Model construction, critique, and revision in magnetism: The importance of integrating conscious and intuitive knowledge

Meng-Fei Cheng and David E. Brown,
University of Illinois at Urbana-Champaign
Paper presented at the American Educational Research Association (AERA), April 9-13, 2007, Chicago, IL

Abstract

In this study we explore the spontaneous explanatory models children construct, critique, and revise in the context of tasks in which children need to predict, observe, and explain phenomena involving magnetism. Our findings indicate that several of the children were able to construct explanatory models. However, of the six children interviewed (three third graders and three sixth graders), only one was consistently able to critique and revise her models to arrive at a consistent, coherent, and sophisticated explanatory model. This research indicates that instruction should help students to become meta-conceptually aware in order to critique and revise explanatory models drawing on both intuitive and conscious knowledge.

Introduction

To explore the use of analogies and models in the real-time thought processes of living scientists, Clement (1988, 1989) asked scientists to consider problems on their “personal frontier,” that is, problems for which they did not have ready-made theories or explanations. One such problem concerns the question of how “stretchy” a spring would be that is made of the same kind of wire but has twice the diameter of another spring. While all those interviewed made the initial (and correct) prediction that the wider spring would stretch more, when asked how they could increase their confidence they generated many analogies and models. One subject in particular exhibited several cycles of generation, critique, and modification of models that would help him explain, not just predict, the behavior of the spring. This behavior - generation, critique, and modification of explanatory models - is similar to processes in the history of science explored by philosophers and historians of science such as Black (1962), Hesse (1967) and Harre (1972). Models and analogies are now widely recognized as central in scientific thinking.

Models and analogies are also recognized as central in learning science. Didactic use of analogies can help students map a well understood base structure to a less well understood target structure (Gentner, 1983; Glynn, 1994; Dagher, 1998; Duit, 1991). But while such didactic use of analogies is an important area of research, here we focus on student-initiated models and analogical reasoning with those models. Processes of model construction, critique, and revision have been shown to help students to make sense of initially counterintuitive ideas. Brown and Clement (1989; Brown, 1993, 1995) argue that explanatory models provide a means for students to refocus their intuitions by enriching target situations with unseen explanatory mechanisms. Clement and Steinberg (2002; Clement, 1989) show that a model construction cycle of generation, evaluation, and modification (GEM Cycles) prompts students' conceptual growth in science learning. Wong (1993a; 1993b) shows that spontaneous analogies students generated were helpful in explaining unfamiliar phenomenon related to air pressure. Just as model construction, critique, and revision is central to scientific advance, so it can be important in advancement of student understanding.

In studying student understanding in science, it is important to use a modeling language that allows for the appropriate representation of the range of phenomena under consideration. In this case we needed a modeling language that allowed for the detailed representation of children's conceptual thinking as they grappled with ideas and phenomena related to magnetism. One possible modeling language is that of early work on misconceptions and conceptual change (Driver & Easley, 1978; Posner, Strike, Hewson, & Gertzog, 1982; Hewson & Hewson, 1984; McCloskey, 1983). From this perspective students' conceptions are represented as theories similar to historical theories in science (e.g., impetus theory, phlogiston theory, etc.). There are several difficulties with this perspective for our purposes. First, when closely examined, students' ideas often share some features of the historical theories, but not others. Second, historical proponents of these theories used them fairly consistently, which is typically not the case with students. Third, the common view of such "misconceptions" is that they are simply wrong. But a constructivist view of knowledge and learning would imply that the seeds of "correct" conceptions lie in these "misconceptions." Fourth, this perspective focuses on conscious theories or propositions. In our work we often found that unarticulated, intuitive or "subconceptual" aspects seemed to be operating.

Two more recent perspectives that attempt to deal with these issues are those of Vosniadou (1994, 2002) and diSessa (1988, 1993). While these perspectives are often cast as conflicting, Brown (1995b) and Brown and Hammer (to appear) argue that these perspectives are more similar than different. Both of these views focus on the gradual evolution of students' conceptions (rather than all or nothing shifts), both of them focus on intuitive or subconceptual aspects (presuppositions for Vosniadou, phenomenological primitives or p-prims for diSessa), and both see students' ideas as complex systems of interrelated elements rather than unitary wholes. This said, there are differences. Vosniadou tends to focus on the construction of conscious "synthetic models" from relatively stable subconceptual presuppositions, while diSessa tends to focus on comparatively less stable configurations of subconceptual p-prims. Brown (1993, 1995a, 1995b) proposes a framework that attempts to bring these perspectives together into a larger perspective that enables focus on subconceptual as well as conceptual aspects. The elements of this model include core intuitions, implicit models, conscious models (including explanatory models), and verbal-symbolic knowledge. This framework gave us a vocabulary for deeply analyzing the students' conceptions.

Theoretical framework

Following are descriptions of the different elements of Brown's framework for interpreting students' conceptions. To illustrate each of the elements we employ examples from thinking about circuit electricity.

Verbal-symbolic knowledge: In this category are consciously remembered generalizations, such as “V=IR,” “electric current only flows when there is a complete circuit,” or “power is energy per time.” While such generalizations are important and often powerful, it is typically how they are connected to conscious and implicit models and core intuitions that determines the sense that students make of them.

Conscious models: In this category are visual images of both observable elements (e.g., visualizing a battery connected to wires and light bulbs) and unobservable elements (visualizable models that explain why observable phenomena occur – these are called here “explanatory models”). An example of an explanatory model in circuit electricity might be visualization of unseen positive current flowing from the positive side of the battery and unseen negative current flowing from the negative side that meet at the bulb, interacting to produce light. Explanatory models typically involve unseen elements interacting in comparatively complex ways (as compared with implicit models below).

Implicit models: In this category are tacit or taken for granted aspects of models. For example, in the model of current flow, the current may be tacitly assumed to be like rainwater flowing in a gutter rather than water under pressure in a garden hose. Implicit models are taken for granted (rather than consciously employed, as are explanatory models) and they are comparatively simple, typically involving single elements rather than multiple interacting elements as with explanatory models. They differ from core intuitions in being domain specific rather than domain general.

Core intuitions: In this category are causal intuitions attached to elements of implicit or conscious models. In a subject's consideration of a situation, causal intuitions of agency or response become attached to elements of the situation. The particular configuration of causal intuitions forms what Brown (1993) calls an "attributive cluster." For example, when current causes a bulb to light, the current may be considered to be an initiating agent (with causal power of its own) and the bulb just to be affected by the current. If the situation is considered in a broader context, the battery may be considered to be the initiating agent with its own causal power, the current is then considered to have causal power that has been transmitted to it, and the light bulb is again affected by the current. If the subject's attention is drawn to the wire, this may be considered to be an inert object simply constraining the flow of the current. Thus we can see that in a given situation, several different attributive clusters may be instantiated depending on the focus of attention of the subject and what, at the moment, the subject considers salient.

This multilevel framework allows for sophisticated analyses of students’ conceptions and changes in their conceptions as it allows for focus on both conscious and implicit elements of students’ thinking. This framework enabled us to address the following research questions:

1. To what extent did students make use of conscious explanatory models, verbal symbolic knowledge, and intuitive knowledge (core intuitions and implicit models) in their thinking about magnets and magnetic phenomena?

2. If students did make use of conscious explanatory models:
    a. How did these models change and develop?
    b. In what ways were the explanatory models connected to intuitive knowledge and to verbal symbolic knowledge?
    c. Did students consciously critique and revise their explanatory models

An important point needs to be made here. A "sophisticated" or "powerful" explanatory model is not necessarily the "correct" or "canonical" or "scientific" model. Students were not receiving any direct instruction in these interviews, and so it is not to be expected that they would spontaneously develop models that took many years, if not hundreds of years, to develop in the scientific community. However, we argue that students who are well developed in their abilities to construct, critique, and revise models will be in a good position to benefit from more directive instruction moving them toward canonical models. As such we view helping students to become better at constructing, critiquing, and revising models as having important content ramifications as well as ramifications for involving them in scientific processes and for helping them to consider the nature of science as centrally involving modeling.

Methods

Participants

The participants in this research were recruited from 3rd and 6th grade classes of a private Christian school. Five 3rd graders and three 6th graders with pseudonyms of Paula(6), Vivian(6), and Yong(6) participated in this research, but only three 3rd graders, Lily(3), Donna(3), and Kate(3) were included in the analysis to equalize the numbers between grades, to represent other third graders' similar responses, and to exclude a student who was not able to concentrate on the tasks, hindering him from answering interview questions (the number in parentheses indicated the grade level).

Procedure

This interview adopted a clinical interview approach (Clement, 2000). In order to explore students' construction, critique, and revision of explanations, the interviewer (first author) employed a predict-observe-explain (POE) approach in the interviews. The interviewer asked students to make a prediction before they did the activities, to observe the phenomenon during the activity, and to explain the phenomenon during and after the activity. The questions were not standardized because the interviewer would adjust or alter the questions according to students' varied responses in order to induce students to make predictions, observations, and explanations.

The responsibility of the interviewer was to keep students on task, and to help students to focus on relevant phenomena that were employed by students to construct explanations. The other responsibility of the interviewer was to explore what students thought about magnetism when they played around with materials with less intervention. However, the interviewer's exploratory questions or confrontational questions sometimes influenced how students answered the questions. During the process of clarifying their thinking, students might have been aware of the inconsistency of their explanations. Or sometimes the interviewer would ask them to explain why they did not mention specific terms that they used in the previous explanation or activity.

Every student was interviewed four times, except for Kate(3), who was interviewed only three times due to her time constraints. Interview times varied from 40 to 60 minutes. There were two or three activities in each interview. The names and sequence of the activities are as following Table 1.

Table 1
The names and sequence of the activities.

Interviews	Activities
First Interview	M1: Pre-knowledge
	M2: Two Magnets
	M3: Donut Magnets
Second Interview	M4: Paper Clip
	M5: Metal Bars
Third Interview	M6: Iron Filings over One Magnet
	M7: Iron Filings over Two Magnets
Fourth Interview	M8: Compass
	M9: Final Review

In M1: Pre-knowledge Interview, the students were asked their impression about magnets before playing with magnetic toys. Then, the students were asked to predict which among the toys in front of them were magnets and explain why they thought those toys were magnets. After playing with magnetic toys, the students then were asked to pick up the ones which are magnets and explain how and why magnets work. In M2: the two magnets activity, the students made a prediction before playing with two bar magnets, and created an explanation about the attraction and repulsion between two bar magnets after playing with them (see Figure 1). In M3: the donut magnets activity, the students made a prediction with an explanation before playing with two donut magnets put on a vertical stick, one on top of the other. Then, after playing with donut magnets, they were asked to explain how and why magnets work (see Figure 2).

Figure 1. Kate(3)'s drawing of her observation of the two magnets activity

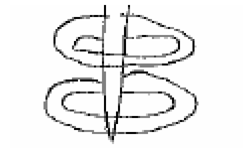


Figure 2. Paula(6)'s drawing of her observation of the donut magnets activity as the top magnet "floated" because of repulsion

In M4: the paper clip activity, the students were asked to predict what would happen between a magnet and a paper clip tied to a piece of string (such that the paper clip is attached to the magnet but does not touch it), and then to observe and explain it. Then, they predicted what would happen when putting different materials, such as a piece of paper and different kinds of metal plates in the gap between the magnet and the paper clip. Then, after their observations, they were asked to explain how the magnet works to attract the paper clip, and why some material would make the paper clip fall down, but other materials would not (see Figure 3). In M5: the metal bars activity, students predicted and explained the attraction of the different parts of the magnet to a metal bar. They gave further explanations after playing with the magnets and metal bars. Then they were asked to predict and explain how to use the metal bar to pick up the other metal bar. After further observation, they were asked to explain how the magnet can make metal bars connect to each other (see Figure 4).

Figure 3. Yong(6)'s drawing of his observation of the paper clip activity

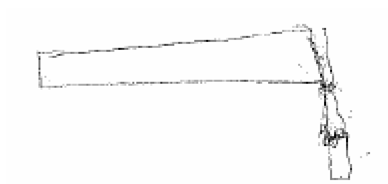


Figure 4. Vivian(6)'s drawing of her observation of the metal bars activity

In M6: the iron filings over one magnet activity, the students were asked to predict what will happen to the iron filing on the plastic plate after putting a magnet under the plate. After observing what happened to the iron filings, they were asked to explain why the magnet would cause the particular pattern of iron filings (see Figure 5). In M7: the iron filings over two magnets activity, the students were asked to do the same thing with two unlike poles of two magnets and two like poles of two magnets (see Figure 6).

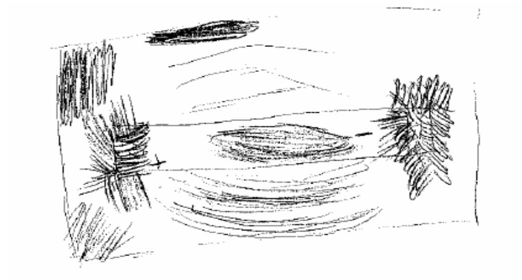


Figure 5. Paula(6)'s drawing of her observation of the iron filings over one magnet activity

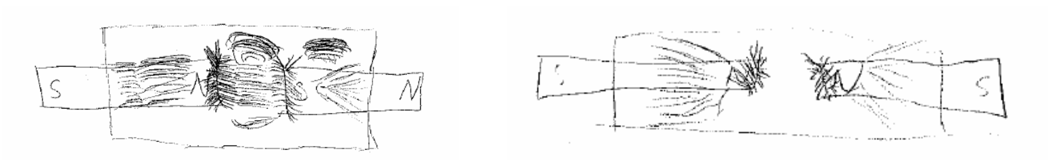


Figure 6. Paula(6)'s drawing of her observation of the iron filings over two magnets activity

In M8: the compass activity, the students were first asked if they knew how to use a compass. If they did not know how to use a compass, the interviewer would tell them how to read and use the compass. Then, the students were asked to predict and observe what would happen when they moved the compass around the magnet and moved the magnet around the compass. After that, they were asked to predict what would happen when they put several compasses around the magnet. Then, after observing the arrow of the compass, they were asked to give an explanation about how the magnet works to make compasses point in certain directions or form certain patterns (see Figure 7). In M9: the final review, the students were asked to review the pictures that they had drawn and the explanations that they had made in the previous activities. After that, they were asked to make a final explanation for how and why magnets work.

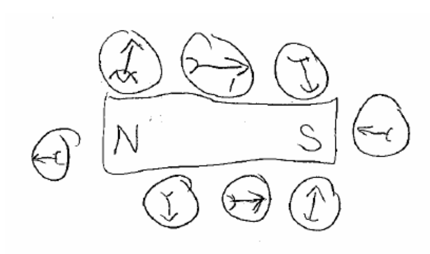


Figure 7. Paula(6)'s drawing of her observation of the compass activity

Data Sources and Analysis

Students were individually interviewed and videotaped in their school classroom or in a university classroom. Students' verbal responses and non-verbal behaviors were transcribed from the videotape, and students' drawings were used to supplement and clarify students' explanations. The microanalysis of students' conceptions was coded using Brown's framework to analyze how students changed their conceptions, with internal agreement between two researchers.

In this framework, the categories of core intuitions and implicit models helped with analyzing students' unconscious, intuitive levels of knowledge, and the categories of verbal-symbolic knowledge and conscious models helped with analyzing students' conscious levels of knowledge. Brown's framework also helped investigate how core intuitions and implicit models can be involved in the conscious levels of knowledge.

Brown (1993) hypothesizes that explanatory models help students make intuitive connections by providing images that help students attribute agency in different ways. For example, many students view a table as inert and therefore unable to exert a force on a book resting on it. However, after helping the student see the table as microscopically springy, it now makes sense to many students that the table would exert an upward force, just as a spring will push on your hand if you press on it. The unseen attribute of springiness in the table has helped the students view the table as having "reactive agency." The core intuitions attach to the conscious and taken for granted images (that is, conscious and implicit models) of situations, and so helping students to image the situations differently may help them re-focus their core intuitions, allowing for conceptual change at an intuitive level.

Results

During the interviews, some students had difficulties observing some phenomena of magnetism. Therefore, the interviewer tried to direct students to observe what should be observed in order to answer the following interview questions. For example, Lily(3) drew a radiant shape of iron filings to represent the attraction between iron filings and the magnet (see Figure 8). The interviewer asked her to observe the patterns of iron filings over different parts of the magnets and compare her drawing with her observations in detail in order to make close and accurate observations of the pattern of iron filings. Moreover, some students also had problems answering how and why magnets work. Sometimes they explained the phenomena observed instead of answering how and why magnets work. Thus, in order to comprehend students' explanations, the interviewer tried to ask further questions to prompt students to explain the phenomena in detail. Sometimes, these questions caused cognitive conflicts so that students had to try to re-consider their explanations.

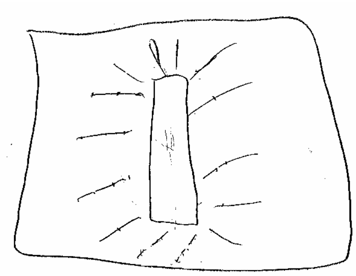


Figure 8. Lily(3)'s drawing of her observation of the pattern of iron filings over one magnet.

Paula(6) was the only student able to consistently integrate her intuitive and conscious knowledge in order to construct coherent and sophisticated explanatory models. She exhibited meta-conceptual awareness during the process of developing her explanatory models by explicitly critiquing and revising her models. By contrast, the third graders seemed to be “captured” by their intuitive knowledge—they were able to construct explanatory models in several cases, but in a new context they tended to simply discard the old model and either rely directly on their intuitive knowledge or construct a new explanatory model based on their current view of the situation, rather than striving for consistency by critiquing and revising an earlier model. The other two sixth graders seemed to be “captured” by their verbal symbolic knowledge, showing little tendency to even construct a model, let alone critique and revise one.

In the beginning of the interview, most students who employed their intuition to construct explanations in their following interviews started with a very simple explanation based on their initial “intuitive take.” For example, Lily(3), Donna(3), Kate(3), and Paula(6) started with the explanations that magnets work because of something inside the magnets, such as metal, special lead, black metal powder, or negatives and positives, as initiating agents acting on other objects. On the other hand, other students, such as Yong(6) and Vivian(6), who mainly employed verbal symbolic knowledge in their explanations, started their explanations with some terminology, such as magnetic field, magnetic material, or invisible forces of gravity or electricity, which they thought could be related to magnetism. However, how they developed their conceptions were different in the following interviews. Following are some findings from the six case studies.

The Effect of Different Contexts

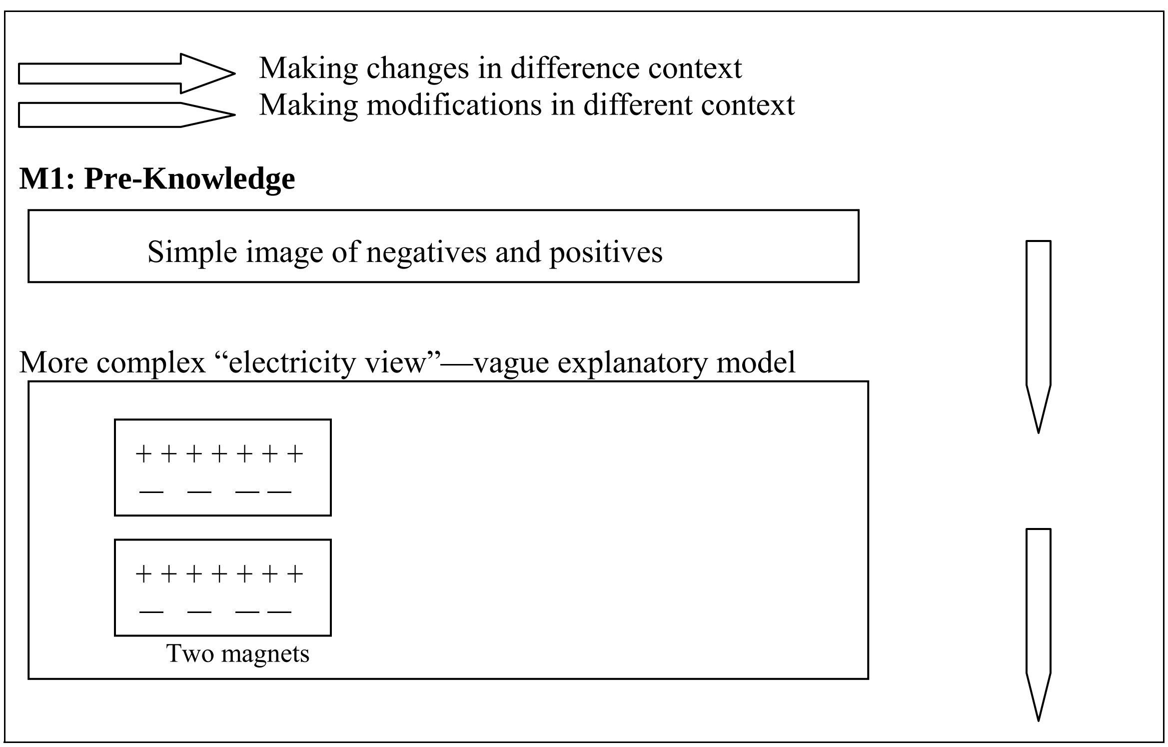
Through different activities in four interviews, some students modified or changed their explanations in the different activity contexts, but some of them consistently applied the same or similar notions in different activities. Among these students, Paula(6) was the only student who seemed to make a consistent and conscious attempt to revise her models.

Paula(6) began with the simple image of the attraction between positives and negatives to explain magnetic attraction before she played with magnetic toys: “A magnet is made out of positive electrons and negative electrons. Positive electrons are attracted to negative and negative to positive.” After playing with the toys, in order to clarify the “stickiness” between two magnets, Paula(6) further developed a more complex “electricity view.” She began to mention that when two magnets stick together, the magnet would split in half. One half is more positive; the other half is more negative, same with this the other magnet. The reason why two magnets would attract or repel is because positives and negatives attract each other, but positives and positives, or negatives and negatives repel each other.

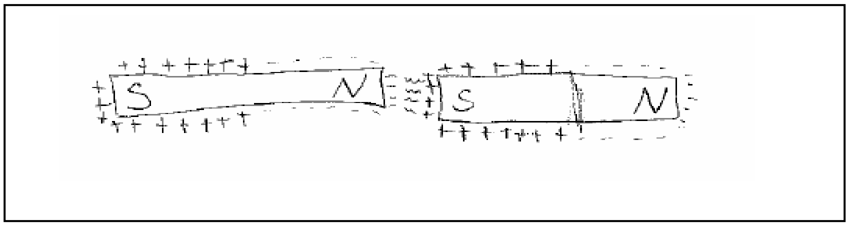
After putting her finger between two magnets in M2: the two magnets activity, Paula(6) started to build on this explanatory model by adding a notion that electricity may go

though her finger. She asserted that the S end of the magnet has positives, and that the N end of the magnet has negatives. As she explains, the negatives and positives are mixing in the middle of the magnet. There is a divider that splits them or pushes them away from each other. This divider is like a non-conductor, which cannot affect positives or negatives. In M3: the donut magnets activity, she also used this developed "electricity view" to explain the attraction and repulsion between two donut magnets.
Then, in M4: the paper clip activity, Paula(6) added the radius of action into her "electricity view" to represent the range of the magnet. Next, in M5: the metal bar activity Paula(6) shifted her "electricity view" to a "moving negatives view" to explain how moving negatives from the magnet to metal bars enabled the magnet to make metal bars stick together in a chain. Afterward, in M6 and M7 the iron filing activities, Paula(6) applied the "electricity view" and added "stretching of iron filings" to explain how iron filings are pulled to the two ends of the magnet. After reviewing all of the activities that she had done, Paula(6) modified her bubble shape of "electricity view." Originally, she asserted that there is a bubble shape of field around the magnet, but after considering how the magnetic field of the earth can pass a long distance to affect the compass in the classroom, she thus employed the term "wave" to represent the energy of magnetism, which can pass through a long distance, rather than imagining an invisible bubble (see Figure 9).

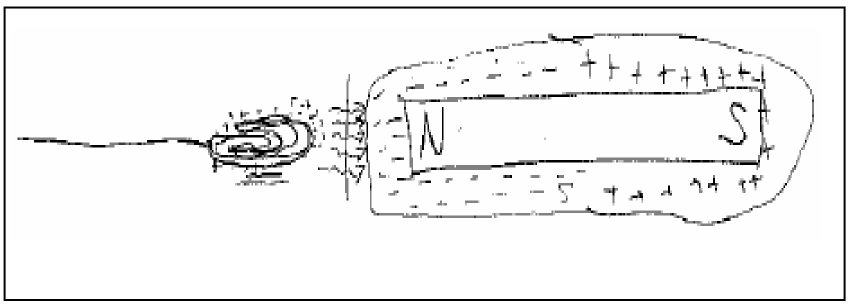
Hence, except in M5: the metal bars activity, Paula(6) used a persistently evolving "electricity view" to explain most of the phenomena of magnetism. She added different features, such as the radius of action of the magnet or the stretching of iron filings, to explain different phenomena observed, or modified her previous explanation from the bubble view of magnetism to waive view of magnetism to explain her new consideration that a wave can travel though a long distance than a bubble.



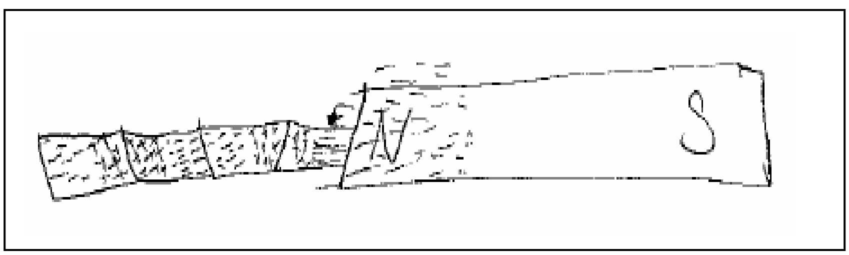
M2: Two Magnets and M3: Donut Magnets
"Electricity view" Explanatory model



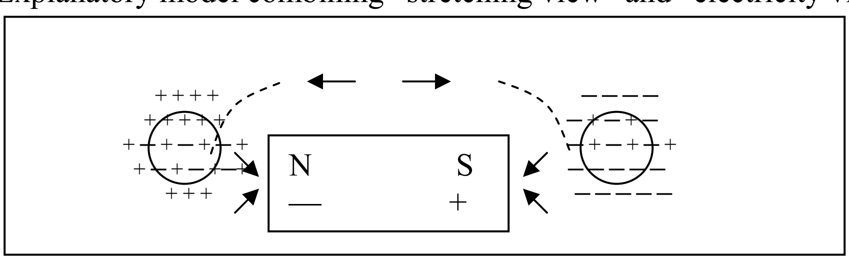
M4: Paper Clip
"Electricity view" explanatory model



M5: Metal Bars
"Moving negatives view" explanatory model



M6: Iron Filings over One Magnet and M7: Iron Filing over Two Magnets
Explanatory model combining "stretching view" and "electricity view"



M9: Final Review
"Wave view"—Modification of "electricity view"

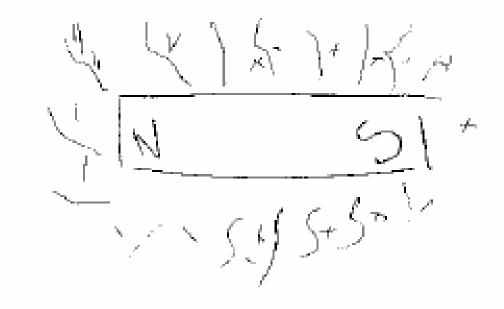


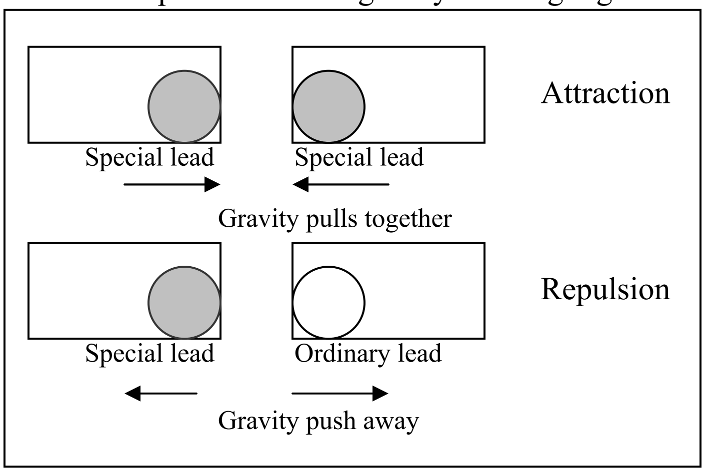
Figure 9. Representation of Paula(6)'s explanations in different contexts

Yong(6), Vivian(6), and Lily(3) also showed more consistent explanations in the four interviews than other students, but they did not appear to consciously tend to make consistent and coherent explanations. Yong(6) used a consistent explanation that magnets work because of electricity and gravity. Although he tried to explain the interaction between the two magnets in M2: the two magnets activity and M3: the donut magnets activity by referring to the relationship between the sexes, he did not integrate this analogy into his other explanations in the following activities. Vivian(6) also consistently used the terms, "magnetic force" and "magnetic field" to explain how magnets send out the force to attract other objects. While she had mentioned the anthropomorphic idea that two magnets do not like each other so they would repel each other, she did not apply this notion in other explanations. In M5: the metal bars activity, she further developed an explanation that a magnetic field keeps moving down from the magnet to several metal bars, which is close to the explanatory model that Brown (1993, 1995a, 1995b) defines. However, she did not employ this notion in other activities. Lily(3) used a consistent explanation of a "sameness view"—same things stick together—throughout the interviews. She began to construct the "sameness view" in M3: the donut magnets activity, and used the "sameness view" in the following activities. Later she developed a more sophisticated explanation regarding how magnet-like material moved through the magnet to the metal bars, which enable them to stick together in M5: the metal bars activity. Later still, she shifted back to employ the "sameness view."

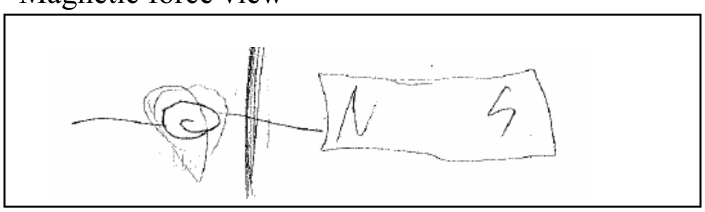
By contrast, Donna(3) and Kate(3) used very diverse accounts to explain different phenomena of magnetism that they observed. They not only used different explanations in different activities, but also spontaneously modified or altered their explanations in the same contexts.

Take Donna(3) as an example to illustrate how these two students use different explanations in different contexts. In order to explain the attraction and repulsion between two magnets, Donna(3) used a series of evolving "lead and gravity view." In the end of M3: the donut magnets activity, she clarified her "modified special lead and gravity working together view": "because gravity and lead kind of work together with like… like if the special lead is facing each other, then gravity will pull it together, but if the special lead is not facing each other, then gravity will push it apart.” However, in M4: the paper clip activity, she shifted to a completely different explanation, the “magnetic force view,” which did not involve gravity or lead, to point out that the magnet sends out invisible force to act on the paper clip. In M6: the iron filing over one magnet activity, she employed the “magnetic power view”—the two ends of the magnet have more magnetic power than the middle part of the magnet, so the two ends of the magnet pull the iron fillings toward them, but the middle part of the magnet pushes the iron filings away—to explain the pattern of iron filings over one magnet (see Figure 10). These examples showed that Donna(3) applied distinct explanations in different contexts.

M3: Donut magnets
“Modified special lead and gravity working together”



M4: Paper clip
“Magnetic force view”



M6: Iron filings over one magnet
“Magnetic power view”

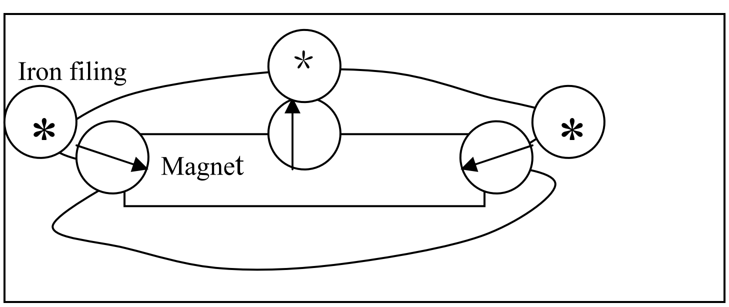


Figure 10. Examples of Kate(3)’s different explanations in different contexts.

Kate(3) used the “direction view”—if both of the magnets move to the right direction, they would attract each other; if one of the magnets moves to the wrong direction, they would repel each other—to explain the interaction between the two magnets, but used the “black powder view”—magnets attract other metal because of the black powder inside the magnet—to explain how magnets attract metal.

In the same contexts, Donna(3) and Kate(3) may also suddenly shift their original explanations to a completely distinct new explanation. Take Donna(3) as an example. In M4: the paper clip activity, when the interviewer further asked her to explain how magnets work, Donna(3) suddenly shifted from the “magnetic field view”—the magnetic field produced a magnetic tension to pull the paper clip—to the “positive and negative view”—the negative and positive sides attract, but the negative and negative sides or the positive and positive sides repel (see Figure 12).

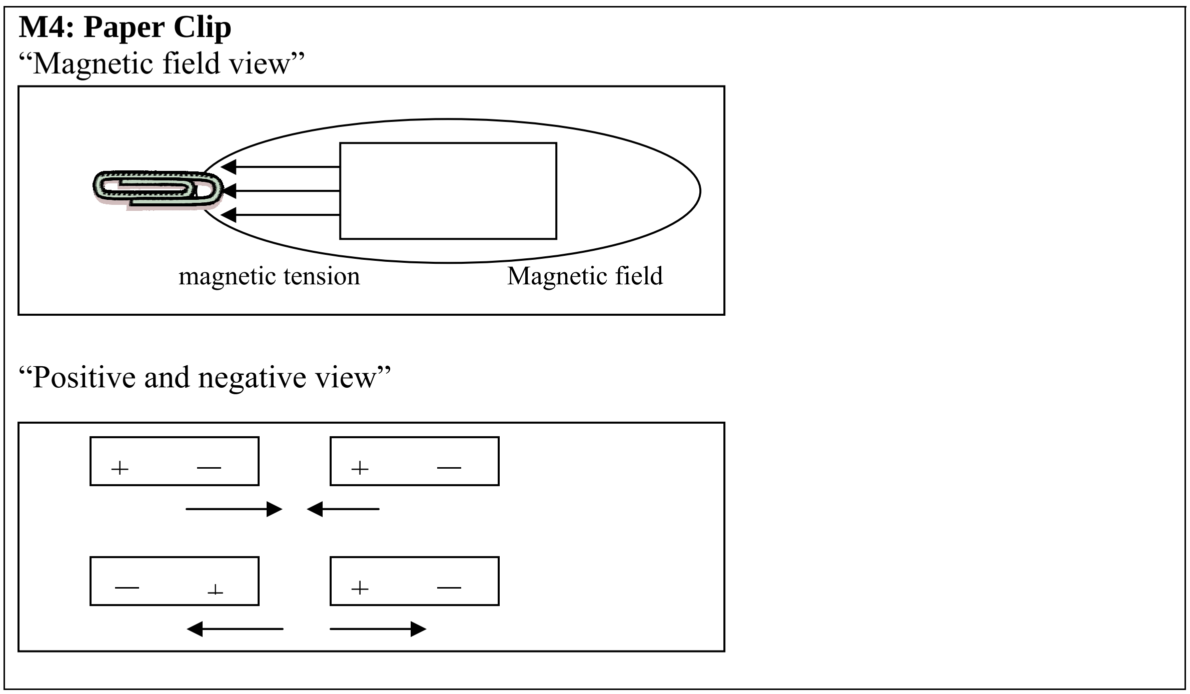


Figure 12. The example about how Donna(3) spontaneously changed her explanations in M4: the paper clip activity

In M2: the two magnets activity, Kate(3) mentioned the “nail and ball view”— two magnets stick together because there is a nail or metal in between to connect the two magnets; the two magnets cannot stick together because there is something like a ball between the two magnets to prevent them from going together. When she spontaneously asked the interviewer the north side of the classroom, she shifted from the “nail and ball view” to the “direction view.” For clarifying the rationale of the attraction and repulsion between the two magnets, she compared the north and south sides of the classroom with the North and South poles of the magnet with a view to defining whether the magnets move to the right or wrong direction.

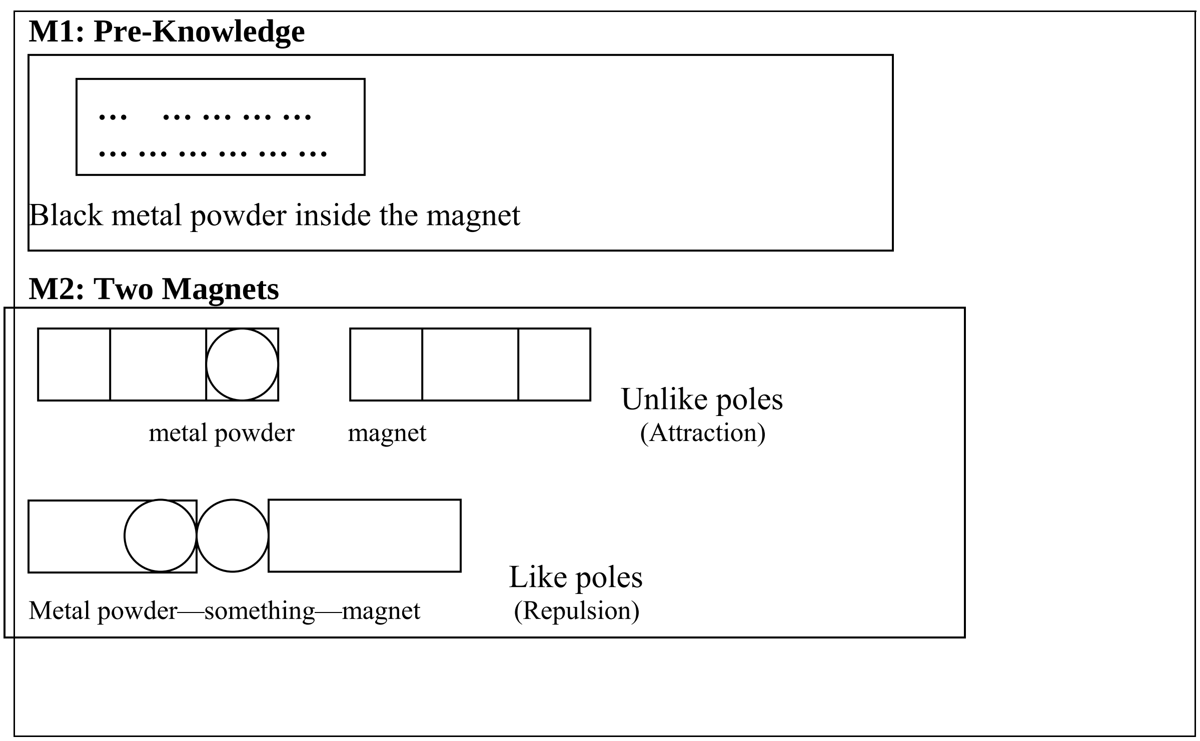
Nevertheless, there are still some differences between Donna(3) and Kate(3). Compared to Kate(3) who did not progressively develop the specific explanations within the same contexts, Donna(3) appeared to develop her primary explanations to more sophisticated explanations in the same contexts. In M2: the two magnets activity, she started with the notion that magnets work due to the special lead inside the magnets. Next, she added gravity into her explanation, and then she integrated or modified the elements of lead and gravity in her following explanations. Her explanations evolved from the "special lead view," the "gravity view," the "lead and gravity view," and the "lead and substance like gravity view," to the "special lead and substance-like gravity view." In these five progressive explanations, Donna(3) developed the notion of special lead to substitute for her original notion of lead so as to have more explanatory power to discuss the attraction and repulsion between the two magnets. She developed the notion of substance-like gravity to substitute for her original notion of invisible force of gravity in order to make the abstract invisible force become concrete. The details of the different explanations and how they progressed are in Table 2.

Table 2
The development and progression of Donna(3)'s explanations in M2: the two magnets activity

Special lead view	Special things in the magnets cause the repulsion of the two magnets.
Gravity view	Gravity in the air between the two magnets pushes the magnets away, while gravity in the magnets connects the two magnets.
Lead and gravity view	Lead inside the magnets makes the magnets connect; gravity in the lead makes them repel each other.
Lead and substance like gravity view	The same ends of the two magnets will not stick together because gravity or something between them; on the contrary, different ends will stick together because there is nothing between these two.
Special lead and substance-like gravity view	One side of the magnet has special lead; the other side of magnet has ordinary lead. When special and ordinary leads are put together, they will stick together. When the same special leads face each other, they will not stick together because of the gravity in between.

Even though Donna(3) and Kate(3) both showed the inconsistency of their explanations in different contexts, the complexity of their final explanations were quiet distinct. Donna(3) appeared to use different explanations in different contexts. Although she gradually developed some sophisticated explanations in the same contexts, in the final interview Donna(3) did not develop a sophisticated model to explain magnetism. She only employed her intuition that a magnet has an invisible arm to pull other materials. She mentioned that she could not remember the explanations that she made before. Hence, using different explanations in different contexts did not seem to help her develop a sophisticated explanatory model in the end of the interview, because she tried different explanations in different contexts without focusing several explanations and developing them across different contexts.

On the other hand, Kate(3) seemed to also use different explanations in different activities, but during the four interviews she appeared to mention about the black metal powder in several activities. Before the start of the activities, she claimed that magnets would work because of black metal powder inside the magnet. In M2: the two Magnets activity, she continued to modify her "black powder view" to explain the attraction and repulsion between two magnets. She stated that the black metal powder is in one end of the magnet, so it would stick to the other end of the magnet, unless something is between two magnets to make metal powder not work. In M5: the metal bars activity, she articulated the "moving back powder view"—the powder inside the magnet moves to the two ends of the magnet to send out power from the magnet to the following metal bars—to explain why the magnet attracts a chain of metal bars. In M6 and M7: the iron filings over one or two magnets activity, she mentioned that there is a connection between powder in the magnet and iron filings outside the magnet. In M9: the final interview, she developed a refined "moving black powder view"—most magnet-like powder moves to two ends of the magnet to attract other metal, and there are two different ends of the magnet, the iron end and the metal end. From the evolution of Kate(3)'s explanations, we can find that although how she employed the black metal powder in her explanations are varied, in the final interview she constructed a refined "moving black powder view," which can cover most of the phenomena of magnetism that she had observed. That is to say, notwithstanding Kate(3) did not have a similar progression as Donna(3) did in developing her conceptions within the same contexts, she developed her conceptions about "black metal powder" through different activities, and finally constructed a more sophisticated explanatory model (Figure 13).



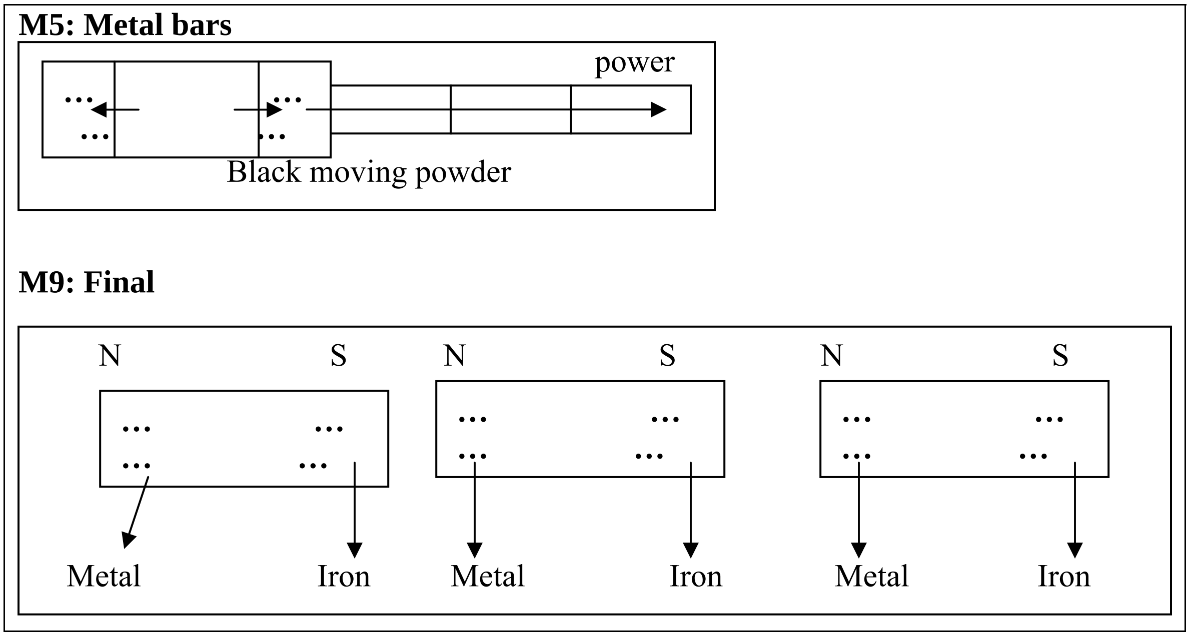


Figure 13. Kate(3)'s progression of the "black powder view"

In the above examples of different students' explanations in the different contexts, it appears that Paula(6) used a consistent "electricity view" to explain most of the phenomena of magnetism. She only added additional features into her "electricity view" to explain specific contexts or modified some features of her "electricity view" to become a more coherent theory to make sense of some phenomena of magnetism. Vivian(6) and Yoon(6) consistently utilized verbal symbolic knowledge related to magnetism, and Lily(3) consistently employed her intuition that same things stick together. By contrast, Donna(3) and Kate(3) seemed to change their explanations according to different contexts, and even altered or modified their explanations in the same contexts.

The different contexts seemed to help Paula(6) modify and refine her explanations. When she faced new events, she would revise and amend her explanation. The factor of different contexts did not seem to affect Lily(3), Yoon(6), and Vivian(6). They appeared to hold consistent explanations to elucidate different phenomena of magnetism. The different contexts appeared to influence Donna(3) and Kate(3) to some extent. Not only did they apply different explanations in different contexts, but they also modified or changed their explanations within the several contexts.

Furthermore, there are some contexts that seemed to have a particularly strong influence on inspiring students to develop explanatory models. For example, Lily(3), Kate(3), and Vivian(6) only constructed an explanatory model in M5: the metal bars activity. In other contexts, they relied more on using only intuition, or using only verbal symbolic knowledge to make sense of the phenomena. There is another context, M3: the donut magnets activity, which aroused Paula(6), Donna(3), and Lily(3)'s intuitive implicit model—same things stick together. This strong implicit model overwhelmed students' verbal symbolic knowledge about the attraction between unlike poles and the repulsion between like poles, because there is no symbol on the donut magnets to help students to distinguish different sides of the magnets. Nevertheless, there are also some contexts that did not seem to encourage students to construct explanatory models, such as M8: the compass activity, in which most of students only employed the verbal symbolic knowledge about the attraction between unlike poles to explain the rotation of the arrow of the compass.

The Effect of Confrontational Questions

Confrontational questions (e.g., "why do metal bars stick together when attached to a magnet but not otherwise?") did not always help students to create or develop their explanatory models. For Paula(6), confrontational questions seemed to help her to further develop her explanatory model and make her explanations become more coherent and consistent, but for other students, they were not as helpful. Sometimes, the confrontational questions even made students go back to using their intuitive knowledge, moving away from an explanatory model. Moreover, the confrontational questions did not seem to make students' explanations more consistent: they only enabled students to consider other factors or aspects that they had not considered in their explanations.

When Paula(6) was asked whether she could feel anything when putting her finger between two magnets, Paula(6) responded that she could feel the pull and pressure in her finger. She clarified her idea that electricity, like the extension of the magnet, would go through her finger, further developing her explanatory model. Moreover, in M3: the donut magnets activity, she mentioned, "If one side was positive and one side was negative, they would repel each other," which was contrary to her previous statement that positives and negatives attract. She also claimed, "I'm guessing probably if they are opposite (they) would probably repel about here. If they are sort of opposite, they don't like each other. They will push away and then they will be hovering here." This statement was strongly influenced by her implicit model that opposite things do not like each other so they would repel. This strong implicit model overwhelmed her verbal symbolic knowledge that negatives and positives attract. However, Paula(6) shifted back to using her verbal symbolic knowledge after the interviewer asked her specifically whether she meant positive and negative poles would repel or whether positive and positive poles would repel.

By contrast, when Lily(3) faced a confrontational question about why metal bars would not stick to metal bars alone, she shifted her explanation from her "sameness view"—same things stick together— to a more sophisticated explanatory model that magnet-like material would go from the magnet to metal bars to make them stick. Yet, she employed this explanatory model for only a short time. After she was confronted with another question about how such material could go through the magnet and metal bars, she shifted back to her "sameness view" and claimed that because metal bars are smaller than magnets, they were not as strong as magnets and so could not stick to each other (see Figure 14). In this case, the confrontational question made Lily(3) return to her implicit model.

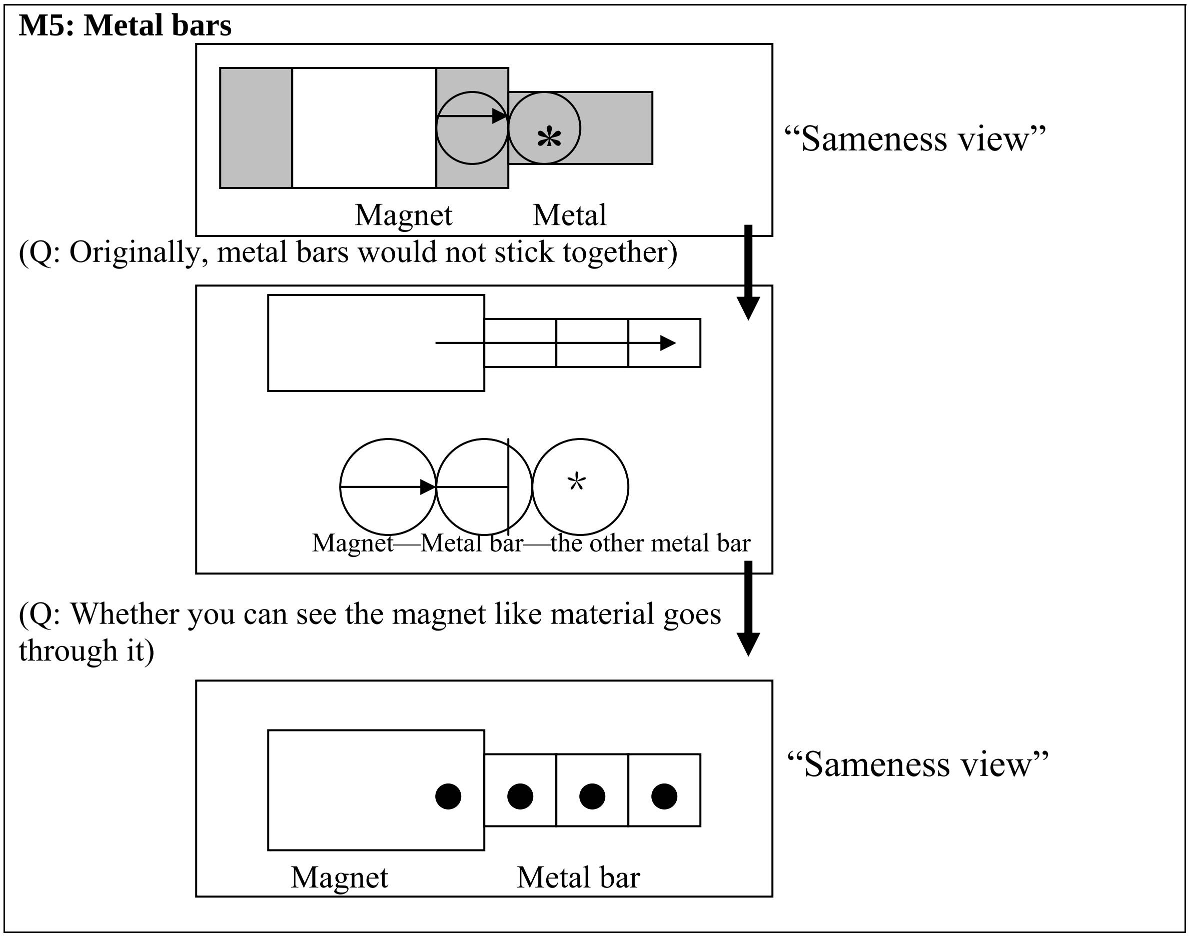


Figure 14. Lily(3)'s changing explanations in M5: the metal bar activity.

The other student, Donna(3), who used different explanations in different activities usually spontaneously modified or changed her explanations during her clarification of magnetism. The confrontational question did not make her explanation more consistent or further developed. For example, in the paper clip activity, the reminder from the interviewer that she had mentioned gravity in the previous interview made her involve gravity in her explanation to explain gravity keeping the paper clip floating, but after that, she did not involve gravity in her explanation as she did in the first activity. Hence, confrontational questions only helped her to re-consider the factors that she did not consider, but they did not help her to develop a more consistent and coherent explanation.

The Effect of Conflict between Prediction and Observation

During the interviews, students usually did not offer explanations for their predictions. Sometimes they would mention that the prediction is only their "guess," but in other cases, they would offer their explanations for their prediction. Conflict between predictions and observations also seemed to prompt students to make slight modifications of their explanation related to magnetism. However, it did not seem to help students further develop more sophisticated explanatory models, even for Paula(6).

For example, in M4: the paper clip activity, after Paula(6) found that putting an iron plate between the paper clip and the magnet would make a floating paper clip fall down (which contradicted her prediction), she shifted her explanation to a "new goal view"—the magnet has a new goal to go for the negatives in the iron plate instead of in the paper clip. This vague explanatory model explained why the iron plate would block magnetic force, but this change did not seem to enable her to further develop her explanatory model in the following activities.

There is another episode in which Paula(6)'s prediction contradicted her observation. In M7: iron filings over two magnets activity, Paula(6) predicted that there were a bunch of iron filings between the two opposite N poles of the magnets to stop the force between two magnets. She clarified, "Because since the little iron pieces have positive and negative. I'm guessing it's gonna use all of the little iron piece for the negative (two opposite N poles) in between these two (magnets)." Nevertheless, after she found that her prediction contradicted her observation, she added the "electricity view" into her "stretching view," which states that iron filings are pulled by different directions of forces from the ends of the magnets and the attraction between iron filings. In other words, originally, Paula(6)'s "stretching view" was sufficient to explain the patterns of iron filings over one magnet and over two unlike poles of the magnets. Nevertheless, after the conflict between her prediction and observation about the pattern of iron filings over two like poles, she added the "electricity view," which was already employed to explain other phenomena of magnetism in the previous interviews, into her "stretching view." She claimed that some of the iron filings have more negatives than positives so they would push away from the two opposite North (negative) ends of the magnet. Hence, the conflict between prediction and observation did not make Paula(6) construct a sophisticated explanatory model, but this conflict intrigued Paula(6) to consistently and coherently apply her "electricity view" in the new context.

In another case, Lily(3) predicted that putting paper in the space between the magnet and paper clip would make the paper clip fall down. After finding that the paper clip still floated after putting a piece of paper in between, she changed her explanation to "Because the magnet is so strong that it pulls the paper clip." In this case, Lily(3) neither changed her explanations related to magnetism, nor did she construct any explanatory model to describe the invisible force. In order to reconcile the conflict, she only shifted the focus of her core intuition from the paper as an obstacle to the magnet as a stronger initiating agent to act on the other object.

The Importance of Meta-conceptual Awareness

Paula(6) was the only student who explicitly and consistently exhibited meta-conceptual awareness. She was aware of the changes in her thinking and explanations, and she tried to consistently apply an "electricity view" in different contexts. During the interviews, she was usually aware of her changing explanations, saying, "I am kind of changing my theory," or "I just totally contradicted myself." Furthermore, Paula(6) was aware of the inconsistency of her different explanations and assessed and revised her previous explanation based on her information about magnetism to develop a more powerful explanation. For example, in the paper clip activity, she claimed there was a bubble-like magnetic field around the magnet from her knowledge about the solar system. Nevertheless, in the review of this activity, she modified her theory to a “wave view” of magnetism because she claimed that magnetic waves should be like ocean waves which can pass away for a longer distance, but the bubble-like magnetic field cannot. The following is how she modified her bubble view to waive view:

> Now that I think of it, they are more like waves. Because of the compasses, they will be pulled by waves. And there are waves from, like, even from, you know, the North is many, many, many miles that way and since the North cannot have a bubble. Well, it kind of does already all around it, and right here it probably would have waves coming off it. And that’s also what creates wave currents in the sea.

The other instance in which Paula(6) showed her meta-conceptual awareness was at the end of M5: the metal bars activity. After she found that the metal bar could stay in the middle part of the bar of the magnet, instead of moving to one of the two ends of the magnet, she altered her idea about the divider inside the magnet in the previous interview. She declared:

> Yesterday I said there was probably some divider in there. But I'm guessing not today, because if there was a divider, it would be attracted there and there (two ends of the magnet). So...that's just the answer. So here (two ends) is probably almost completely positive and here is almost completely negative. And as here (middle of the magnet), they get all mixed up. And then you know...
>
> Positive is probably here and here (S end). A few negative, but most positive. There are a few negatives there. And make a line. Then, there are negative here (N end), a few positive, but not many. They are still like mine together.

Paula(6) was aware of her previous explanations about the divider, which separates the positives and negatives inside the magnet, so as to explain the attraction and repulsion between two magnets. However, after she found that the metal bar could stay in the middle of the magnet, she changed her idea about the divider. Her drawing and explanations showed that there is a stratum of the level of negatives and positives. The North end of the magnet has mostly negatives. The density of negatives decreases as you move to the South end of the magnet. The South end of the magnet has mostly positives. The density of positives decreases as you move to the North end of the magnet. The middle of the magnet is the mixture of positives and negatives (see Figure 15).

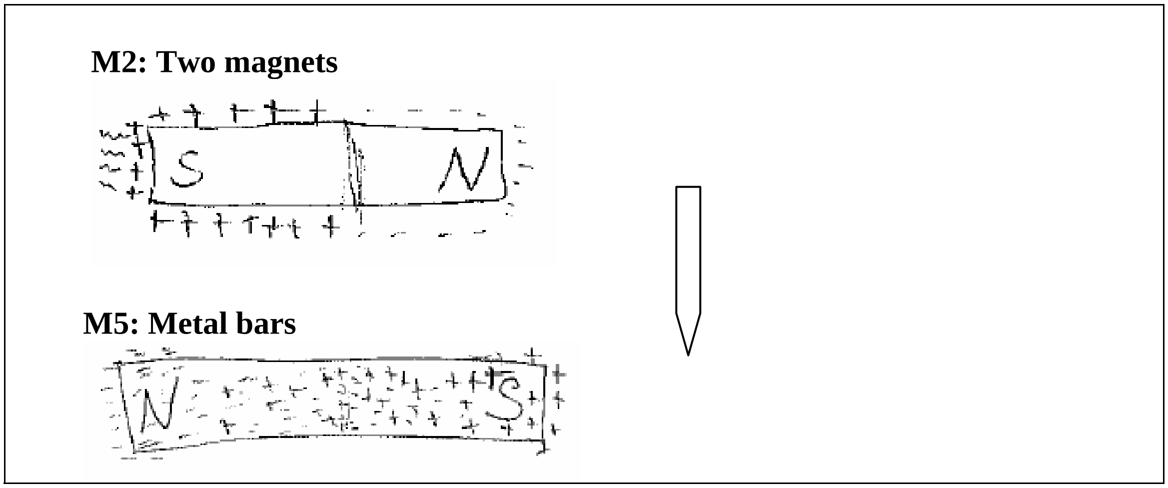


Figure 15. Paula(6)'s drawing about the divider inside the magnet in M2: the two magnets activity and M5: Metal bars activity

Compared with Paula(6), other students did not explicitly show concern about consistency in their explanations, nor did they evaluate their explanations. Although some students consistently used similar explanations with slight modifications in different activities, such as Lily(3), Yong(6), and Vivian(6), the consistency of their explanation seemed to be a product of their strong implicit models or abstract verbal symbolic knowledge, not meta-conceptual awareness and conscious efforts to remain consistent.

Other students, Donna(3) and Kate(3), seemed to use different explanations to illustrate different phenomena of magnetism. They did not appear to feel a need to construct consistent explanations which covered all of the phenomena of magnetism and were inclined to construct new explanations when the new findings in the new contexts arose. Donna(3) even forgot what she had mentioned in the previous interviews, not to mention developing her explanations from her previous notions. Therefore, lacking meta-conceptual awareness inhibited Donna(3) and Kate(3) from constructing sophisticated consistent and coherent explanatory models.

The Importance of Integrating Conscious and Intuitive Knowledge

There were different degrees and different methods for how individual students employed their conscious and intuitive knowledge to construct explanatory models. The following is a diagram showing the differing ways in which students employed different levels of knowledge to construct explanations.

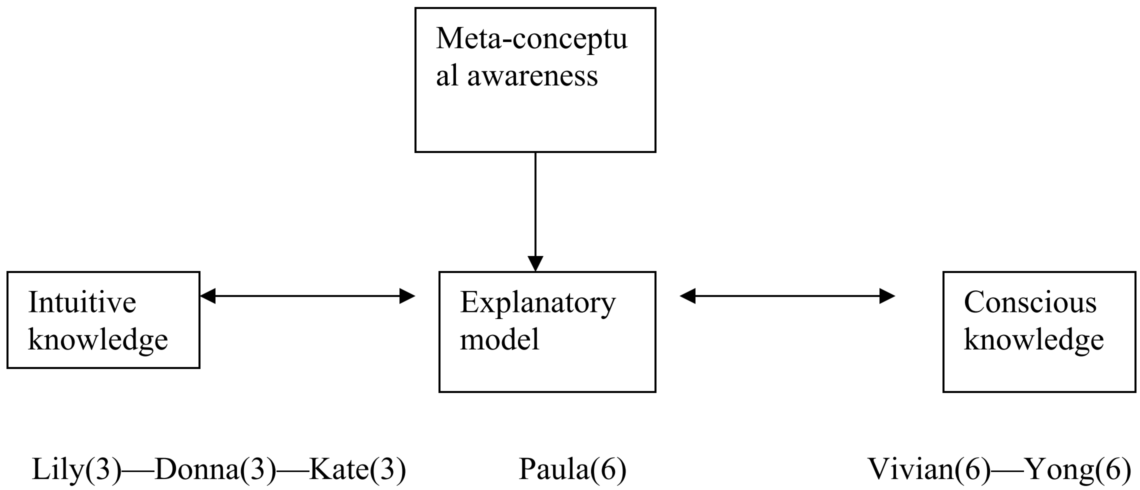


Figure 16. Representation of how different students employed different levels of conscious and intuitive knowledge and meta-conceptual awareness to construct their explanations

Lily(3) and Yong(6) are two extreme cases among the six selected cases in this study. These two cases show that strongly relying on implicit models or verbal symbolic knowledge can impede students from constructing explanatory models. Lily(3) primarily relied on her implicit model, "sameness view," from her intuitive knowledge to construct her explanations. The influences of verbal symbolic knowledge from other resources were much less than her intuition. For instance, in M2: the two magnets activity, she described the verbal symbolic knowledge from her mother about the attraction between N-S of the magnets, and the repulsion between N-N and S-S of the magnet to construct an explanation that something in one end of the magnet is the same, and makes them push each other away. Yet, in the M3: the donut magnets activity, in which there was no sign to indicate different sides of the magnets, she shifted her explanations to the "sameness view"—the same things stick together, in contradiction to her previous explanations from verbal symbolic knowledge. Afterward, she relied on her "sameness view" to explain most of the phenomena of magnetism and never employed her original explanations from her verbal symbolic knowledge again. Thus, we found that although Lily(3) tried to use her intuition to make sense of the verbal symbolic knowledge from her mother, once the abstract verbal symbolic knowledge did not make as much sense to her as her intuitive implicit model, she changed to essentially depend on her intuition.

Yong(6) leaned heavily on his verbal symbolic knowledge from his conscious knowledge about the similarity between magnetic force, electricity, and gravity to apply this notion abstractly in different activities without association with his intuitive knowledge so he failed to construct an explanatory model. Yong(6) seemed to believe that there was a correct and standard answer to explain how and why magnets work, but he did not know the answer, so he usually responded, "I don't get the fact. I don't get the answer," or "I don't know quite sure. That's why I cannot answer." In M5: the metal bars activity, most of the students constructed explanatory models to represent how the magnet attracts metal bars. However, Yong(6) is the only one who used passing germs in the process of infection as an analogy to describe how the magnet attracts other metal bars. Using verbal symbolic knowledge about passing germs did not assist Yong(6) to explain the abstract notions which is related to magnetic force, gravity, or electricity.

On the other hand, Donna(3), Kate(3), and Vivian(6) were on the scale between Lily(3) and Yong(6) (see Figure 16). They incorporated their implicit models and core intuitions with their verbal symbolic knowledge to create explanatory models in certain activities, but they did not succeed in connecting their intuitive and conscious knowledge to construct explanatory models in most of the activities.

Donna(3) sometimes associated verbal symbolic knowledge with her intuition to construct explanatory models. Her "special lead and substance-like gravity view" showed the gravity-related information from her verbal symbolic knowledge as well as the conceptions of special lead as an initiating agent and substance-like gravity from core intuitions and implicit models. She also used magnetic field, force, or tension to explain the invisible force from the magnet, which combines the terms related to magnetism from verbal symbolic knowledge and core intuition that the magnet is an initiating agent to send out the magnetic force. Nevertheless, in most of the cases when she relied on using only her verbal symbolic knowledge, such as an abstract relationship between the positive and negative symbol of the magnets, or only her intuition, such as magnet having invisible arm to pull other magnets, she did not construct an explanatory model.

Kate(3) used the abstract "direction view" from verbal symbolic knowledge related to geographic direction of the classroom to explain the attraction and repulsion between two magnets. Then, she used the "moving black powder view" from her intuition to describe how the black metal powder moved to the two ends of the magnets to send out power to act on the other objects. In these two different kinds of explanations, she involved either only her symbolic knowledge or only her intuition to explain different phenomena of magnetism, instead of incorporate her verbal symbolic knowledge with her intuition. It seemed there was no connection between how she used verbal symbolic knowledge and how she used her intuition.

Vivian(6) used the terms magnetic field or magnetic force from her verbal symbolic knowledge consistently. Yet she did not associate these terms with other intuition, such as magnetic field with the pattern of iron filings or how magnets produce a magnetic field. In M5: the metal bars activity, she developed a primary explanatory model which described how the magnetic field moves from the magnet to the metal bars, which associated her verbal symbolic knowledge of a magnetic field with the causal relationship in her core intuition.

Paula(6) was the only student who consistently constructed, critiqued, and revised coherent and sophisticated explanatory models. She borrowed the notion of "positives and negatives" from electricity that she had learned, and integrated it with her intuitive knowledge to construct a more consistent and powerful explanatory model across different contexts.

It appeared that the 3rd grade students, Lily(3), Donna(3), and Kate(3) relied more on their intuition and less on their verbal symbolic knowledge related to magnetism to explain the phenomena of magnetism. The other two 6th grade students, Yong(6) and Vivian(6), depended more on verbal symbolic knowledge about magnetism to make explanations. They seemed to only apply the terminology they had learned and seemed to lack motivation to develop their own explanatory models drawing on their verbal symbolic knowledge. It seemed that if students over relied on their intuition or on their verbal symbolic knowledge, either would impede their progress toward construction of sophisticated explanatory models. Only Paula(6) associated verbal symbolic knowledge about the "positive and negative view" with her intuitions to construct a consistent and coherent explanatory model.

Due to lack of real experience of what happens inside the magnet, students will spontaneously use their intuition and imagination to explain the phenomena they cannot see. For those 6th graders who preferred to use verbal symbolic knowledge, they possibly did not feel comfortable to use their intuition and imagination in science to construct their own explanatory model, since they knew some of the terminology. Therefore, they used these abstract terms to substitute the intuitive explanations for magnetism so they did not have to construct their own explanatory models.

Conclusions

Intuition and imagination were essential for students to construct explanatory models in this research. Intuition and imagination are also recognized as important in scientists' scientific reasoning and discovery (Monsay, 1997; Reiner, 1997), and in solving unfamiliar problems (Clement, 1994; Monsay, 1997). Gilbert, Ampere, and Maxwell, substantially involved imagination and intuition in explaining electromagnetism (Botser & Reiner, 2005) Faraday invented the notion of magnetic fields and lines of force drawing on his intuition and imagination without mathematical abstractions (Monsay, 1997; Nersessian, 1995; Reiner, 1997). Field work with modern scientists has shown the importance of creative reasoning with analogies and models (Dunbar, 1997). When comparing how scientist practice science and how science is taught in the classroom, there is a huge gap. Scientist involve intuition and imagination to help their reasoning and discovery, but students are typically taught abstractions divorces from intuition and imagination rather than being involved in imaginative process of developing scientific principles. Nersessian (1995) suggests that schools should teach the invisible thinking and reasoning that scientists go through instead of only teaching scientific principles.

In this study different contexts induced students to change, modify, or refine their models to explain different phenomena. Confrontational questions made students aware of the points which they had not considered, but most of the students did not seem to be aware of the inconsistency in their explanations. Only Paula(6) had the meta-conceptual awareness to critique and to revise her explanatory models, drawing on both her intuitive and conscious knowledge. The other two sixth graders mentioned abstract conceptions about magnets without much connection with intuitive knowledge; the third graders drew on their intuitive knowledge about magnets without much connection with abstract knowledge. Therefore, how to help students connect intuitive knowledge with conscious and abstract knowledge should be investigated in future research. Teaching students about meta-conceptual awareness and how to evaluate different explanations or theories might help students to construct sophisticated and powerful explanatory models.

References

Black, M. (1962). Models and archetypes. In M. Black, *Models and metaphors* (pp. 219-243). (Ithaca, New York: Cornell University Press).

Botser, G. & Reiner, M. (2005). Imagery in physics learning – From the physics practitioner to the naïve learner. In John K. Gilbert, (Ed.) *Visualization in science education* (pp. 147-168). London: Springer.

Brown, D. E. (1993).Refocusing core intuitions: A concretizing role for analogy in conceptual change. *Journal of Research in Science Teaching*, *30* (10), 1273-1290.

Brown, D E. (1995a, April). *Concrete focusing on re-focusing: A cross-domain perspective on conceptual change in mechanics and electricity*. Paper presented at the annual meeting of the American Educational Research Association, San Francisco, CA.

Brown, D. E. (1995b, April). *Theories in pieces? The nature of students' conceptions and current issues in science education*. Paper presented at the Annual Meeting of the National Association for Research in Science Teaching, APRIL 22-25, San Francisco, CA.

Brown, D., and Clement, J. (1989). Overcoming misconceptions via analogical reasoning: Factors influencing understanding in a teaching experiment. *Instructional Science*, *18*, 237-261.

Brown, D. E., & Hammer, D. (to appear). Conceptual change in physics. In S. Vosniadou (Ed.), *Handbook of Research on Conceptual Change.* Hillsdale, NJ: Erlbaum.

Clement, J. (1988). Observed methods for generating analogies in scientific problem solving. *Cognitive Science, 12*(4), 563-586.

Clement, J. (1989). Learning via model construction and criticism: Protocol evidence on sources of creativity in science. In Glover, J., Ronning, R., and Reynolds, C. (Eds.), *Handbook of creativity: Assessment, theory and research* (pp. 341-381). NY: Plenum.

Clement, J. (1994). Use of physical intuition and imagistic simulation in expert problem solving. Tirosh, D. (Eds.), *Implicit and explicit knowledge* (pp. 204-244). Norwood. NJ: Ablex Publishing Corp.

Clement, J. (2000) Analysis of clinical interviews: Foundations and model viability. In Lesh, R. and Kelly, A (Eds.), *Handbook of research methodologies for science and mathematics education* (pp. 547-589). Hillsdale, NJ: Lawrence Erlbaum.

Clement, J. and Steinberg, M. (2002) Step-wise evolution of models of electric circuits: A "learning-aloud" case study. *Journal of the Learning Sciences, 11*(4), 389-452.

Dagher, Z. (1998). The case for analogies in teaching science for understanding. In J. Mintzes, Wandersee, J., Novak, J. (Ed.), *Teaching science for understanding* (pp. 195-211). San Diego: Academic Press.

Duit, R. (1991). On the role of analogies and metaphors in learning science. *Science Education, 75*, 649-672.

Dunbak, K (1997). How scientists think: On-line creativity and conceptual change in science. In T.B. Ward, S.M. Smith & J. Vaid (Eds.) Conceptual structures and process: Emergence, discovery, and change. Washington D.C: American psychological Association Press.

diSessa, A. A. (1988). Knowledge in pieces. In G. Forman and P. Pufall (Eds.), *Constructivism in the computer age.* (pp. 49-70). Hillsdale, NJ: Lawrence Erlbaum.

diSessa, A. A. (1993). Toward an epistemology of physics. *Cognition and Instruction, 10* (2/3), 105-225.

Driver, R. & Easley, J. (1978). Pupils and paradigms: A review of literature related to concept development in adolescent science students. *Studies in Science Education*, 5, 61-84.

Gentner, D. (1983). Structure-mapping: A theoretical framework for analogy. *Cognitive Science, 7*, 155-170.

Glynn, S. M. (1994). *Teaching science with analogies: A strategy for teachers and textbook authors*. Technical Report 15, National Reading Research Center.

Harre, R. (1972). *The philosophies of science*. New York: Oxford University Press.

Hesse, M. B. (1967). Models and analogies in science. In Edwards, P. (Ed.), *The encyclopedia of philosophy*, (pp. 354-359). Free Press.

Hewson, P. W., & Hewson, M. G. (1984). The role of conceptual conflict in conceptual change and the design of instruction. *Instructional Science, 13*(1), 1-13.

McCloskey, M. (1983). Intuitive physics. *Scientific American, 248* (4), 122-130.

Monsay, E.H. (1997) Intuition in the development of scientific theory and practice. In R. Davis-Floyd & P.S. Arvidson (Eds.), *Intuition: The inside story* (pp. 103-120). New York: Routledge.

Nersessian, N. J. (1995). Should physicists preach what they practice? Constructive modeling in doing and learning physics. *Science & Education, 4*(3), 203-226.

Posner, G. J., Strike, K. A. Hewson, P. W. & Gertzog, W. A. (1982). Accommodation of a scientific conception: Toward a theory of conceptual change. *Science Education, 66* (2), 211-227.

Reiner, M. (1997). A learning environment for visualization in electromagnetism, *International Journal of Computers in Mathematics Learning, 2* (2), 125-154.

Vosniadou, S. (1994). Capturing and modeling the process of conceptual change. Learning and Instruction 4, 45-69.

Vosniadou, S. (2002). On the nature of naive physics. In M. Limon & L. Mason (Eds.), "Reconsidering conceptual change: Issues in theory and practice" (pp. 61-76). Dordrecht: Kluwer.

Wong, E. D. (1993a). Understanding the generative capacity of analogies as a tool for explanation. *Journal of Research in Science Teaching*, *30*(10), 1259-1272.

Wong, E. D. (1993b). Self-generated analogies as a tool for constructing and evaluating explanations of scientific phenomena. *Journal of Research in Science Teaching, 30*(4), 367-380.