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DEVELOPING EXPLANATORY MODELS OF MAGNETIC PHENOMENA THROUGH MODEL-BASED INQUIRY

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Abstract: *The main purpose of this study was to bridge the gap between how scientists practice and how students learn science. To achieve this, an innovative student-centered curriculum was designed to teach 42 undergraduate students. The program involved scaffolding activities, an interactive computer simulation, and reflection on scientific modeling criteria to address the students' difficulties in reasoning at the microscopic level and the scientific evaluation of their models during their development of an explanatory model of magnetism. To address the students' difficulties in reasoning at the microscopic level and the scientific evaluation of their models during their development of an explanatory model of magnetism, t he program involved scaffolding activities, an interactive computer simulation, and reflection on scientific modeling criteria. The results of the study indicated that more than half the students developed scientific and coherent microscopic N-S dipole models to explain observed magnetic phenomena, and students' understanding of the nature of models was significantly enhanced after the instruction. This study contributes to modeling theory and the methods that can help students self-develop scientific models of magnetism as opposed to rote learning.*

Key words: *explanatory models, magnetism, modeling, scientific inquiry, undergraduate students.*

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Introduction

Current science education research emphasizes that the educational methods for teaching and learning science should reflect how scientists practice science (NRC, 1996, 2007, 2013). The role of models and modeling has been recognized as essential to the process of scientific inquiry. Scientists employ models as representations of ideas about the structure and behavior of systems. Constructing these models allows scientists to manipulate explanatory representations mentally and simplify complex phenomena as well as to develop and examine their explanations for the mechanisms of target phenomena (Chin & Brown, 2000; Nersessian, 2008, 2012; Windschitl, Thompson, & Braaten, 2008).

However, the current science curricula do not offer adequate opportunities for students to develop, evaluate, and revise their explanatory models for scientific phenomena as scientists do, so the scope of scientific inquiry is limited to a narrow representation of scientific practice. In light of discrepancies in simple forms of scientific inquiry in schools and in authentic scientific inquiry that scientists practice, Chinn and Malhotra (2002) advised that students' inquiry activities should involve the broader characteristics of authentic scientific inquiry, such as the development of theoretical models.

The purpose of this study is to facilitate the students' modeling process as one way of scientific inquiry in order to construct models to explain magnetic phenomena. Based on the ideas of constructivist learning approaches, this study encourages students to actively engage in the spontaneous modeling process in order to explain magnetic phenomena. In accordance with an authentic view of scientific inquiry, this study intends to offer students an experience of engaging "model-based inquiry" to finally develop explanatory models of magnetic phenomena.

Some researchers have encouraged students to develop models in the inquiry process to account for scientific phenomena (e.g., Coll & Lajium, 2011; Coll & Taylor, 2005; Cosgrove, 1995; Feng, 2012; Louca, Zacharia, & Constantinou, 2011; Maia & Justi, 2009). Nevertheless, fewer studies have emphasized how to enhance students' abilities to self-develop scientific models and their understanding of scientific models during their scientific inquiry. Therefore, the aim of this study is to investigate how model-based inquiry can facilitate students' development of scientific models as well as their understanding of the nature of models and modeling.

Learning Magnetism

The topic of magnetism is typically taught through either observation of magnetic phenomena or as an introduction of abstract verbal symbolic knowledge, such as magnetic fields or magnetization, without asking students to self-develop explanatory models of magnetic phenomena. Knowledge of magnetism is usually taught abstractly and introduced in a piecemeal way.

The nature of physics is perceived as abstract because scientists hypothesize physics concepts, such as magnetic fields and atoms, which cannot be directly observed (McComas, 1998). Therefore, these concepts are usually regarded as counterintuitive and different from students' existing knowledge. Nevertheless, previous studies showed that the domain model or atomic magnets model of magnetism can be reasoned from students' existing and intuitive ideas (Cheng & Brown, 2010, 2012, 2013). Thus, we believe that scientific microscopic models can be intuitive and accessible to students through scaffolding activities.

The Difficulty of Learning and Teaching Magnetism

Two challenges exist regarding the development of coherent microscopic explanatory models of magnetism: reasoning at the microscopic level and understanding of the differences and similarities between electricity and magnetism.

Difficulties in Reasoning at the Microscopic Level

In science, microscopic levels of explanations are usually regarded as providing underlying mechanisms that help make sense of observed phenomena. However, understanding and explaining hidden and unobservable mechanisms at the microscopic level are often difficult for students (Chiou & Anderson, 2010; García-Franco & Taber, 2009; Gilbert, 2008). Even after learning microscopic levels of content knowledge, secondary school students have also been found to encounter difficulties in providing explanations progressing from observational to microscopic levels (Margel, Eylon, & Scherz, 2008; Taber, 2008).

According to previous studies about students' models of magnetism (Borges & Gilbert, 1998; Erickson, 1994), secondary students can be observed as possessing two major types of models. The simpler type of model is a description of the activities of a magnet without involving the unseen components as a mechanism. In this model, magnetic phenomena are regarded as intrinsic properties of magnets. The more complicated types of models are microscopic models, which encompass hypothesized microscopic components, such as electric charges, electric dipoles, and electrically charged particles, to explain the behaviors of the magnets. Nevertheless, most of student models are far from scientific models.

In previous studies (Cheng & Brown, 2010, 2012, 2013), students were often observed to encounter difficulties in developing microscopic explanatory models of magnetism because of limited mental simulation at the microscopic level. Previous studies also showed that even after students have learned about scientific and microscopic domain models, students still had problems applying the model to coherently account for all observed magnetic phenomena (Harlow, 2010; Sederberg & Bryan, 2010).

In this study, an interactive computer simulation tool was integrated into the program to help students develop and manipulate their models at the microscopic level. The purpose of the animation tool is to assist students in visualizing and experimenting with their ideas at a microscopic level, thereby making the interaction of the microscopic elements they have hypothesized accessible to them.

Difficulties in Connecting and Differentiating between Electricity and Magnetism

Research has documented that it is common for students to spontaneously apply the concepts behind static electricity to explain magnetism (Guisasola, Almudi, & Zubimendi, 2004; Guth & Pegg, 1994; Hickey & Schibeci, 1999; Saglam & Millar, 2006; Sederberg & Bryan, 2010). The application of knowledge from electricity, a familiar domain, to magnetism, an unfamiliar domain, usually results in confusion among students. In previous studies, the application of knowledge from static electricity to magnetism led students to hypothesize monopole elements, that is, positive or negative elements instead of dipole elements to account for magnetic phenomena (Cheng & Brown, 2010, 2012, 2013).

The topic of magnetism is taught at school, but teachers often do not introduce the model of magnetism let alone encourage students to develop their own models. This practice may prompt students to borrow the static electric model already learned to explain magnetic phenomena, which involves attractive and repulsive forces as static electricity. As a result, students commonly perceive that magnetism is the same as electricity without distinguishing between them, similar to the findings of the above studies.

The current study employs reflection on scientific criteria, called "scientific modeling criteria," to guide students' development, evaluation, and revision of their models. Through these reflections, students will be expected to be able to integrate appropriate verbal symbolic knowledge into their model reasoning at the microscopic level as well as connect and differentiate the ideas between magnetism and electricity. In addition to developing scientific models, this study also intends to explore whether model-based inquiry, which engages students in reasoning at the microscopic level and reflecting on the scientific criteria, may enhance their understanding of scientific models in some ways.

The current study attempts to answer two primary research questions:

1. Does engaging in model-based inquiry at the microscopic level improve students' development of explanatory models of magnetism?
2. Does reflecting on the scientific modeling criteria in model-based inquiry improve students' understanding of scientific models?

Research Methodology

The purpose of the curriculum was to enhance students' inquiry processes, their understanding of scientific models and modeling, as well as their self-development of the explanatory model of magnetism being close to the scientific domain model or atomic magnets models of magnetism. The scaffolding activities were meant to activate students' related conceptual resources at the observational level to facilitate their further reasoning at the microscopic level. A computer simulation tool was integrated into the activities to foster students' experimentation with their ideas at the microscopic level. Reflection on the scientific modeling criteria aims to help students activate, apply, and reorganize appropriate conceptual resources as well as enhance their understanding of models and modeling.

Research Design

Participants and Teacher

This project was piloted in two courses at the undergraduate level with non-science major students. There were a total of 42 students who had completed the entire three sessions of the experimental curriculum taught by the same instructor.

The role of the instructor was to introduce and guide the procedures of the activities, including facilitating students' discussion of their models and selecting the best model by using their existing modeling evaluation criteria. The instruction also included introducing a computer simulation tool as well as the scientific modeling criteria to students and guiding them to use these criteria to evaluate and revise their models of magnetism.

Curriculum

In this study, in order to help students construct scientific models of magnetism, we designed a curriculum including the following main elements: a series of inquiry activities, an interactive computer simulation tool for reasoning at the microscopic level, and an introduction of reflection on the revised scientific modeling criteria.

The rationale of the project design was based on the processes and the difficulty of developing coherent tiny-magnet models in previous studies (Cheng & Brown, 2012, 2013). First, the context of the design activities activated students' related conceptual resources at the observational level. Next, reflecting on the scientific modeling criteria further activated their appropriate conceptual resources among these related conceptual resources. Then, students applied and reorganized these appropriate conceptual resources into the processes of model construction, evaluation, and modification at the unobservable levels. In the end, students made connections and integrated appropriate knowledge at macroscopic, microscopic, and symbolic levels, helping them to finally develop coherent and microscopic explanatory models of magnetism.

The program was aimed at helping students generate coherent microscopic models of magnetism through reflection on the scientific modeling criteria and enhancing their understanding of the nature of models. For developing models of magnetism, students constructed models for magnetic phenomena they observed, then evaluated and revised their models according to learned scientific modeling criteria. For understanding of models and modeling, students practiced self-developing their models with reflection on scientific criteria in a way similar to how scientists make sense of the world.

The first three activities were taught in the first class of learning about magnetism. The fourth activity was taught in the second class. The first activity was to develop initial explanatory models. Students began by observing magnetic phenomena with which they were already familiar, such as attraction and repulsion between two magnets or the interaction between a magnet and other objects, to activate their related conceptual resources. They were then asked to propose a model to explain their observations. The second inquiry activity was to develop an explanatory model at the microscopic level. Students were asked to use their model to predict what would happen when they cut a magnet in half. After observing and examining the properties of the cut pieces of magnet, they needed to examine whether their models were able to explain their observations and determine whether their models should be revised.

The third activity was to conduct thought experiments with a computer simulation tool to develop explanatory models at the microscopic level. A computer simulation tool was introduced that students used to examine the different models they proposed. They then debated the best consensus model. The fourth activity was to evaluate the models according to scientific criteria and conduct an open-ended inquiry. Scientific modeling criteria were introduced by using the comparison of solid and hallow earth models. After that, students continued an open-ended inquiry by designing their own activities and using these criteria to evaluate and modify the model they developed.

Interactive Computer Simulation Tool

An interactive computer simulation tool was designed according to the hypothesized models that students previously proposed in the teaching experiments (Cheng & Brown, 2010, 2012, 2013). The reason for designing this tool was due to the limitations of students' thought experiments at the level they were not able to directly observe. Hence, this computer simulation tool provided students an ideal platform to assist in visualizing and experimenting with their ideas at a microscopic level, thereby making accessible to them the interaction of the microscopic elements they hypothesized. The most unique function of this tool is that it does not intend to only show students the animation of their models; students are able to experiment with their ideas on this simulation tool. For example, if they hypothesized that the microscopic elements should work like tiny magnets or static electricity, they were able to test what happens at the microscopic and macroscopic levels according to their hypothesized model. This tool helps them to mentally manipulate and visualize what occurs between these elements, which reduces the students' cognitive load and facilitates their higher levels of thinking and reasoning. The interactive computer simulation tool developed by (Cheng, 2013) can be downloaded from the website (http://blog.ncue.edu.tw/mcheng2/doc/35148).

Scientific Modeling Criteria

Scientific modeling criteria in this study were designed as prompts that students were encouraged to use to evaluate their explanations in order to regulate their cognitive processes. Previous studies have shown that following the approach of focusing only on the relationships between evidence and explanations was not enough to regulate the students' modeling processes. Although students may sometimes spontaneously develop the criteria of explanatory power to evaluate their models, the results showed that students also used other inappropriate criteria to evaluate and revise their models (Baek, Schwarz, Chen, Hokayem, & Zhan, 2011; Pluta, Chinn, & Duncan, 2011; Schwarz et al., 2009). Hence, in this study, we expected students to regulate their modeling processes scientifically by employing the scientific modeling criteria to reflect on their explanations.

Previous studies on students' model development showed that when students were asked to think, verbalize, and argue their thinking explicitly using scientific criteria, such as the criteria of visualization and explanatory power, to evaluate their models, it enhanced their cognitive capacities for reasoning; thus, they were able to develop coherent and sophisticated explanatory models (Cheng & Brown, 2012, 2013).

In this study, we prompted students to reflect on their models according to the scientific modeling criteria of explanatory power, predictive power, and consistency to examine whether their models visualized the hidden mechanisms to predict and explain the phenomena and whether the components of their models logically connected with each other and were consistent with other knowledge that they had learned. Through reflection on the following criteria, students were expected to not only activate appropriate conceptual resources to construct explanatory models but also revise or modify their models. These criteria were introduced by using the black box activity (Lederman & Abd-El-Khalick, 1998) and a comparison of the solid and hollow earth model.

Assessments

Two dimensions Qexplanatory models of magnetism and views of the nature of models Qwere assessed in order to explore students' learning progression and the impact of the proposed curriculum. A pre-test and post-test were administered before and after the instructions were given. The tests included the same survey about students' understanding of models in science and their explanations of magnetic phenomena.

Assessing students' explanatory models of magnetism. Before and after the curriculum was taught, students were asked to record their explanations of why iron nails are attracted to the two ends of a magnet, why ordinary iron nails do not stick to each other, and why the iron nails that attach to a magnet attract other iron nails. During the instruction, students also needed to record their explanations of magnetism to keep track of their progress with their models.

Students' explanations were coded by three researchers using an initial coding scheme that identified whether they described the microscopic mechanism and coherently explained the observed mechanism (Cheng & Brown, 2012; Machamer, Darden, & Craver, 2000). The definition and an example of levels of the students' explanation from 1 to 5 are illustrated in Table 1. Higher levels of explanation showed students could develop more advanced microscopic and coherent models.

Table 1. Levels of Explanation.

Level	Definition	Example
1	Description of observable magnetic phenomena	Students only described that the two magnets had two strong ends to attract the iron nails.
2	Visualization of unseen and unknown elements to explain magnetic phenomena	Students imagined unknown and special material in the magnet or matter to explain the attraction of the magnet.
3	Visualization of unseen microscopic elements to explain only one specific magnetic phenomena	Students visualized one specific type of microscopic element, such as N–S dipole components, N and S monopole components, or positive and negative electric monopole components, inside the magnet and the iron nails to explain why the magnet attracts iron nails.
4	Visualization of unseen microscopic elements to explain only two specific magnetic phenomena	Students visualized one specific type of microscopic element inside the magnet and the iron nails to explain not only why ordinary iron nails would not attract other iron nails, but also to explain why the iron nails attracted other iron nails after they were attached to the magnet.
5	Visualization of unseen microscopic elements to explain all three magnetic phenomena	In addition to the visualization in level 4, students visualized the alignment of the microscopic elements in the magnet to explain the two strong ends of the magnet.

This assessment of the explanatory models helped researchers track the evolution of students' models in the curriculum and identify the progress of students' model development between the pre-test and post-test. Inter-rater reliability was 0.83. Rating inconsistencies were resolved during the discussion.

Assessing the views of the nature of the models. The students were asked to complete a Students' Understanding of Models in Science (SUMS) survey (Gobert et al., 2011; Treagust, Chittleborough, & Mamiala, 2002) before and after the curriculum to allow the researcher to evaluate their understanding of the nature of models.

The SUMS survey was generated by Treagust et al. (2002) based on empirical studies used to promote the understanding and use of models in science (Grosslight et al., 1991; Treagust, Chittleborough, & Mamiala, 2001). This survey was designed to investigate students' understanding in five model sub-factors: multiple representation of models (MR), models as exact replicas (ER), models as explanatory tools (ET), use of scientific models (USM), and changing nature of models (CNM). This survey asked students to rate the items on a 1–5 Likert scale, ranging from strongly disagree to strongly agree.

This instrument was modified and translated into Chinese. This assessment helped researchers explore whether students changed their views of models and modeling processes, which can be seen as a subset of scientific inquiry. The reliabilities of each of the SUMS scales in Treagust et al.'s study ranged from 0.71 to 0.84. In our study, each instrument's scale had a high internal consistency. The pre-test reliabilities ranged from 0.766 to 0.806, and the post-test reliabilities ranged from 0.708 to 0.974.

Data Analysis

To answer the research questions, students' explanations before and after the teaching experiment were coded according to the above defined five levels of explanations. The students' views of the nature of models in the pre-test and post-test were assessed based on the SUMS survey (Gobert et al., 2011; Treagust et al., 2002). Finally, the pre-test and post-test of the students' explanatory models of magnetism and their views on the nature of models were compared. Paired *t*-tests were conducted to examine the differences between students pre-test and post-test scores on the students' explanatory models and on students' understanding of the sub-factors of the models in science.

Results of Research

Analysis of Students' Models of Magnetism

Through this curriculum, students' explanatory models progressed from lower levels (pre-test M=3.05, SD=1.50) to higher levels (post-test M=3.9, SD=1.65) of explanatory models. A paired sample *t*-test showed significant improvement in students' development of explanatory models between the pre- and post-test [t (42) = 2.13, p=0.047].

Table 2 shows the distribution of the levels of students' explanatory models of magnetism in the pre- and post-test. The data reveal that in the pre-test, students either developed more observable explanations of magnetism or used microscopic models to explain only two observed magnetic phenomena. In the post-test, more students developed microscopic small-magnet models to explain all observed magnetic phenomena. This progression manifests that students' models progressed from the observational level to the microscopic level and from the more fragmented level to the more coherent level.

Even within level 5, students were able to revise their models. All students who previously employed positive and negative electric monopole models revised their models to become microscopic N–S dipole models. This result demonstrates that students could distinguish the difference between the magnetism and electricity models by the end of instruction.

On the other hand, based on the post-test, 19% of students still could not distinguish the differences between the descriptive and explanatory models for magnetic phenomena. This shows the difficulty of developing an unseen mechanism to explain observable phenomena; thus some students continued to rely on more intuitive observational explanations.

Table 2. Numbers and percentages of students' explanatory models across different levels in pre- and post-tests (N=42).

Level	Pre-test		Post-test	
	Number	Percentage	Number	Percentage
1	15	35.7	8	19
2	3	7.1	2	5
3	4	9.5	2	5
4	16	38.1	6	14
5	4	9.5	24	57

Analysis of Students' Understanding of Models in Science

Students' understanding of the nature of models in science improved significantly in three sub-factors: MR, ET, and USM from pre- to post-test; however, there was no significant improvement in two sub-factors: ER and CNM (described in Table 3).

Table 3 shows that the sub-factor ER had the lowest mean score in the pre- and post-tests, indicating that students were not sure whether models were exact replicas of a target situation. Nevertheless, after instruction, students still had difficulty understanding that the purpose of the model is not to serve as an exact replica of the world, rather than a tool for understanding the world. Also, the sub-factor CNM had the highest mean score in the pre-test, yet this score did not significantly improve after instruction. This may be because students already had better existing knowledge about the changing nature of models. Thus, this instruction faced the challenge of further enhancing student understanding of CNM.

Table 3. Pre- and post-tests of students' understanding of models in science (N=42).

Sub-factors	Pre-test		Post-test		t-Test	
	Mean	SD	Mean	SD	Score	p
MR	4.17	0.40	4.45	0.40	4.02**	0.001
ER	3.09	0.64	3.09	0.63	.06	0.954
ET	4.13	0.41	4.53	0.13	3.08**	0.006
USM	4.20	0.70	4.70	0.43	3.00**	0.007
CNM	4.50	0.56	4.68	0.46	1.19	0.248

**Significant difference at the 0.05 level.*
***Significant difference at the 0.01 level.*

Discussion

With regard to students' development of explanatory models of magnetism, more than half of the students could progress from lower levels of observational and fragmented models to higher levels of microscopic and coherent microscopic N–S dipole models, which are close to the scientific domain models or atomic magnets models of magnetism. Research has uncovered that even undergraduate students with science majors have problems reasoning at the microscopic levels with the scientific models they have learned (Chiou & Anderson, 2010; Karataş, Ünal, Durland, & Bodner, 2013; Kautz, Heron, Shaffer, McDemott, 2005) or have confusion between magnetism and static electricity models (Dega, Kriek, Mogese, 2013; Guisasola, Almudi, & Zubimendi, 2004; Hickey & Schibeci, 1999; Maloney, 1985). In this study, we found that by encouraging students to practice reasoning at the microscopic level and assess their models with scientific modeling criteria during their model-based inquiry, students with non-science majors were able to start reasoning at the microscopic level and finally developed, evaluated, and revised their naive models to become scientific dipole models in order to coherently explain all their observed phenomena. Through reflection on the scientific modeling criteria, they were able to articulate and differentiate the differences between magnetism and electricity.

Nevertheless, the results also indicated that some students in this study could not visualize the unseen mechanism or use their microscopic models coherently to explain magnetic phenomena. These findings unveil that practicing model-based inquiry at the microscopic level and reflecting on their self-developed models may not always encourage students to coherently employ the scientific model to explain observed phenomena. Researchers have identified the positive relationship between students' epistemology of science and their conceptual learning in science (Deng, Chen, Tsai, & Tsai, 2011; Stathopoulou & Vosniadou, 2007). Accordingly, students' understanding of scientific models as one aspect of the epistemology of science is possibly associated with students' development and application of scientific models, thereby requiring future study to investigate whether improving students' views of scientific models can further enhance students' development and application of models.

With regard to students' understanding of scientific models, this study revealed that model-based inquiry at the microscopic levels and reflection on self-generated models enhanced students' understanding of scientific models in terms of model as multiple representation (MR), models as explanatory tools (ET), and the use of scientific models (USM). However, students' understandings of models as not exact replicas (ER) and the changing nature of models (CNM) were not significantly improved due to the difficulties in understanding in ER and existing clear understanding of the CNM. Studies have also indicated that students often have a lower understanding that models are not ER and already have a better understanding of the CNM than other aspects of the nature of models (Gobert et al., 2011; Park, 2013). Hence, researchers need to further design a curriculum that specifically targets improving students' understanding of models as not ER.

Conclusions

This study revealed that through engaging in model-based inquiry, undergraduate non-science major students were able to develop, evaluate, and revise their models according to scientific modeling criteria, thereby finally self-developing coherent scientific models of magnetism. This designed curriculum not only enhanced students' inquiry processes and their explanations of magnetic phenomena but also improved their understanding of models and modeling.

This study contributes to modeling theory about how students can be scaffolded to engage in a scientific modeling process and to self-develop scientific models, instead of being offered students scientific models directly. This study also identified a number of difficulties that students had in developing microscopic scientific models or in understanding models not replicating the target situation. Thus, further studies are required to identify the reasons underlying students' difficulties in order to design curricula to target these difficulties.

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