit in high school physics.

The high school classes comprising these first two samples were all high school physics classes; the majority (approximately 95%) of the students in these classes was in the 11th grade. Both teachers incorporated questions into their assessments contributed by researchers, developed in part as part of a nanoscience teacher professional development program, but tuned to the pedagogy of the specific teachers’ practice. Both high school teachers structured their magnetism units to culminate with a lesson on magnetism at the nanoscale. While one researcher (the first author) was present in both classrooms as an observer during portions of the teachers’ instruction of each lesson, his role was as a non-participant observer. He did not participate in the instruction of the lessons and did not interact with the students. The researcher and classroom teacher collaborated on the design of the assessments used for lessons, but the actual version of each of the assessments used was the final decision of the classroom teacher, aligned with instruction. The researcher participated with the teachers, to the extent of the teachers’ request, in the design and sequencing of the lessons and in the design of various levels of assessment. The sequence of lessons and the nature of assessments between these two samples were similar in content and format.
The third group comprising our sample consisted of physics graduate students, solicited as part of an on-line survey relative to a training project in survey design and analysis. The survey was administered to the population of students enrolled in a university graduate physics program. The survey consisted of three questions related to magnetism. The opportunity to participate in the survey was sent to the list-serve of graduate physics students, explaining the nature and purpose of the training project. While the response rate to the survey was approximately 70 percent, not all students who began the survey completed all questions. Only those students who completed all of the magnetism questions were used as part of this analysis.

The final two samples used in this analysis came from a study of two groups of students in Finland. The first class consisted of eighteen students in a lower secondary (LF) science class (ages 14-15, comparable to 8th grade students in the US). The second group consisted of an upper secondary (UF) chemistry class (comparable to 11th grade students in the US, Sample 4 11th grade. Both classes were taught by the same teacher. With the help of a Finnish university professor, six of the questions used in the US high school magnetism assessments were translated into Finnish. One researcher was present during the administration of one of the survey questionnaires. Both sets of surveys were then translated into English for analysis.

Data Analysis

Analysis was carried out for all groups concurrently in an iterative process. Initially, all responses were transferred into spreadsheet for ease of comparison and sorting. The process of deciphering and transferring students’ written responses into an electronic format provided researchers the first pass at an open coding process (Strauss & Corbin, 1998). With continued readings of completed data set from each of the groups, preliminary codes were designated for each of the groups and then revised, each group informing the other in a convergence of themes. As axial codes emerged, all of the data were coded once again for consistency. Codes developed for each of the concepts analyzed are presented in the respective sections that follow.

Results

The driving force behind this research and for the nature of the design of student assessments is to elicit and define those concepts of magnetism most relevant to students’ learning about magnetism at the nanoscale and to describe a framework of possible conceptual pathways of learning. In the sections that follow we discuss our findings and begin to outline levels of performance and understanding that will guide us in defining and describing student a conceptual progression for learning magnetism.

Concept of a Magnet

In all three groups of middle and high school students, from both the US and Finland, the characteristic defining a magnet most often referred to was an element of electric charge. Students often saw charge as accumulating at the poles, one positive, one negative, or the accumulation of charge as being the cause of magnetism.

Magnets are objects that have a positive and negative side and each side has a type of magnetic field. (MC-32).
It’s a device that has electrons, negatively charged particles that create a polar field of attraction. (MC-42).

A magnet is a piece of metal with one end charged positively and the other end negatively. (UF-13).

There are two kinds of magnets, + and -. + and - are a suitable couple, but + and + or - and - are not. (LF-17).

In light of prior research described previously (Maloney, 1985) these sorts of answers are not be surprising. However, of interest is the higher percentage of 11th grade students (61.9%) who chose charge compared to Finnish 8th grade students (44.4%), and that the US students cited charge less often that either (31.3%). Among the graduate physics students, only 2 students of 27 cited charge as a characteristic.

Table 2

US high school physics classes (grade 11, n=76): What is your definition of a magnet?

<table>
<thead>
<tr>
<th>Feature</th>
<th>Examples</th>
<th>Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charged</td>
<td>Positive and negative poles; excess of charge; migration of charge; absorption of charge; rock with charges</td>
<td>31.3</td>
</tr>
<tr>
<td>Attracts things</td>
<td>Attract metal objects</td>
<td>28.8</td>
</tr>
<tr>
<td>Attracts and repels</td>
<td>Attracts or repels items; charges that attract or repel to other charges; opposite sides attract, like sides repel</td>
<td>25</td>
</tr>
<tr>
<td>Acts on metals</td>
<td>Rock that attract metals; attracts some metals</td>
<td>21.3</td>
</tr>
<tr>
<td>Have poles</td>
<td>Poles at different ends; two kinds of poles; north and south</td>
<td>11.3</td>
</tr>
<tr>
<td>Composition</td>
<td>Metal; metallic; rock; solid; hard; substance; material</td>
<td>7.5</td>
</tr>
<tr>
<td>Magnetic field</td>
<td>Magnetism is stronger at ends</td>
<td>6.3</td>
</tr>
<tr>
<td>Actions</td>
<td>Moves, sticks, pulls</td>
<td>3.8</td>
</tr>
</tbody>
</table>

Table 3

Finnish lower secondary students (grade 8, n=18): What is your definition of a magnet?

<table>
<thead>
<tr>
<th>Feature</th>
<th>Examples</th>
<th>Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charged</td>
<td>Any positive or negative piece of metal</td>
<td>44.4</td>
</tr>
<tr>
<td>Acts on metals</td>
<td>Attracts most metals; attracts iron or other metals</td>
<td>38.8</td>
</tr>
<tr>
<td>Attracts and repels</td>
<td>Attracts most metals and the reverse; + and - poles get together, + and + repel</td>
<td>27.7</td>
</tr>
<tr>
<td>Moves and pulls</td>
<td>Takes action on objects; moves, pulls metals, sticks, repels</td>
<td>27.7</td>
</tr>
<tr>
<td>Have poles</td>
<td>has + and – poles</td>
<td>27.7</td>
</tr>
<tr>
<td>Composition</td>
<td>A piece of metal; a kind of metal; piece of iron;</td>
<td>22.2</td>
</tr>
<tr>
<td>Attracts things</td>
<td></td>
<td>16.6</td>
</tr>
<tr>
<td>Acts on other magnets</td>
<td>Attracts another object or magnet</td>
<td>16.6</td>
</tr>
</tbody>
</table>
Table 4
Finnish upper secondary students (grade 11, n=21): What is your definition of a magnet?

<table>
<thead>
<tr>
<th>Feature</th>
<th>Examples</th>
<th>Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charged</td>
<td>Different size charges in different parts; internal charges; static charge; one end positive, other end negative</td>
<td>61.9</td>
</tr>
<tr>
<td>Attracts and repels</td>
<td>Differently signed poles stick together and opposite signed poles repel</td>
<td>28.6</td>
</tr>
<tr>
<td>Magnetic field</td>
<td>Magnetic field inside of it; creates a magnetic field around; magnetic field causes charge distribution in conductors</td>
<td>23.5</td>
</tr>
<tr>
<td>Magnetic poles</td>
<td>Plus and minus poles; similarly marked poles repel</td>
<td>19.0</td>
</tr>
<tr>
<td>Acts on metals</td>
<td>Sticks on metals; object which repels metals; can influence two metallic pieces</td>
<td>9.5</td>
</tr>
</tbody>
</table>

Table 5
Graduate physics students (n=27): What is your definition of a magnet?

<table>
<thead>
<tr>
<th>Feature</th>
<th>Examples</th>
<th>Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnetic field</td>
<td>Produces magnetic field; creates a field without the flow of charge; device or material that creates a field; field lines</td>
<td>51.8</td>
</tr>
<tr>
<td>Domains</td>
<td>Domains of atoms; aligned domains; charged domains</td>
<td>33.3</td>
</tr>
<tr>
<td>Magnetic poles</td>
<td>Distinct poles; N and S pole; has poles; aligned poles</td>
<td>29.6</td>
</tr>
<tr>
<td>Attract and repel</td>
<td>Attracts or repels using a field force</td>
<td>11.1</td>
</tr>
<tr>
<td>Charged</td>
<td>Material with aligned negative and positive charged domains</td>
<td>7.4</td>
</tr>
</tbody>
</table>

The primary factor that emerges from these groups is charge. Clearly, charge is the most common identifying characteristic among the secondary students, but is virtually unmentioned by the graduate students. Conversely, the graduate students were more likely to describe magnets by having magnetic fields and atoms aligned in domains. Even so, several graduate student response two recurring conceptions which are inaccurate, (1) that a magnet would oppose something that is not a magnet, and (2) that domains are charged.

A material composed of domains of aligned atoms that produce an attractive field and opposing field to different materials. (GR-25)
A magnet is a material with aligned positively/negatively aligned domains. (GS-27)

Among the secondary students, the 11th grade Finnish students (UF) show the greatest tendency toward a more scientific view of magnetism, with the notable exception of charge. They most often indicated that magnets can both attract and repel and exhibit a field, and were less likely to describe magnets by “actions.” It is interesting that between the upper and lower Finnish students, the upper students were more likely to refer to charge with respect to magnets. We consider that this may be a result of further study in chemistry of the types of Columbic interactions among molecules and ions and students applying this model to the behavior of magnets. A summary of the descriptive terms among the student groups if shown in Figure 1.
Figure 1. Comparison of key words for magnets for all groups

Only the US high school physics classes were asked the question to describe a magnet both in a pilot survey and after a unit of instruction. The frequencies with which each of the descriptive features occurred are presented in Figure 2.

Figure 2. Percent of Responses by Key Word

The data comparing students’ conceptions of a magnet show several vivid contrasts before and after the lesson. Prior to instruction students focused on the idea that magnets, or regions of them, are charged, that they have the effect of attraction (not recognizing repulsion), and that they act on metals. There was little focus on the concept of poles and magnetic field, and not a single student mentioned domains. The trend reversed after the lessons with students referring to poles, field, repulsion in addition to attraction, and domains. There is a sharp reduction in the view that magnetism involves magnets which are
charged. Table 6 suggest possible levels with which student concepts of “magnet” might be categorized.

**Dimensions of Magnetic Interactions**

Students portrayed the results of their investigation using a variety of graphical representations. Some students organized their observations based on the types of interactions observed; others based their diagram on the types of materials used. Some students used a flow chart approach, others more a description. At the most basic level, exhibited by the drawings in Figure 3, some students made reference to the objects without regard to the strength of the magnetic interaction or a distinction between attraction and repulsion. None of these drawings account for no interaction, or the “not magnetic” type of action.

![Figure 3. Drawings representing types of magnetism](image)

Students who do not quite make the cognitive connections to affect a conceptual grasp of either the task or the concepts involved may be more likely to limit their analysis to the behavior of the object rather than the material or type of interaction, demonstrated by students PL-12 and PL-17. Student MC-54 gave no consideration to either strength of direction in his or her drawing.

The pyramid diagram of student PL-18 shows an interesting case. It is difficult to conclude form the drawing what is represented by the pyramid and the relative positions of the types of magnetism listed. At first inspection, we would conclude that this student showed no correct conception of direction with the plus and minus signs and not knowing if these are intended to represent direction or charge. Regardless, diamagnetism would be marked negative, as repulsion. One might conclude that the area of each part of the pyramid indicated the relative occurrence of each type of magnetism, in which case the student would be correct – everything is diamagnetic and very few materials are ferromagnetic. It would be unlikely, however, that this would have been known by the student.
The drawings of students MC-42 and MC-2 (Figure 4) demonstrate a higher order of perception and reflection. MC-42 began by dividing the interactions observed into magnetic and non-magnetic, further differentiating between attraction and repulsion. While MC-42 accounts for relative strength in attraction, this student does not differentiate strength with repulsion, not taking into account that two magnets can strongly repel in the correct orientation.

While the center of focus of the drawing by MC-42 was the object of interaction, the drawing of MC-2 focuses on a differentiation of the strength of interaction. MC-2 realizes that repulsions can be either weak or strong, a concept not revealed in most diagrams.

![Figure 5. Drawings representing types of magnetism](image)

Some students’ diagrams took the form of a key as a guide to sort objects into the three kinds of magnetism investigated, such as the drawing by student MC-52 in Figure 5. The drawing accounts for non-magnetic interactions, repulsions, and names the kinds of magnetism. It does not include the concept of strong repulsion between two magnets.

![Figure 6. Student drawing of types of magnetism (MC-52)](image)

A few students took the approach of summarizing their results as a histogram. Student S1P1 used a simple diagram that depicts the relative strength of the magnetic interaction. This is the only student who used the term susceptibility and the only student who referred to the interaction in a strictly ordinal sense. This student did not however consider the possibility of an object such as a magnet having a strong repulsion.
Engaging students in investigating the ways in which these materials interact, and asking them to describe their findings in terms of similarities and differences focuses their attention and increases their perception. Using multiple objects composed of the same material (e.g., paper clip, nail, staples) enables them to consider more the material and less on the object. Moreover, comparing properties among materials that a magnet attracts but does not repel, or that interacts with a magnet weakly versus strongly, allows students to move beyond basic perceptions to a more sophisticated, theoretically based analysis.

Table 7 lists categories of responses that might be used in the differentiation of levels of students’ conceptions.

<table>
<thead>
<tr>
<th>Level</th>
<th>Key features of drawings</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>Includes magnetic and non-magnetic, attraction and repulsion, strong and weak; specifies magnet-magnet interactions, types of magnetism; specifies which types are permanent or temporary</td>
</tr>
<tr>
<td>3</td>
<td>Includes magnetic and non-magnetic, attraction and repulsion, strong and weak, includes magnet-magnet interactions, types of magnetism</td>
</tr>
<tr>
<td>2</td>
<td>Includes magnetic and non-magnetic, strong and weak, types of magnetism</td>
</tr>
<tr>
<td>1</td>
<td>Strong and weak, types of magnetism</td>
</tr>
<tr>
<td>0</td>
<td>Graphic had no predictive value</td>
</tr>
</tbody>
</table>

**Concept of a Magnetic Field**

The groups of US physics students (BL, MC and PL) were given the following question, both prior to and after the magnetism lessons: Magnets “create” what is called a magnetic field in the area around them. Using the outline of a magnet below, draw what you think the magnetic field might look like.
Students’ mental models prior to intervention

A lower anchor for a progression of students’ mental models of the nature of the field surrounding a magnet may elicited from students’ drawings prior to any intervention. Despite the fact that these students had not formally studied magnetism in a physics course, there were at least a few students who had a reasonable prior conception of the concept of a magnetic field. A progression of student models is presented in Figures 8 through 11.

Figure 8. Student field models (no intervention)

The models of students MC-44 and MC-15 in Figure 8 are similar to models found by previous researchers (Borges & Gilbert, 1998) in which the magnetic field is believed to exist as a cloud surrounding the magnet, with student MC-15 adding a charge component to the model. The models of students MC-43 (Figure 8) and LF-9 (Figure 9) indicate an electric polarization of the magnet of the area surrounding it. Both of these models have some degree of reason, recognizing that the ends of the magnet are somehow different in nature or behavior. It is of interest as well that the models of students LF-9 and LF-10 (Figure 9) are lower secondary students from Finland and despite their being at the 8th grade level resent models above what we would consider most basic in nature.

Figure 9. Student field models (no intervention)

The models drawn by students MC-21, UF-21 and MC-9 (Figure 10) more closely resemble the natural features of magnetic fields although spatially they are inaccurate and model UF-21 includes a charge component.

Figure 10. Student field models (no intervention)
The models of students UF-16 a grade 11 Finnish student and MC-41 (Figure 11) are reasonably good representations of magnetic fields, despite that the directional component is inaccurately depicted.

![Image of student field models](image1)

**Figure 11. Student field models (no intervention)**

**Students’ models of field lines – embedded assessment**

In the course of the lessons, students created two different models of the field surrounding a magnet as an embedded assessment to spur discussion about the characteristics of their models. In one activity, they used iron filings shaken over magnets of various types and shapes; in the other, they constructed a map using a compass, plotting around the magnet, making a mark at each position of the compass needle, connecting the dots and then marking the direction. Constructing both types of models provide students with the opportunity to compare and contrast features and brainstorm in groups a consensus of findings. Examples of students’ models are shown in Figure 12.

![Image of student field models](image2)

**Figure 12. Student field models (embedded assessment)**

**Students’ mental models after intervention**

Students’ drawings of the field surrounding a magnet after the completion of the lessons were surprisingly consistent. The drawings were coded into two categories – those with an accurate representation of field lines, but without arrows to show direction, and those with arrows. Out of the 66 students from the group (MC) that answered this question at the culmination of the lessons 52 students (78.8%) drew diagrams the correctly showed field lines and arrows. Figure 13 provides an example of each category.
We recognize that we cannot draw inference about students’ accurate conceptions of magnetic fields from these drawings alone. As we continue to develop our learning progression, we will seek to create questions appropriate for interviewing students about their drawings and the rationale behind them. Among key concepts related to field, we will probe students’ understanding of the following key ideas for field lines. Magnetic field lines,

- in a single bar magnet attempt to form closed loops from pole to pole.
- do not cross one another.
- all have the same strength.
- decrease in density with increasing distance from the poles.
- are considered to have direction as if flowing, though no actual movement occurs.
- flow from the south pole to the north pole within a material and north pole to south pole in air.

It is important that students realize that field lines are not concrete. Visualizing them with iron filings or a compass allows students to see the effect of the presence of the field, not the field itself. The concept of field and field lines is visited again later in the lesson series when students investigate the behavior of the ferrofluid and observe a pattern related to that of the iron filings here.

Considering a progression of concepts relative to field lines, there are characteristics which are both common and unique among these student models. With the conception of charge, we would propose that while charged poles or charge polarization models are not scientifically accurate, they do represent the view that there is a polar nature to the magnet and the orientation of the magnetic field, thus giving these models more explanatory power than, let’s say a “cloud” model. Further, a model with a geometric shape with lines surrounding the magnet that fan out or disperse with distance may imply that field strength decreases further from the magnet.

Table 8

**Preliminary Progression of Concepts Relative to Magnetic Field Lines**

<table>
<thead>
<tr>
<th>Level</th>
<th>Key features of drawings</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>Correct field pattern with direction, north to south</td>
</tr>
<tr>
<td>3</td>
<td>Correct field pattern with incorrect direction</td>
</tr>
<tr>
<td>2</td>
<td>Symmetrical lines in natural field pattern, no direction</td>
</tr>
<tr>
<td>1</td>
<td>Charges poles or orientation; direction to or from magnet</td>
</tr>
<tr>
<td>0</td>
<td>Cloud with no features</td>
</tr>
</tbody>
</table>
Models of Magnetization – Iron Nails

At the beginning of the series of lessons students were asked to informally fill in an outline of a nail, representing how they believe it might appear if they were able to “see inside.” These models provide a basis to inform instruction as well as to provide a means of eliciting initial levels of conceptual development.

**Charge models**

The belief that magnets and magnetic materials are charged was common among students of all of the groups in our sample. Examples of students’ models are provided in Figure 14. Each of these students’ drawings depicts nails which are charged in both the magnetized and unmagnetized states, pointing to the persistence of the notion of charge in students’ models, and the variety of ways in which students envision the charges to be distributed.

<table>
<thead>
<tr>
<th>Non-magnetized</th>
<th>Magnetized</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.png" alt="Image" /> LF-11</td>
<td><img src="image2.png" alt="Image" /> LF-11</td>
</tr>
<tr>
<td><img src="image3.png" alt="Image" /> UF-21</td>
<td><img src="image4.png" alt="Image" /> UF-21</td>
</tr>
<tr>
<td><img src="image5.png" alt="Image" /> MC-57</td>
<td><img src="image6.png" alt="Image" /> MC-57</td>
</tr>
<tr>
<td><img src="image7.png" alt="Image" /> UF-10</td>
<td><img src="image8.png" alt="Image" /> UF-10</td>
</tr>
<tr>
<td><img src="image9.png" alt="Image" /> UF-5</td>
<td><img src="image10.png" alt="Image" /> UF-5</td>
</tr>
</tbody>
</table>

Figure 14. Charge models of non-magnetized and magnetized nails

Models LF-11 and UF-10 both show a polarization of charge which we would interpret to indicate the nature of magnetic poles. Model UF-21 is interesting in that it is polarized from side to side rather than end to end. This was a common conception of among
initial student models. The model draw by student UF-5 might as well be included in the alignment category which follows, but is included here for its charge nature.

**Composition models**

Another typical way in which students conveyed their beliefs about the difference between magnetized unmagnetized nails was by showing a difference in composition of the nail. Variations in composition could include changes in the overall density or nature of the material, material being lost or gained, or migration of material from one part to another.

![Composition models for non-magnetized and magnetized nails](image1)

**Alignment models**

Figure 16 show two examples in which students considered alignment in their conceptions of magnetization. Models in which students show a structural nature and an alignment within the structure of the nail when magnetized most closely resemble the process of magnetization.

![Alignment models of non-magnetized and magnetized nails](image2)
The first example in Figure 16 (LF-1) shows a nail with embedded mini-magnets, what might be accurately construed as domains. While this is a reasonable model and one often seen in textbooks (neglecting the charge component), it leaves the student to believe that there are two components in the nail, one suspended in the other, rather than a uniform material. This notion also may cause problem in trying to reconcile the particle nature of matter. This model does nevertheless convey the accuracy of the concept of domains. The model drawn by student UF-9 is an accurate representation as well for the concept of magnetization.

The models in Figure 16 can be examined in the context of explanatory power, based on students’ conceptions that nails in the magnetized and unmagnetized states are in some way different, from the perspective of a structural alignment process. From a scientific perspective, the alignment models both coincide with the idea that a ferromagnetic material, like an iron nail, contains domains. In an un-magnetized state the domains are randomly oriented, but when the nail is magnetized, the magnetic orientations of the domains align.

We were able to follow a progression of student conceptions in the high school physics classes using student artifacts from embedded assessments. At the culmination of the lesson in which students constructed a working model of a magnet, they verify that the magnet model is not already magnetized using a compass and then proceed to magnetize it with a magnet. They verify that their model magnet exhibits the same field as a permanent magnet and envision each of the filing pieces as a tiny magnet on its own. Re-visiting the models they had drawn previously for magnetized and un-magnetized nails provides students with reinforcement to the field concept as well as a foundation for the next lesson, the magnetization of a nail.

Using evidence from these investigations, comparing electrostatic charge and magnetism and then the modeling of a magnet, students are allowed to revise their initial models of magnetized and non-magnetized nails in light of the new evidence. Examples of some of these models are shown in Figures 17 and 18. Revision of these models will continue throughout the next lessons.
Each of the students in Figure 18 proposes two alternative models for the way in which magnetized and unmagnetized nails may differ. Both models drawn by each of these students show a more accurate representation of what happens inside the nail with respect to alignment of domains, although the notion of domains had not yet been proposed by the teacher. The diagrams are surprisingly similar in that the arrows in the nail that is not magnetized are all facing the same way on opposing sides of the nail in both models. It is also interesting that in the magnetized nail, the arrows are pointing away from the middle and toward what would be the poles of the magnetized nail.

Beginning with eliciting students initial conceptions of how they might envision two states of a nail, magnetized and not magnetized, allows students to reflect upon and congeal their own mental model. It enables them to express what they believe, based on whatever experiences they may have had and through discussion or in writing defend their model. Revisiting students’ models throughout the lesson, allowing students to weigh new evidence and revise their models in light of the evidence enables them to construct knowledge in a progressive and scientific way.

**Magnetic Induction**

One of the most common beliefs among students is that if one end of a magnet attracts an object, the other end will repel the object; it will push the object away. Applying what they learned in the previous inquiry with the magnet model, how it can be magnetized and un-magnetized, and how its magnetic field compares to that of a magnet, students can transfer their understanding to the magnetization and de-magnetization of a solid object – a nail.

The previous sections illustrates predictive models that students created prior to any instruction for how they believed magnetized nails might differ from non-magnetized ones. These models provide a means to help students to focus their conceptions and ……We posed an addition pre-intervention question to elicit a written response for what students believed would happen when a paper clip is approached by a magnet.

Mark and Inez are playing with magnets notice that one end of the magnet seems to attract a paper clip. Mark says if they turn the magnet around and touch the other end of the magnet to the paper clip, the clip will be pushed away. Inez disagrees and believes that both ends of the magnet will attract the paper clip equally. Pick a side and explain.

We will examine students’ initial responses, look at drawings created after the magnetization of a nail lesson, and then present results from a similar question asked as a follow-up. Finally we will present a tentative conceptual progression of responses.

Of the 66 students presented with this question, 22 correctly agreed that the clip would be attracted to either side of the magnet, while 37 students believed that the opposite end of the magnet would repel the clip. Reasons for repulsion were varied, but many centered on concepts of charge in one way or another, as illustrated in the following.

I say it will push it away because those ends have the same charge and the same charged things repel (MC-3).

I think that the paper clip will be pushed away because both ends of the magnet are opposites and if it attracts to one side it should repel from the other side (MC-39)

The first child is correct. The magnet has positive and negative ends (MC-13).
One side will attract and the other side will repel due to a North and South pole (MC-5).

The students who believed that both ends of the magnet would attract the paper clip were about equally divided between those who cited reasons of charge and those who reasoned that the paper clip was not magnetized. While some students correctly assumed that if the paper clip was not magnetized it would be attracted to either end of the magnet, none of these students explained why this would be the case.

[I agree with the] 2nd child. The magnet affects the position of the electrons in the paper clip. If the first end pushes the electrons away, it is negative and will be attracted to the remaining protons. The other end will then be positive, and therefore attract the electrons in the paper clip, and will attract the paper clip (MC-69).

Both ends will attract the paper clip; paper clip is a magnet and doesn't have N or S poles (MC-14).

Students’ construction and manipulation of the model magnet, mapping its field, and contemplation of the structure of domains, followed by the process of magnetizing and then demagnetizing the nail, begins to guide students through the construction of the concept that there is an alignment process involved. It also provides them with the opportunity to once again revise their models to approach a more accurate scientific view. Taking a magnetized nail and cutting it into smaller pieces, each piece a complete magnet itself, helps to generate the conception that the magnetized object must contain a piecemeal organization, each piece capable of conformity or not with the others. These bits of material within the nail, groups of atoms called domains, relate as well to the nanoscale materials, such as a ferrofluid, where each atomic cluster is a single domain, and just like in the nail, paper clip, or a permanent magnet, domains may align relative to an applied field.

The drawings in Figures 14 and 15 provide student artifacts from the posttest administered by the teacher at the completion of the magnetism unit. The question asked students to fill in the nail as a model of how they believed it might appear if they had magic glasses to see. Virtually all of the students (65 out of 66) created drawings indicative of domain structure for the nail, although some variations emerged. The drawings in Figure 19 both indicate correct representations of the domain concept. Figure 20 presents an interesting case in that the domains are aligned in opposing directions. This student appears to have the concept of the structure of domains and the requirement for alignment, but misrepresents that in the magnetized object the domains would all point in the same direction. The opportunity to interview student MC-52 would provide further insight and rationale for the drawing.

Figure 19. Student models of unmagnetized and magnetized nails (posttest).
Lastly, on the posttest for the magnetism unit we again pose the scenario of a magnet approaching a paper clip. The context of the question is slightly different from the initial question, but the concept is the same. The most detailed of students’ responses accounted for domains in both the magnet and the nail, that the nail is not initially magnetized, and that the domains in the nail can align in any direction influence by an applied field. Such a response was provided by student MC-69, who on the initial question (see above) based his or her account solely on the pushing of electrons and protons.

The north and south poles of the magnet align the domains in the paper clip. The north pole aligns the domains so that the south end of the domains are closer, causing the paper clip to attract the magnet, while the south pole draws the north sides closer.

A similar response was provided by student MC-66.

The magnet magnetizes the paper clip, which means it causes the domains within it to be lines 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.

Other responses, in order of decreasing order of theoretical complexity and capacity to explain the phenomenon, include the following. Each of the responses is coded to a preliminary level and summarized in Table 9.

Since the magnet is magnetizing to the paper clip, you can tell that there is somewhat of a magnetic field around the paper clip. But since the paper clip can not be permanently magnetized, it can be attracted to either end of the magnet (MC-40, level 3).

On the magnet the north and south poles are distinct, but the poles in the atoms of the paper clip are not. Because of this, when one of the magnet is moved over the paper clip, the opposite pole in each atom attract to the magnet. Example: the magnet north pole attracts the paper clip's south poles in the atoms (MC- 51, level 3). The domains of the magnet will shift according to what side of the paper clip is presented allowing it to pick up the paper clip (MC-67, level 2).

Both ends of the magnet are attractive; the paper clip can be attractive by both ends because it is not like another magnet (MC-14, level 2).

The magnet has both North and South poles in it, so each side of the magnet attached to the opposite poles in the paper clip MC-58, level 1).

This is because each side of the magnet has its own north and south pole, so the paper clip can be attracted to both sides (MC-16, level 1).
Some parts might be negative and some might be positive, attracting to different parts (MC-46, level 0).

Table 9

<table>
<thead>
<tr>
<th>Level</th>
<th>Key concepts</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>Nail contains domain; nail is unmagnetized; magnet has field; field aligns domains in nail; nail exhibits field; fields interact</td>
<td>MC-66, MC-69</td>
</tr>
<tr>
<td>3</td>
<td>Includes key elements listed above but lacks overall clarity of explanation</td>
<td>MC-40; MC-51</td>
</tr>
<tr>
<td>2</td>
<td>Argument limited to one or two concepts</td>
<td>MC-14</td>
</tr>
<tr>
<td>1</td>
<td>Limited to statement of attraction; exhibiting lack of evidence or application of mistaken concept (argument of charge)</td>
<td>MC-58</td>
</tr>
<tr>
<td>0</td>
<td>No coherent explanation</td>
<td>MC-46</td>
</tr>
</tbody>
</table>

Magnetism at the Nanoscale

The primary impetus for beginning to trace a learning progression for magnetism came from the backward design of a series of lessons to help students learn about and understand magnetism at the nanoscale. The term nanoscale implies that at least one dimension of a structure or device is in the range of from 1 to 100 nm. The lessons culminated with students synthesizing a ferrofluid, a material consisting of a suspension of nanoscale magnetic particles, the particles being a form of iron oxide. Beyond the novelty of students observing a liquid which responds to a magnetic field but does not remain magnetic, we believe it is important, both for student understanding as well as creating a fit into the curriculum, that observing the ferrofluid be preceded by experiences which could enable students to construct a cognitive framework within which they would be able to understand and appreciate the science behind the behavior of nanoscale materials which separated them from bulk science.

Magnetism as a size dependent property

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. A cognitive and conceptual sequence that may help lead students to an understanding of the nature of nanoscale magnetic materials could include the following key concepts;

- Atoms can have a magnetic dipole orientation.
- Atoms can align to form domains with an overall uniform magnetic moment or orientation.
- Nanoscale particles are single domain particles.
- Thermal energy has a randomizing effect on the magnetic orientation of atoms
- In a nanosize cluster of atoms, the ratio of surface to interior atoms is extremely high

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As a result of the effect of thermal energy on the surface atoms, materials which are ferromagnetic (can be magnetized) at the macroscale cannot be at the nanoscale.

Superparamagnetism

The investigation and explanation of the behavior exhibited by a ferrofluid, ties together all of the concepts presented in the preceding lessons. It not only provides students to see a material truly unique in magnetic behavior and totally outside their realm of experience, it is a means of transferring the concepts they have learned to a new situation. Figure 21 shows students’ models created to correlate their observations with the concepts they had learned.

![Figure 21. Student representations of a ferrofluid in a magnetic field.](image)

There is a progression of elaboration in these drawings indicating students’ varying levels of perception of what they observed or their ability to interpret their observation in light of their previous study. The essential idea is that the ferrofluid forms spikes in the presence of an applied magnetic field which make a pattern similar to the iron filings model completed earlier. Students will also observe that as they move the magnet further away the spikes become fewer, or that if they lay the magnet flat they will observe that there are no field lines emerging form the sides. These observations correlate directly to the previous study of the magnetic filed using both the iron filing and compass models.

At the culmination of the week-long series of lessons on magnetism conducted by the teacher of the high school physics classes in our sample, students were asked several questions to elicit their understanding of why nanomagnetic particles do not remain magnetized when larger samples of the materials of the same composition do. The day prior to the last lesson, the teacher posed an informal question in discussion and then asked...
students to respond in writing to reflect on their thoughts. They were given the following open ended question,

An iron bar, a nail, or even iron filings can be magnetized and remain magnetized. The nanosize particles in a ferrofluid will be magnetized in the presence of a magnetic field, but can not stay magnetized when the magnet is removed. Explain why nanoscale particles like those in a ferrofluid can not stay magnetized.

The rationale behind this question is to elicit students’ to translate their conceptions of magnetic orientation, magnetic domains, the consequences of thermal energy… the effects of particle size on alignment of atoms within a domain, consequences of thermal energy… and the behavior of a material like a ferrofluid as a whole. We coded students’ responses into three levels, representing a hierarchy of conceptual synthesis.

Table 10

<table>
<thead>
<tr>
<th>Level</th>
<th>Examples of student responses</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>The magnetic pieces in a ferrofluid are single domains. Since the particles are suspended in a liquid the domains will only align when a field is applied. Otherwise thermal energy is sufficient to keep the domains randomly oriented. If the particle domains will not stay aligned, the material can not stay magnetized. (Theoretical)</td>
</tr>
<tr>
<td>2</td>
<td>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). They are unable to hold the magnetization because there is not enough volume to counteract the relative size of the surface. The particles want to move around too much (MC-22). The particles move and lose their magnetism, just like when we shook the nail (MC-58) Because the particles can move more, so when a magnet comes close they clump together and attract, but when the magnet is removed they spread back out and are no longer magnetized (MC-66).</td>
</tr>
<tr>
<td>1</td>
<td>They don’t have enough atoms on the inside to make up domains to stay lined up to keep magnetized (MC-15). It is hard to stay magnetized because they are tiny particle with a large surface-to-volume ratio (MC-46). They are moving too fast to stay magnetized (MC-6).</td>
</tr>
<tr>
<td>0</td>
<td>Jostles around easier (MC-23). There is less space for the domains to solidly stay magnetized (MC-1)</td>
</tr>
</tbody>
</table>

Finally, even at the end of the series of lessons, addressing differences between electrostatic and magnetic interactions, the process of magnetization and the role of magnetic domains, there remains a continued perception of electrostatic charge being a factor in the magnetic behavior of the nanoscale particles.
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).

**Discussion**

As we state when we began, this is a pilot study in which we are researching the process and progress of students learning about magnetism and how they are able to apply that cognitive foundation to understand the behavior of magnetic materials at the nanoscale. In attempting to document the progression of concepts learned by students along the way, we might ask about what is “progressing?” Permit me to draw a personal analogy, to my first few years teaching high school chemistry. I had a degree, I had a license, I had a classroom, I had a class; and so I began. At about the beginning of my fifth year, I reflected upon how I would begin the year and I found myself with a new found feeling of confidence. It had taken a lot of practice; it required getting used to unfamiliar demands, knowing how to manage my time, where to find the right resources and how to plan ahead. More than anything I had learned to plan in action and think on my feet. I believe that I could document that process of my experience in writing as a progression in learning – call it a personal learning progression. Allow me to compile the experiences of those around me and those before and I can begin to compile a map for others.

A learning progression is a documentation of the learning experience, research-based and research-validated. It starts with a goal or an outcome and documents the journey of learning how to learn, how to process information, how to reflect on one’s progress, how to know where one is at a given place and time relative to the final goal, what obstacles might crop up and how they might be effectively and efficiently dealt. A learning progression should help one get back on track when they are lost.

Creating a learning progression, such as a progression for learning magnetism is not much different in theory than one for teaching chemistry. It should require a scrutiny of grain size and the necessity for focus. It should be grounded in research, taking into account how we learn and why we might not. If we wish for students to understand what it means for materials to behave differently at the nanoscale over other scales, we must decide, what are the essential concepts required? How many different ways can they be learned? We are only at a beginning in our learning progression.

This research is just a start. As we continue to study students learning, we will continue to design new and better ways of assessing students’ conceptual development and status. We will build our knowledge base of student thought processes by looking more at asking students to predict the outcome before they perform the task, or draw and analyze models of processes along the way. We will plan ways to gain access to students’ understanding in non-threatening ways and promote making them part of the development process. We believe that as we continue to pilot our lessons and assessments, interviews and informal conversations with students will be a valuable resource to fill in the many missing details absent from written responses.
References


## Appendix A

*A synthesis of research in conceptions of magnetism*

<table>
<thead>
<tr>
<th>Conception</th>
<th>Literature reference (see References)</th>
<th>Grade</th>
</tr>
</thead>
<tbody>
<tr>
<td>Some objects attract others; some objects do not</td>
<td>Constantinou, et al. (2001)</td>
<td>K-1</td>
</tr>
<tr>
<td>Objects sometimes attract; sometimes repel</td>
<td>Constantinou, et al. (2001)</td>
<td>K-1</td>
</tr>
<tr>
<td>Magnetism is seen as an interaction between two bodies, not a property of an object</td>
<td>Constantinou, et al. (2001)</td>
<td>K-1</td>
</tr>
<tr>
<td>Magnets are attracted by a type of gravity</td>
<td>Barrow (1987)</td>
<td>2</td>
</tr>
<tr>
<td>Poles are only on the ends of a magnet</td>
<td>Barrow (1987)</td>
<td>K-3</td>
</tr>
<tr>
<td>Magnets work by pulling (pulling model)</td>
<td>Erickson (1994); Meyer, (1991)</td>
<td>4</td>
</tr>
<tr>
<td>In magnets there are little small magnets, like molecules</td>
<td>Barrow (1987)</td>
<td>5</td>
</tr>
<tr>
<td>Magnets only attract metals</td>
<td>Brademante &amp; Viennot (2007)</td>
<td>4-6</td>
</tr>
<tr>
<td>Needles [compass] only go to the ends of the magnet</td>
<td>Brademante &amp; Viennot (2007)</td>
<td>4-6</td>
</tr>
<tr>
<td>A round magnet would make the same map as that of the earth</td>
<td>Brademante &amp; Viennot (2007)</td>
<td>4-6</td>
</tr>
<tr>
<td>Electrons in one, protons in the other makes magnets attract</td>
<td>Barrow (1987)</td>
<td>6</td>
</tr>
<tr>
<td>Magnets work by emitting rays (emanating model)</td>
<td>Erickson (1994); Meyer, (1991)</td>
<td>7-10</td>
</tr>
<tr>
<td>Magnets work by controlling a bounded area around them; area of influence (enclosing model)</td>
<td>Erickson (1994); Meyer, (1991)</td>
<td>7-10</td>
</tr>
<tr>
<td>Magnetic poles are regions at the ends of a magnet; they have an excess and lack of electricity</td>
<td>Borges &amp; Gilbert (1998)</td>
<td>10</td>
</tr>
<tr>
<td>An over-literal view, magnetic field is a ‘flow’ of something</td>
<td>Saglam &amp; Millar (2006)</td>
<td>10-12</td>
</tr>
<tr>
<td>Magnetic field is a region in which there is a force that may attract or repel other bodies</td>
<td>Borges &amp; Gilbert (1998)</td>
<td>12</td>
</tr>
<tr>
<td>Magnetism is a type of gravity</td>
<td>Borges &amp; Gilbert (1998)</td>
<td>12</td>
</tr>
<tr>
<td>There are charges circulating there is a magnetic field</td>
<td>Borges &amp; Gilbert (1998)</td>
<td>12</td>
</tr>
<tr>
<td>The north pole in a magnet is positively charged, the south pole is negative</td>
<td>Maloney (1985); Saglam &amp; Millar (2006)</td>
<td>10-16</td>
</tr>
<tr>
<td>Field lines are material entities; tubes with matter or charge flowing through them</td>
<td>Procovi (2007)</td>
<td>13-16</td>
</tr>
<tr>
<td>A magnet of opposite charge will pull electrons</td>
<td>Maloney (1985)</td>
<td>13-16</td>
</tr>
<tr>
<td>Magnetic force on charges at rest in a magnetic field</td>
<td>Maloney (2000); Saglam &amp; Millar (2006)</td>
<td>10-16</td>
</tr>
<tr>
<td>Magnetism is an intrinsic property of the material</td>
<td>Borges &amp; Gilbert (1998)</td>
<td>&gt;16</td>
</tr>
</tbody>
</table>