

Conceptual Resources in Self-developed Explanatory models

Meng-Fei Cheng and David E. Brown,
University of Illinois at Urbana-Champaign

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Abstract

This study explores two questions: first, what conceptual resources do students use, and in what ways do they use them, to construct explanatory models? Second, what are the obstacles preventing them from constructing a useful explanatory model? Our findings indicate that students employ their conscious and unconscious knowledge in their reasoning process. Connecting intuitive knowledge and abstract knowledge is important for students to construct coherent and sophisticated explanatory models. If students rely only on intuitive knowledge, they may construct a tentative and non-sophisticated explanatory model; however, if students rely only on verbal symbolic knowledge at an abstract level without connection with their intuition, they may not have the ability to construct an explanatory model. This research shows that instruction needs to help students connect their verbal symbolic knowledge and intuition to construct their own explanatory model to make sense of abstract scientific 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. First, we explore how students involve different levels of knowledge to help themselves construct explanatory models by using this framework. We also investigate the interrelationships between conscious and unconscious knowledge that students employed to explore conditions under which students would develop useful or powerful explanatory models. Next, we also explored obstacles preventing students from constructing explanatory models. In order to answer these questions, we will examine the episodes in which they succeeded or failed to construct explanatory models in order to explore how they employed their conceptual resources and the interrelationships among the different levels of knowledge.

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.

Design

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.

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 may be 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 use 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

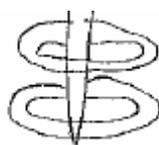


Figure 2. Paula(6)'s drawing of her observation of the donut magnets activity as the top magnet “floated” because of repulsion

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).

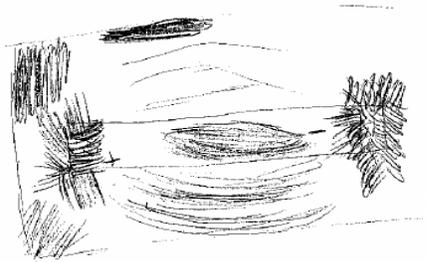


Figure 5. Paula(6)'s drawing of her observation of the iron filings over one magnet activity



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.

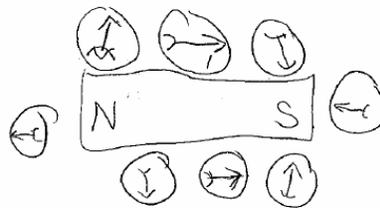


Figure 7. Paula(6)'s drawing of her observation of the compass activity

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 behavior 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 change 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.

Figure 8 shows the core intuitions that came into play in these analyses. An initiating agent is seen as having its own agency to act on other entities. An initiated agent has agency that has been transferred to it from another agent. An affected responder is influenced by another entity's agency. An instrumental responder conveys agency from another agent, and an inert responder is not affected by agency, it simply provides a constraint or obstacle (Brown, 1993, 1995a). These elemental core intuitions combine into "attributive clusters" as the perceived agency of different entities interacting in a situation.

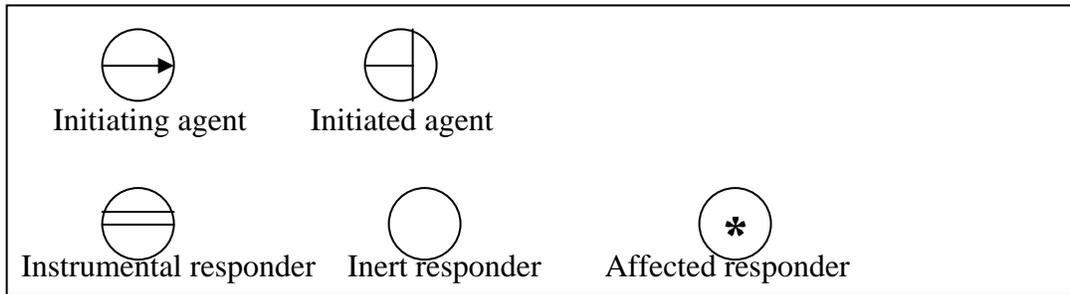


Figure 8. Brown's diagram (1993, 1995a) of representation of attributive cluster

Consider an example from this study to illustrate the meaning of attribution agency. One of Donna(3)'s explanations about magnetism, as interpreted from attribution of agency, is that the magnet is the initiating agent to send out magnetic force as the initiated agent to attract the paper clip as the affected responder. The other example from Paula(6) is that the magnet is the initiating agent to send out electricity as the initiated agent to go through the finger as the instrumental responder to reach the other magnet as the affected responder.

The thin paper is the inert responder in Donna(3)'s explanation, because Donna(3) thinks that thin paper is too thin to cut off the magnetic force, whereas to Paula(6) the finger is the instrumental responder, because she thought that she could feel the electricity going through her finger to attract the other magnet. The two examples of attributive cluster are in Figure 9.

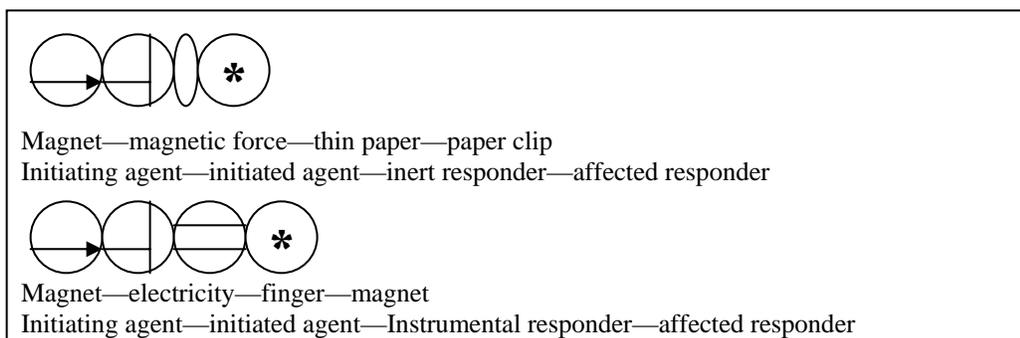


Figure 9. Representation of attributive clusters about how magnets attract a paper clip or another magnet

Results

When students constructed a useful explanatory model, they always involved implicit models and core intuitions in their explanatory models, which include how they perceive the nature of the world and the casual relationships of interacting entities. Sometimes they also employed verbal symbolic knowledge in their explanations; however, this element was not necessarily involved in constructing explanatory models.

Paula(6), a sixth grader, 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 agent to act on the 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.

In what follows we use Paula(6) as a model for the comparison with the other five students in order to explore what conceptual resources they used when they constructed explanatory models, and what obstacles prevented them from constructing an explanatory model. The following are some findings from the six case studies.

How Different Levels of Knowledge Helped Students Construct Explanatory Models

Associating verbal symbolic knowledge with intuitions or using only intuitions. There were two different ways in which students constructed their explanatory models. The first was that students constructed their explanatory models by associating their verbal symbolic knowledge with intuitions, as Paula(6) did. The second is that students constructed their explanatory models by using only their intuitions, as Donna(3), Lily(3), and Kate(3) did.

When Paula(6) connected her verbal symbolic knowledge about the positives and negatives of the magnet with her core intuitions—positives or negatives as initiating agents to act on the other positives or negatives of the magnets—and the implicit models about the nature of magnetism, such as substance-like magnetism, she began to construct her “electricity view” explanatory

model. During the process of refining her explanatory model, she still connected her verbal symbolic knowledge with her intuitions in her “electricity view” while adding some new features into her explanations, such as the positives and negatives on the paper clip and iron filings, or the bubble shape of magnetic fields (see Figure 10).

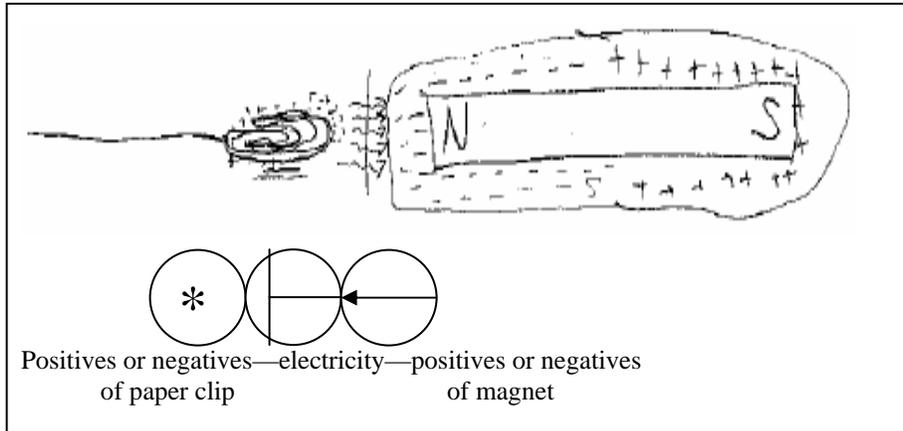


Figure 10. Paula(6)’s drawing and attributive cluster about how a magnet attracts a paper clip when there is a piece of paper between the magnet and paper clip. This picture shows the positives and negatives on the magnet and the paper clip, and the bubble shape of the magnetic field.

Other students who had constructed more than one explanatory model in their explanations also involved core intuitions and implicit models in their reasoning, but they seldom involved verbal symbolic knowledge in their explanatory models. For example, Lily(3)’s explanatory model was that magnet-like materials travel from the magnet to the metal bars, making them stick in a chain (see Figure 11). Lily(3) appeared to use her intuitions that the moving materials in the magnet acted as initiating agents to act on other metal bars, and that the moving of the materials enabled the magnet to stick to other metal bars. She did not employ verbal symbolic knowledge to construct her explanatory model, even though she had mentioned some verbal symbolic knowledge from her mother in the previous interview: “I think my mom once told me that about the North side and South side, and that, when they’re the same, you can’t get them together. And, but when they’re touching...” Moreover, this explanatory model that Lily(3) constructed by using her intuitions only was maintained for only a short time and was not applied to other contexts.

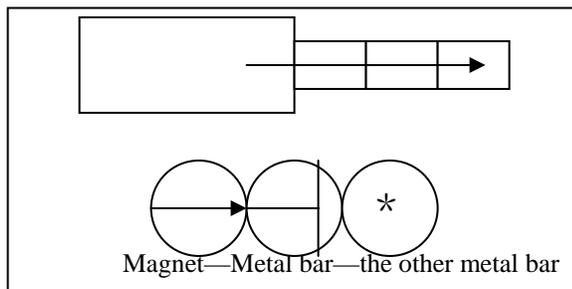


Figure 11. Representation of Lily(3)’s explanation about how things go through the magnet and metal bars to make them attract

Donna(3) and Kate(3), also constructed unstable explanatory models. Donna(3)'s explanatory model was that if the "special leads" in the magnets face each other, gravity would pull them together, but if the special lead and the ordinary lead face each other, gravity would push them apart. The use of the term "gravity" might imply the use of verbal symbolic knowledge, but Donna(3) seemed to be using this term simply to indicate a kind of vague initiating agency. Kate(3)'s explanatory model was that the black powder moves to two ends of the magnet and the power travels from the magnet to the metal bars. None of them utilized the verbal symbolic knowledge they had mentioned to construct explanatory models, nor did they apply their explanatory models consistently to the different contexts.

Therefore, employing only core intuitions and implicit models enabled students to construct explanatory models, but the explanatory models that they constructed were rather tentative, and they did not apply the same explanatory models in other contexts. They seemed to be "at the mercy" of their intuitive knowledge.

Using verbal symbolic knowledge to overcome implicit models. The other observed role of verbal symbolic knowledge was to help students overcome their inappropriate implicit models, helping them to construct more sophisticated explanatory models. In the donut magnet activity, Paula(6), Donna(3), and Lily(3) mentioned that the same sides of the magnets stick together and that opposite ends of the magnets push away. Their conceptions were strongly influenced by their implicit model that same things stick together. The implicit model became stronger here because there was no symbol on the donut magnets to help students identify the different sides of the magnets. However, after the confirmation of the relationships between the different ends of the two magnets from the interviewer, Paula(6) shifted back to her "electricity view" by reconsidering the relationship between negatives and positives, whereas Donna(3) and Lily(3) still maintained their notion that same things stick together.

Yet, in the review of the two magnets activity, Donna(3) shifted from her view that different leads would push each other away to a new view that different leads would pull together by employing the symbols on the magnets to overcome her implicit model. She referred to the N and S symbol on the magnets, so she thought that different symbols represent different leads, so she changed her explanations to the view that different leads go together. While Lily(3) had mentioned her verbal symbolic knowledge from her mother about the attraction between N-S and the repulsion between N-N and S-S, she only involved the verbal symbolic knowledge into her explanation that if the same sides of the magnet face each other, they would push away and vice versa, but she did not further develop her explanation from this verbal symbolic knowledge. She was strongly influenced by her implicit model—that same things stick together—in the rest of the activities.

In the comparison of these three cases, it appeared that students have different levels of proficiency in utilizing their verbal symbolic knowledge. Paula(6) seemed to have better skill to utilize her verbal symbolic knowledge to enable her to overcome her inappropriate implicit model. Donna(3) did not utilize her verbal symbolic knowledge to help her overcome her implicit model during the most of interviews until the final review of two magnets activity. Lily(3) did not seem to be proficient in using her verbal symbolic knowledge. When she used her

implicit model to construct explanations, she did not involve her verbal symbolic knowledge in her reasoning.

Borrowing verbal symbolic knowledge from other domains. Another reason why Paula(6) succeeded in constructing a coherent and sophisticated explanatory model is that Paula(6) projected the notions of the other domain, electricity, with which she was more familiar, to magnetism, with which she was unfamiliar. She used the attraction between negatives and positives and the repulsion between negatives and negatives or positives and positives in the magnet to explain the attraction and repulsion between two magnets. Paula(6) did not abstractly apply the conceptions of positives and negatives to explain magnetism, compared with Donna(3) who used the terms, positives and negative to represent the North and South ends of the magnets. Paula(6) speculated that the negatives and positives are electron or particle like inside the magnet, and they are the initiating agent to cause the attraction and repulsion.

Furthermore, after reviewing all of the activities that she had done, Paula(6) shifted from the “bubble view of electricity” to the “wave view of electricity.” She projected the notion of wave currents in the sea to the “positives and negatives view” to explain how the waves of the magnetism from the earth could travel for a long distance to affect the compass. Following is her statement to explain why and how she modified her explanations:

I thought of it as having more of a bubble around it, because when you are in... Like when you are learning about the solar system, you learn that earth has a magnetic field around it. It's basically in the shape of a bubble.... So it looks like a bubble so you think of it of course as a bubble. So that's where I got this theory. 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.

Despite the fact that the way she used a wave view to equate electricity and magnetism is not the way that scientists explain magnetism, applying a sophisticated explanatory model from one domain to the other indeed helped her to make sense of magnetism—a concept with which she was not familiar before. The wave notion is regarded as a more abstract and less tangible conception than other notions, which can be intuitively perceived from daily life experience (Bube, 1992). Thus, employing verbal symbolic knowledge about ocean waves enabled Paula(6) to develop her bubble view of magnetic fields to into a more abstract wave view of magnetic fields.

Besides Paula(6), other students also mentioned some verbal symbolic knowledge from other domains, but the verbal symbolic knowledge did not help them successfully construct explanatory models. For example, Yong(6) seemed to use verbal symbolic knowledge from a domain he was more familiar with as an analogy to magnetism. He used the passing of germs as an analogy to describe how gravity, electricity, and forces traveled through the magnet and metal bars. He also used an analogy regarding the two sexes to explain the attraction and repulsion between two magnets. Yong(6)'s self-generated analogies helped him to explain an unfamiliar

domain, but they did not help him to construct an explanatory model, because he did not associate his verbal-symbolic knowledge with his core intuitions, as Paula(6) did.

Brown (1993) proposed that analogies can help students construct more abstract concepts so as to promote students' conceptual change. The role of analogy in conceptual change is to "help enrich or further concretize representations of specific situations with concrete objects or properties that fruitfully engaged intuitions about the situations" (p.1273). This creates a bridge between anchor conceptions and target conceptions. Wong (1993a; 1993b) also claimed that students' self generated analogies help them to explain the unfamiliar phenomena.

Obstacles Preventing Students from Constructing Explanatory Models

Applying verbal symbolic knowledge abstractly. Although some of the students applied verbal symbolic knowledge in their reasoning, they did not construct explanatory models in the way Paula(6) did. Apparently the reason why the other students could not construct coherent and sophisticated explanatory models is that they applied their verbal symbolic knowledge abstractly, without connection with their intuitions. They tried to use their existing verbal symbolic knowledge to respond to different phenomena of magnetism in different activities without trying to associate it with their intuition in order to construct explanatory models. For example, Yong(6) is a student who deployed verbal symbolic knowledge at an abstract level; therefore, all of his explanations revolved around the notion that gravity, electricity or magnetic forces would cause the attraction of the magnets. In the metal bar activity, he stated how the analogy of passing germs was applied to explain the magnetic force:

It's part...the germ was the electricity. The electricity will hold how much it can. They are made of magnetic and they have gravity powers that the magnet can't... So the magnet will try to hold it by using it's ability, but some of them, when they are magnetic, the ability will stick and make the magnet stick.

He also stated the similarity and difference between these magnetic force, electricity, and gravity:

Magnetic force and gravity are kind of different. But I believe that's how the magnet works...some people say it works by gravity. Some people say it works by electricity. Some people say it works by force. It just...those three are possible in how the magnet works. I just don't know for sure.

The gravity, it pulls anything. It's like a force. Like Star Wars, like Jedi, using the force to pull anything, or push something. It could be like force. Or those kind of force is like gravity. It can pull anything like Earth, or push like the gravity is gone. It could be like that. I think that the gravity would be more like how the magnet works. Well, also electricity. Because it's like they're pulling something.

He recognized that there were differences between electricity, gravity, and magnetic forces, but nonetheless believed that they worked the same way. However, presenting all of the verbal symbolic knowledge that he remembered did not help him to construct an explanatory model.

The reason why he persisted in using verbal symbolic knowledge may have been that he was a student who seemed most to assume there were correct scientific answers to the questions, so when facing a difficulty in answering how and why magnets work, he responded, “I don’t get the facts. I don’t get the answer.” or “I don’t know quite sure. That is why I cannot answer.”

In comparing how Paula(6) employed her verbal symbolic knowledge with Donna(3), both of them employed verbal symbolic knowledge about the positives and negatives of the magnet. However, Paula(6) associated positives and negatives with the initiating agent of magnetism, but Donna(3) only applied positives and negatives as the N and S symbols of the magnet to identify different sides of the magnet, without any connection with her core intuitions.

Compared with Vivian(6), Paula(6) also mentioned verbal symbolic knowledge about magnetic fields, but she only used them to describe the ranges that magnets can affect. Furthermore, Paula(6) projected other verbal symbolic knowledge, such as negatives and positives from electricity, to explain how magnets work, rather than employing abstract conceptions of magnetic fields. Vivian(6) held a “magnetic field view”—that the magnetic force from the magnet acts on other matter—as her main explanation for how magnets work in different contexts. Vivian(6) used the term “magnetic field” to substitute for the invisible “magnetic force” that she had mentioned. Vivian(6) did connect the term magnetic field with her intuitions, but directly with core intuitions. In other words, to her “magnetic field” was just another term for the direct agency of the magnet. Comparing the two cases, we can find that Vivian(6)’s idea was similar to the canonical explanation about magnetic fields, but she did not really “own” this explanatory model. The conception of a magnetic field did not help her to construct her own explanatory model.

Only connecting verbal symbolic knowledge with implicit models. Although Paula(6) is exemplary in showing how a student can develop explanatory models, in the compass activity Paula(6) did not seem to further construct or refine her explanatory model. Her reasoning seemed to be confined by her implicit model and verbal symbolic knowledge, so she did not construct a further explanatory model. For instance, in the compass activity, Paula(6) vacillated between two notions. One was the implicit model that the arrow of the compass should point to positive. The other represented her combining of verbal symbolic knowledge that compasses points to North, and an implicit model that up is positive. Therefore, Paula(6) reasoned abstractly in the compass activity, rather than constructing or refining a useful explanatory model.

Only connecting verbal symbolic knowledge with implicit models also inhibited Kate(3) from constructing an explanatory model. When explaining the attraction and repulsion between two magnets, Kate(3) would associate her verbal symbolic knowledge about the different directions of the classroom with the N and S symbol on the magnet to decide whether the magnet went to the right or wrong direction. She also involved an implicit model that if two magnets went to the right direction, they would stick; if one of them went to the wrong direction, they would repel. Only using verbal symbolic knowledge and implicit models in her reasoning, Kate(3)’s explanation still stayed at an abstract level, instead of constructing a visualized explanatory model.

Overly relying on implicit models. Implicit models seemed to help students make sense of the phenomena that they could not explain, but they by themselves they did not help students to construct explanatory models. The explanatory models indeed contained implicit models, but if students overly relied on implicit models, they would fail to construct an explanatory model.

In Paula(6)'s explanatory model, she indeed involved her implicit models to help her reasoning, such as the idea of electricity as an extra link or extension of the magnet, which represented a substance-like magnetism, after she asserted that she could feel the pressure of her finger between two magnets. However, after she constructed this explanatory model of "electricity view", she did not mention the substance-like magnetism in the following activities. In the final section of interview, from her explanations, electricity became a wave-like energy without the property of a substance. Paula(6) thought that there are waves inside and outside of the magnet. The waves would come off the magnet and are made of positives and negatives electricity in her "electricity view." Therefore, Paula(6) did not appear to over rely on her implicit model. She progressed from her intuition, substance-like magnetism, to a more abstract notion, wave-like magnetism (see Figure 12).

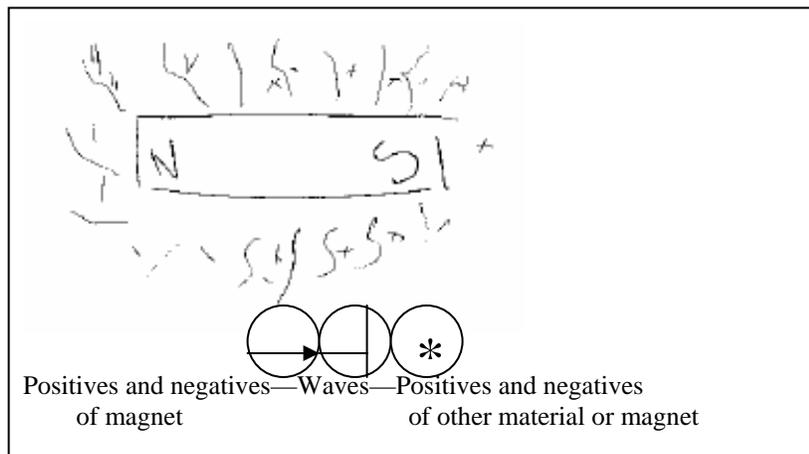


Figure 12. Representation of Paula(6)'s drawing and explanation about "wave view"

On the other hand, Lily(3) used a "sameness view"—that same things stick together—from her implicit model to explain most of the phenomena in the activities. Thus, she failed to construct an explanatory model from her "sameness view." In actuality, Lily(3), Donna(3), and Paula(6) had similar notions while playing with the donut magnet. In the donut magnet activity, Donna(3) appeared changed from her originally idea that "special leads facing each other would repel" to that of a "modified special lead view"—"special lead facing each other would attract" in one statement.

[3 0:24:56].

(3.14) I: So what's going on (pointing to gap between top two magnets) between these two magnets?

(3.14) D: There's a magnetic force that's not letting it connect with each other. Uh, I guess just there's gravity and special lead. The special lead inside the magnets... there's special lead on one of the sides, I guess, and if the special

lead isn't facing, like, then it will go together, if the special leads are facing each other, but if the special leads facing each other (takes magnets off chopstick and puts opposite sides together so they stick), that will go together but, if the special leads are facing each other it will go together, but if the special leads aren't... (Reverses one of the magnets and puts on chopstick.) If the special leads aren't facing each other there will be something between it that will make it not go together. But if the special leads are facing each other, then it will go together.

In the donut magnets activity, Donna(3)'s implicit model—the same things stick together so two special leads facing each other stick together—overcame her original reasoning in the two magnets activity that two special leads push each other away

Paula(6) also happened to apply “sameness view” in her prediction and observation of what happened between the two donut magnets for a short moment. Paula(6) mentioned, “If one side was positive and one side was negative, they would repel each other.” This statement was contrary to her previous statement that positives and negatives would attract, so she was asked to further clarify her meaning: “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.” Therefore, the interviewer asked her again whether her meaning was that positives and positives would repel or positive and negatives would repel. This time Paula(6) changed her answers to positive and positive would repel.

Therefore, from the above episode we found that due to lack of the N and S south symbols on the magnet to assist students to identify different sides of the, all of these three students used “sameness view” in the donut magnet activity. However, only Lily(3) depended too heavily on her implicit models to make explanations throughout the following interviews. Donna(3) and Paula(6) only showed their implicit model of “sameness view” in donut magnet activity. They dropped this explanations in other activities. Hence, overly relying on implicit model maybe prohibited Lily(3) from constructing explanatory models.

Over-reliance on implicit models also made the explanatory models become conceptually fragile. Lily(3) only constructed an explanatory model for a short time in the metal bar activity. When she faced a problem that the metal bars originally did not stick to each other, she developed an explanatory model that something comes from the magnet to go through the metal bars. However, when she faced the challenge that she could not see material going through the magnet and metal bars, she fell back to using her “sameness view” to explain why the magnets would attract the metal bars in a chain, and resolved the previous conflict about why the metal bar did not attract the other metal bar with another core intuition—that metal bars are too small, so that they are not strong enough to stick to each other as a bigger magnet did. In a word, over-reliance on implicit models for explanation made Lily(3) feel no need to construct an explanatory model, and her implicit model also made her new constructed explanatory model become conceptually fragile.

The way to employ core intuition. Employing core intuitions to explain the microscopic structure of magnets or other materials can help students to construct explanatory models. For example, Paula(6) mentioned that more positives or negatives of one iron filing would decide in

which direction the iron filing would move. Kate(3) also mentioned that moving black powders to the two ends of the magnet to send out power from the magnet to the metal bars. Here, core intuitions seemed to be a foundation to help students to construct explanatory models.

On the other hand, sometimes the ways students implicitly employed the causal relationships of core intuitions may have inhibited them from constructing further explanations. For example, Donna(3), Yong(6), Vivian(6), and Lily(3) used the core intuition—more agency leads to more effect—to explain why two ends of a magnet would pull more iron filings (this is essentially diSessa’s “Ohm’s p-prim,” a domain independent and central p-prim in diSessa’s framework). In another case, Vivian(6) used another core intuition relationship—that stronger things can overcome weaker things—to illustrate that because the magnetic field is stronger than a finger, so the magnet can attract a paper clip, even when putting a finger in between. The results showed that when students applied these core intuitions directly to the situations, it seemed to inhibit them from feeling the need to further construct explanatory models to explain the microscopic processes of magnetism.

Anthropomorphic models may hinder students from constructing explanatory models. Some students may use intuitive anthropomorphisms to make sense of the abstract conception of magnetism, thus failing to construct an explanatory model. For example, Kate(3) used intuitive notions, like “the paper clip can feel the magnet,” “they (metal bars) can’t feel the middle (of the magnet),” or “paper clip wants to get on to the magnet” to explain magnetism. Vivian(6) used verbal symbolic knowledge about magnetic fields or forces to explain why magnets work, but in the donut magnet activity, she used anthropomorphism to explain the repulsion between two magnets: “They are both trying to repel each other, because obviously, they don’t like each other.” Using this intuitive response seemed to impede students from feeling a need to construct an explanatory model.

Interestingly, Paula(6) also involved intuitive anthropomorphisms in her brainstorming stage, stating that if two of the similar ends of the magnet do not like each other, they would push away, and if two opposite ends of the magnet like each other, they would go together. However, later in her explanations, Paula(6) shifted to using electricity to explain the attraction between two magnets, and thus started to construct an explanatory model. However, it is unclear why and how she dropped her intuitive anthropomorphic thinking.

Conclusions

From the analysis of six case studies, we found that connecting intuitive knowledge and verbal symbolic knowledge helped students to construct more coherent and sophisticated explanatory models. Paula(6) exemplified how to integrate abstract and intuitive knowledge to construct explanatory models. There were some students—Yong(6) and Vivian(6)—who also possessed verbal symbolic knowledge related to magnetism, but it appeared that they only applied intuitive knowledge in some contexts and applied verbal symbolic knowledge in other contexts. They did not make sense of the abstract verbal symbolic knowledge by using their intuition, nor did they connect these two to construct explanatory models. On the other hand, other students, including Donna(3), Lily(3), and Kate(3), employed their intuitive knowledge to construct one or several

explanatory models in several contexts. However, their explanatory models were fragile, and without either coherence or sophistication.

In this study we observed that there was a disconnect between verbal symbolic knowledge of magnetism (from schooling, parents, books, etc.) and students' intuitive knowledge. Students seemed to have problems connecting these two spontaneously, choosing either intuitive or verbal-symbolic knowledge to explain the phenomenon of magnetism. An important implication is that we need to teach students how to connect their abstract and intuitive knowledge to form their own explanatory models.

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