THE ROLE OF METACONCEPTUAL EVALUATION IN FIFTH GRADE STUDENTS’ CONSTRUCTION OF EXPLANATORY MODELS OF MAGNETIC PHENOMENA

BY

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DISSERTATION

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Abstract

The purpose of this study was to investigate in detail the processes involved when the promotion of metaconceptual evaluation facilitates fifth grade students’ construction, evaluation, and revision of their explanations for magnetic phenomena. Although much recent research emphasized the importance of student modeling and model construction, the topic of magnetism is typically taught as either simply observing magnetic phenomena or as introducing abstract knowledge, without asking students to construct their own models to account for magnetic phenomena. Also, as suggested by educational research, metacognition is important in such model construction. However, little research explores the detailed processes of how metacognition promotes model construction. In this study, a video-taped, multi-session teaching experiment was conducted with a small number of fifth grade students in order to study in detail the interactions between students’ metacognition and their development of explanatory models to account for magnetic phenomena.

In this teaching experiment, two small groups received full scaffolding, and two small groups received partial scaffolding. Students in both the fully and partially scaffolded groups were asked to make their own predictions and explanations before observing magnetic phenomena, as well as to make individual explanations and modifications after their observations. Then, they were asked to elaborate on their individual ideas and to discuss them with others in order to select or develop the best group consensus model. In later activities, they were required to compare their current group model with their previous group models. In addition, fully scaffolded groups were explicitly asked to reflect on the metaconceptual modeling criteria of visualization and explanatory power. Multiple sources of data were collected, including transcripts of pre- and post-instructional interviews and activities, as well as the journals and
papers students used to record and discuss their ideas. In order to explore how students’ metacognitive processes regulate their cognitive processes, these data were analyzed according to three main aspects: sophistication and coherence of explanations, conceptual resources used, and metaconceptual evaluation.

Through reflection on their explanations using these metaconceptual modeling criteria, most students in the fully scaffolded groups gradually developed, evaluated, and revised their explanations to coherent and sophisticated microscopic explanatory models, similar to a simplified version of the scientific domain model of magnetism. They were able to activate, apply, and reorganize appropriate conceptual resources from the observational level to the microscopic level. By contrast, students in the partially scaffolded groups, who relied only on self-generated model-evaluation criteria, lumped together different ideas from different activities, without revising their original ideas toward more coherent and sophisticated explanatory models, so their explanations ended up fragmented and disconnected. They were unable to apply appropriate conceptual resources from the observational level to further hypothesized and unobservable levels. Reflection on the metaconceptual modeling criteria helped the fully scaffolded students to inspect, activate, apply, and reorganize their conceptual resources in order to construct explanatory models with better visualization and greater explanatory power.

The results of this research provide instructional implications from a content perspective, a constructivist perspective, and a modeling perspective, on diminishing the gap between how scientists practice science and how science is taught. The present study brings insights into areas of modeling, conceptual resources, and metacognition, and offers recommendations for theory, methodology, and pedagogy.
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Chapter 1
Introduction

Statement of Problem

In the United States, magnetism is included in the elementary and middle school science curriculum, but concepts related to magnetism are introduced abstractly, and their origin and meaning are rarely explained; therefore, students usually have difficulties understanding these abstract ideas (Harrison & Treagust, 2000). Thus, there is a disconnect between students’ intuition and existing knowledge and their new abstract knowledge. This gap has also been shown in previous clinical interviews with third grade and sixth grade students (Cheng & Brown, 2010).

During several clinical interviews, some students were found to have problems using their intuition or existing knowledge in order to make sense of the phenomena of magnetism. They also had problems connecting their intuition with abstract verbal symbolic knowledge related to magnetism in order to construct their explanatory models. They may have learned the abstract terms from school without developing an explanatory understanding by connecting them with their intuitive ideas. Hence, findings from this earlier research inspired me to explore how I could facilitate the improvement of students’ explanatory models of magnetism.

From a constructivist perspective, learning new knowledge requires students to construct their own knowledge. If students only passively accept the abstract knowledge from outside resources, they may fail to connect this knowledge with what they already know. In other words, students usually develop their models from their intuition, but
textbooks and teachers usually offer more abstract symbolic knowledge. Students are expected to comprehend the terms by constructing models from their existing knowledge and intuition in order to make sense of the new knowledge or events. Therefore, an important issue is how to bridge students’ existing knowledge with abstract knowledge to help them construct their own models and facilitate their model development and revision toward more consistent and coherent models. Although scientists’ mental model construction processes have been studied (Clement, 1989, 2008c; Nersessian, 1999, 2008), students’ model construction processes and the processes or mechanisms leading to model revision still remain unclear (Clement, 2008b).

The importance of metacognition has been emphasized in model construction (Clement & Steinberg, 2008; Harrison & Treagust, 2000; White & Frederiksen, 1998, 2000, 2011). But researchers have done little to explore the detailed processes of how metacognition facilitates model construction. When strategies to facilitate metacognition are used, the results typically only present examples of effectiveness (Beeth, 1998; Georghiades, 2000; Hennessey, 1999; Schwarz & White, 2005; Schwarz et al., 2009; Yuruk, Beeth, & Andersen, 2009). Thus, although the role of metacognition is recognized, how metacognition actually facilitates students’ reasoning processes is still unclear.

Furthermore, it is difficult for students to spontaneously employ metacognition in their learning (Hennessey, 2003). A previous study (Cheng & Brown, 2010) showed that not all students are spontaneous self-regulated learners and most students had problems developing more coherent and sophisticated models in their explanations.

When researchers study students’ conceptions of magnetism, they usually study students’ misconceptions (e.g., Barrow, 1987; Constantinou, Raftopoulos, & Spanoudis,
2001; Guisasola, Almudi, & Zubimendi, 2004; Guth, 1995; Guth & Pegg, 1994; Hickey & Schibeci, 1999; Maloney, 1985); categorize students’ conceptions as belonging to one of several models (Borges & Gilbert, 1998; Erickson, 1994); or use some strategies to enhance learning results (Anderson, Lucas, Ginns & Dierking, 2000; Bradamante & Viennot 2007; Guisasola, Almudi, Ceberio, & Zubimendi, 2009; Narjaikaew, Emarat, Arayathanitkul, & Cowie, 2010; Tatsuki & Fushimi, 2002). These approaches may inform instructors of students’ preconceptions and the effectiveness of teaching strategies in order to provide scientific models to students and convince them to abandon their misconceptions. Nevertheless, it cannot help instructors understand the internal processes of the students’ model construction and facilitate their ability to construct more consistent and coherent models from their intuition and existing knowledge.

In this research, I conducted a teaching experiment to study in detail the interaction between students’ metacognition and their development of models for magnetic phenomena when they reflected on their explanations with and without scaffolding with metaconceptual modeling criteria.

Purpose of the Study

The purpose of this study was to investigate the process of fifth grade students’ model building with and without scaffolding of metaconceptual modeling criteria. I chose the fifth graders based on several reasons, which I will illustrate in the methodology section. In this study, I offered students the opportunity to develop, reflect, and revise their explanatory models, instead of just providing them with scientific models. This approach allowed me to study the processes of students’ knowledge development. By
focusing this study on the learning experience of a small number of students, I aimed to keep track of individual students’ cognitive and metacognitive processes in their model development. I designed this research to address several questions:

1. How do students develop and revise their explanations?

2. What are the conceptual resources involved in students’ explanations for magnetism?
   a. How do students use different conceptual resources in the development or revision of their explanations?
   b. What contextual factors contribute to the construction of students’ explanatory models? If students do not construct explanatory models, what are the barriers preventing them from doing so?

3. How does promoting metaconceptual evaluation facilitate the process of developing explanations and utilizing conceptual resources?

In this research, I first developed categories of progressive levels of sophistication and coherence to investigate the progression of students’ model development and revision. Then I explored the process of their model construction and revision by using different conceptual resources that interplay in a dynamic way. Finally, I examined how scaffolding with and without metaconceptual evaluation may influence students’ model development and revision as well as their engagement of different conceptual resources in their reasoning. This qualitative approach enabled me to conduct a detailed exploration of the issues underlying students’ model construction and metacognition.
**Significance of the Study**

In this research I focused on investigating the processes of students’ model building with and without scaffolding using metaconceptual modeling criteria. This process tends to inform theories about modeling and metacognition on the connection between students’ intuitive ideas and scientific models as well as students’ intuitive metacognition and scientific metacognition. By focusing in detail on individuals’ cognitive and metacognitive processes, this study provides new insights into how students evaluate and revise their ideas according to their metaconceptual evaluations. This study contributes to modeling theory, which to date has focused largely on the essential role of metacognition in model building without articulating how metacognitive processes can actually help with cognitive processes.

In addition, this study has implications for instructional design in terms of considering not only how to diminish the gap between students’ intuitive ideas and abstract scientific knowledge but how to scaffold students’ metacognition to foster students’ model building. Through this research, I intended to explore methods that can help students escape from rote learning, which involves verbal memorization and cannot be mentally manipulated or applied to novel situations by students. In this research I tried to foster meaningful reasoning and learning tied to previous knowledge and integrated with previous learning, in which knowledge can be mentally manipulated and applied to new contexts.
Chapter 2
Theoretical Framework

Constructivist epistemology asserts that students construct knowledge from their existing knowledge and experiences. Within this theory, the emphasis is on students’ active role in the process of learning, as well as investment in the product of learning. Therefore, instruction should facilitate students’ ability to reflect on their own learning and guide them to become autonomous learners (Duit, 1999).

In this study I intended to facilitate students’ modeling processes in order to construct models to explain magnetic phenomena. Modeling—the generation, evaluation, and revision of models—has been recognized as one kind of scientific inquiry in science and science learning (Passmore, Stewart, & Cartier, 2009; Windschitl, Thompson, & Braaten, 2008a, 2008b), so facilitating students’ modeling process to encourage them to actively construct their own knowledge could be regarded as a constructivist learning and teaching approach (Harrison & Treagust, 2000). Based on the ideas of constructivist learning and teaching approaches, I created exercises to encourage students to actively engage in the spontaneous modeling process in order to explain the magnetic phenomena.

In this literature review, I first briefly discuss what kind of explanations students were encouraged to construct in this study. The importance of explanatory models, in science learning in particular, is examined in order to discover how to help students develop explanations. Different types of model-based learning are categorized in order to contextualize the approach I adopted in this study. Second, I review current perspectives interpreting students’ conceptual framework in order to validate my reasons for adopting a multidimensional framework (Brown, 1993, 1995a, 1995b; Cheng & Brown, 2010) to
conduct this teaching experiments, and to interpret and analyze how students develop their explanations. Third, I discuss the importance of metacognition and the methods facilitating metacognition in terms of the limitations on students’ ability to develop their explanations and to use their conceptual resources.

**Explanation in Science Education**

Explanation is usually regarded as an important goal of science (Sandoval & Millwood, 2005; Berland & Reiser, 2009; Strevens, 2009). Although there is no consensus about the philosophical definition of explanation, most researchers agree that the purpose of explanation is to move beyond the description of observable phenomena to provide an account for why things occurred (Achinstein, 1983; Braaten & Windschitl, 2011; Berland & Reiser 2009; Brewer, Chinn, & Samarapungavan, 2000; Halloun, 2007; Salmon, 1990). Philosophers have proposed different models to define or cover all scientific explanations (e.g., Hempel, 1965; Hempel & Oppenheim, 1948; Kitcher, 1981; Salmon, 1990). Among these different models, the causal model of explanation is usually perceived as one important view of scientific explanation (Besson, 2010; Russ, Scherr, Hammer, & Mikeska, 2008; Braaten & Windschitl, 2011; Salmon, 1997; Strevens, 2009). Causal scientific explanations involving underlying mechanisms to make sense of observable phenomena are usually the focus in science education. Due to their essential role in scientific practice, developing causal explanations is encouraged in students’ reasoning (Besson, 2010; Braaten & Windschitl, 2011; Hammer, Russ, Mikeska, & Scherr, 2008; National Research Council [NRC], 1996; Russ et al., 2008; Windschitl et
Generating and evaluating explanations has been emphasized in science as well as science education through the *National Science Education Standards* (NRC, 1996, 2007). It remains an essential component in the scientific inquiry in new standards of K-12 science education (NRC, 2010, 2011). Nevertheless, one persistent criticism of these standards is that when descriptive phenomenology is emphasized in the school, there is less focus on causal explanations of events (Besson, 2010; Braaten & Windschitl, 2011; Gilbert, Boulter, & Rutherford, 1998a; Pasley, Weiss, Shimkus, & Smith, 2004; Russ et al., 2008; Smolkin, McTigue, Donovan, & Coleman, 2009).

Therefore, my purpose in this study is to concentrate on how to encourage students to better generate causal explanations, a learning approach that has less priority in school than other scientific activities.

**Models in explanations.** There is considerable research suggesting how to facilitate students’ construction of explanations through arguments or evidence-based evaluation (Berland & Reiser, 2009; Bricker & Bell, 2008; McNeill, 2009; McNeill & Krajcik, 2008; McNeill, Lizotte, Krajcik, & Marx, 2006; Sandoval & Millwood, 2005; Sandoval & Reiser, 2004; Songer, Kelcey, & Gotwals, 2009). Another approach that is also frequently suggested to assist students to better construct explanations is the use of model development. The essential role of models is emphasized in scientific explanations by philosophers (Giere, 1988, 1999; Hesse, 1966; Suppe, 1977) and in human reasoning by cognitive psychologists (Gentner & Stevens, 1983; Gopnik & Meltzoff, 1997; Johnson-Laird, 1983), both of which emphasize the importance of models and modeling in science teaching and learning (Besson, 2010; Develaki, 2007; Gilbert et al., 1998a, al., 2008a, 2008b).
Models and modeling. The essential role of models and modeling has been recognized in scientific thinking and reasoning (Black, 1962; Coll & Lajium, 2011; Gilbert, 2004; Hesse, 1966; Nersessian, 2002, 2008). Models are employed by scientists as representations of ideas about the structure and the behavior of systems, allowing scientists to mentally manipulate concepts, idealize complex phenomena, and construct and test their explanations for the mechanisms and processes of phenomena (Brewer et al., 2000; Chin & Brown, 2000; Windschitl et al., 2008b). They are also believed to offer predictive and explanatory power to help in the development of new hypotheses and scientific discoveries (Vosniadou, 2002a).

Models are developed through modeling, which refers to the cognitive process that constructs and manipulates models; modeling is a fundamental process for scientific inquiry (Schwarz & White, 2005). For scientists, modeling is also a process of inquiry into problem solving and a means to develop new models or theories. Nersessian (2008) pointed out that conceptual innovation and change in science involves the process of building, critiquing, and modifying models, which not only support reasoning, but also serve as working devices for reasoning and creating new conceptions for theory building.

A number of researchers have emphasized the value of models and modeling in science education (Coll & Lajium, 2011; Gilbert & Boulter, 1998; Gobert & Buckley, 2000; NRC, 1996, 2007). Researchers have proposed that models and modeling should be an essential part of science education, because this process is how scientists conduct science (Gilbert, 2004; Hafner & Stewart, 1995; Halloun, 2011; Justi & Gilbert, 2002a, 2002b; Stewart & Hafner, 1991). Hence, modeling is considered an authentic scientific
inquiry in science learning because it represents the process by which science is conducted.

In comparing students’ and experts’ reasoning, not only do experts know more facts than novices, but they have also developed their models, which appear to enhance experts’ abilities to accumulate, retrieve, and apply their knowledge (Glynn & Duit, 1995). Research shows that students’ difficulty in learning science is partially because they have trouble developing their own models, which require the integration of causal–dynamic and spatial–static aspects of knowledge (Gobert & Clement, 1999) or connecting the intuitive causal relationship with their assumptions about the world to make sense of the abstract knowledge they have learned (Cheng & Brown, 2010).

Without constructing models, students may memorize abstract terms, such as magnetism, by rote. They may use their intuition (for example, the invisible arms of magnets) to avoid thinking about explanations for the unfamiliar phenomena (for example, the attraction and repulsion between magnets) and making sense of or having to reason out unfamiliar phenomena. Hence, in science education, models have been employed as a tool for reasoning through problems, which facilitates students’ learning and understanding of scientific concepts, instead of only memorizing scientific principles and facts (Clement, 2000). It helps students to explain the mechanism underlying the behavior of natural world, instead of only describing the situations they observe (Schwarz et al., 2009; Windschitl et al., 2008b).

In the following section, I review the definition of models and the importance of a special kind of model, explanatory models, in this research. I discuss different approaches to learning in model building in order to identify the purpose of these studies and my
position in the research design.

**A typology of models.** The production of models involves a target situation that removes the irrelevant features and facilitates the inquiry process by focusing on certain behaviors and structures of the phenomena and on spatial, temporal, and causal relationships. Gilbert et al., (1998a) believed that these models, often image-like simplified representations, would facilitate mental manipulation. The dynamic interactive features of these situations are usually emphasized in these models (Lesh & Doerr, 2000). Thus, those models involving essential interrelationships (instead of accumulating isolated facts) are deemed to be useful models that support efficient knowledge representation in reasoning to account for different phenomena (Clement, 2008b; Gilbert & Boulter, 2000).

In science education, models are usually classified according to their different ontological statuses: mental models, expressed models, consensus models, and teaching models. Mental models are personal internal representations of the target phenomena. Expressed models are derived from mental models and are conveyed by individual action, speech, or writing. Consensus models are the expressed models that are examined and agreed upon by certain social groups. When the consensus models are accepted in the scientific community, they are termed *scientific models* by some researchers (e.g., Clement, 2000, 2008b; Gilbert, 2004; Gilbert, Boulter, & Elmer 2000; Harrison & Treagust, 2000; Justi & Gilbert, 2000; Rea-Ramirez, Clement, & Nunez-Oviedo, 2008). Teaching models are the models employed to facilitate students’ understanding of the consensus models and a target situation (Gilbert & Boulter, 1998, 2000; Gilbert et al., 1998a; Gobert & Buckley, 2000).
**Mental models.** Mental models are usually studied in cognitive science in order to understand learning (e.g., Gentner & Stevens, 1983; Johnson-Laird, 1983). Mental models are defined as the human mind’s construction of models with the intention of understanding the world; thus they are structural analogues of events or processes, which include the interrelationship between objects and events (Johnson-Laird, 1983, 1989). When studying students’ cognition, mental models are deemed as being special kinds of individual mental representations generated during cognitive functioning (Vosniadou, 1994).

In the learning process, mental models are not only generated while students try to offer predictions or explanations of the phenomena, but mental models can also be stored and retrieved from their memories (Vosniadou, 2002a; Vosniadou & Ioannides, 1998). Vosniadou (2002a) pointed out the functions of mental models in learners’ conceptual development. Per Vosniadou, mental models can be employed to help with the construction of explanations by drawing on relevant knowledge for unfamiliar phenomena. Mental models, constrained by prior beliefs and presuppositions, also influence the interpretation of outside information that further supports theory creation and revision.

Studies of students’ naïve conceptions (Vosniadou & Brewer, 1994; Vosniadou & Ioannides, 1998) demonstrated that the development of students’ explanations starts with an initial mental model based on the interpretation of every day experiences. Then, students gradually integrate learned scientific information into their existing mental models to develop synthetic models that function as a transitional step in the change from initial intuitive models to scientific models. In order to decrease the gap between
students’ mental models and scientific explanatory models, there is a need to involve
students in the construction of models that have higher explanatory power, coherence,
and consistency, allowing the students to progress toward scientific explanatory models.
The following section elucidates the ideas of explanatory models and explains why
encouraging students’ construction of explanatory models may facilitate the construction
of more coherent, consistent, and sophisticated mental models.

*Explanatory model.* Clement (1989, 2008b, 2008c) identified explanatory models
as one type of scientific model that is created by scientists to explain the hidden
structures and the unobservable processes of situations. Explanatory models are structural
hypotheses of phenomena. The hypotheses include a series of objects, characteristics, and
causal interrelationships that are the basis of observable target situations (Louca, Zacharia,
& Constantinou, 2011; Windschitl et al., 2008b).

Explanatory models are highly valued in theory building. One advantage of using
explanatory models in science is that they allows scientists to solve problems they are not
familiar with or give power to theories that explain and predict novel events. Another
advantage is that explanatory models allow scientists to interpret the target situation from
a new perspective by using analogies that are developed from the scientists’ familiar
knowledge to hypothesize the unobservable structures and causal relationships
underlying the observable target situations (Clement, 1989, 2008b, 2008c). Thus,
explanatory models are viewed as one type of knowledge in scientific theories.
Explanatory models, however, are different from scientific laws. The ability to make
predictions based on scientific laws is different from understanding why and how a
system behaves the way it does (Rea-Ramirez et al., 2008).
Owing to the vital role of explanatory models in scientific reasoning, the importance of understanding and constructing explanatory models has been emphasized in science learning. The instruction should be designed to help students’ comprehension of subjects as well as the development of explanatory models, instead of only focusing on memorizing scientific laws or principles (Clement, 1989, 2008a, 2008b; Hafner & Stewart, 1995). Therefore, when the focus shifts from how scientists solve problems to how students construct models, explanatory models no longer only refer to just one type of scientific model, as previous research defined them.

In student learning, explanatory models can also refer to more complicated mental models that students construct to explain phenomena. Therefore, students’ explanatory models may not be the same as scientists’ explanatory models. Even though students may develop sophisticated explanatory models, it does not guarantee that they will construct explanatory models as powerful as those of scientists. Therefore, the purpose of student instruction should be to employ strategies to help students’ explanatory models to grow closer to scientists’ explanatory models.

In this dissertation, I define an explanatory model as a more complex and sophisticated mental model in light of Brown’s multidimensional framework (Brown, 1993, 1995a, 1995b; Cheng & Brown, 2010). In this framework, the explanatory model is regarded as an imagistic model involving the complex interaction between unseen elements, in which students visualize unobservable elements to explain why observable phenomena happen. Because the explanatory model is a more complex and consciously developed mental model, it involves more complex conceptual resources from students’ unconscious levels of knowledge about their presuppositions regarding the world and
ideas about causal relationships between interactive objects. Sometimes students use the models to integrate their conscious levels of knowledge about their learned verbal symbolic knowledge.

An example of a common explanatory model among students to explain how a battery makes the light bulb light: a battery squirts charges into the wire and causes the flowing of the charges to trigger the light bulb. In this explanatory model, the moving charge is not an element that can be observed. Students visualize the moving charge, make assumptions that the charge can be moved, stored, or used up, and add causal relationships that a battery can initiate the move of the charge to the light bulb.

Students derive explanatory models from their integration and organization of intuitive knowledge in a systematic and complex way to illustrate the causal relationships among unseen elements (Cheng & Brown, 2010). Through reasoning by using explanatory models, students can systematically examine and evaluate their pieces of knowledge. Cheng and Brown (2010) showed that without constructing explanatory models students may easily stick to one simple intuitive idea or some abstract terms and use them for all explanations for unfamiliar phenomena, or they may shift to using different intuitions to explain different phenomena without examining the coherence and consistency of their explanations. In this study, I asked students to develop explanatory models so as to better construct causal explanations of magnetic phenomena.

**Model-based learning.** Model-based learning refers to the approach of employing modeling in science learning, in which students are involved in a dynamic and recursive process of developing, evaluating, and revising mental models of the situation when they respond to a task (Gobert & Buckey, 2000; Halloun, 2011; Louca et al., 2011;
The objective of model-based learning is not to make a list of unrelated discrete information, but to develop internal integrated models that students can employ in their reasoning (Buckley, 2000).

This model construction process is similar to scientists’ model-based reasoning (Clement, 1989; NRC, 2007; Passmore et al., 2009). Clement (1989) found that the experts solved an unfamiliar problem by employing repeated model construction cycles, including generation, evaluation, and modification (GEM) cycles. Clement (2000) perceived that scientists’ and students’ successful model processes were similar, so the model construction cycles are used to facilitate students’ model evolution to remove their learning difficulties and move toward more adequate models (Clement, 2000, 2008a; Clement & Steinberg, 2002, 2008; Rea-Ramirez & Nunez-Oviedo, 2008; Steinberg, 2008).

Rea-Ramirez et al. (2008) maintained that the GEM cycle is a non-formal reasoning process, so it is possible for students to engage in it. Although some research already shows the success of using this modeling cycle on students (e.g., Clement & Steinberg, 2002, 2008; Steinberg, 2008), these studies usually demonstrated the essential role of teachers’ intervention, inasmuch as students are unlikely to construct coherent and consistent models by themselves, without teacher assistance. In these studies, teachers usually needed to provide analogies, confrontational questions, and discrepant events to facilitate students’ model construction.

In model-based learning, there are diverse ways to engage students in the process of model building. Next, I discuss three main ways to foster students’ model-based
Different ways to support model-based learning. Researchers have different perspectives on how to support students’ model-based learning. Figure 1 illustrates the scale from teacher-generated models to student-generated models.

**Figure 1.** This diagram shows the varying emphases of research. On the left end, the studies focus on the teacher generating models for students. On the right end, the studies focus on students generating their own models.

Teachers generate models for students. There is some research focusing on how to present models to students (Botzer & Reiner, 2005; Dedes & Ravanis, 2009; Justi, 2000; Sizmur & Ashby, 1997; Verhoeff, Waarlo, & Boersma, 2008) and how teachers can use some strategies, such as analogies or computer simulations, to help students understand the models presented (Baek, Schwarz, Chen, Hokayem, & Zhan, 2011; Thiele & Treagust, 1994; Treagust, Duit, Joslin, & Lindauer, 1992; Xie & Pallant, 2011). These researchers concentrated more on studying the teaching models and how these models should be delivered to the students or how different kinds of models (such as analogical models or scale models) can help students build and manipulate their mental models.
Harrison and Treagust (2000) recognized the problems of student-generated models, which are far from scientific models. They suggested that teachers should select analogies for students in order to facilitate the connection between the base analogy and the target model. Although teaching models should derive from students’ existing ideas (Dagher, 1995a; Gentner & Gentner, 1983; Gilbert et al., 1998b), in the research, teachers control the product and the process of model building. Teachers usually chose appropriate models and introduced them to students or negotiated them with students (Dagher, 1995b). In this way, students indeed learned with the models, but they did not have ownership of the models as with self-generated models.

**Teacher and student co-construct models.** Rea-Ramirez et al. (2008) proposed a model-based co-construction between students and teachers. During this process, the teacher and the students both contributed their ideas to build, evaluate, and modify the models. This approach is a compromise between only emphasizing teacher-generated models and only emphasizing student-generated models. The model construction is facilitated so that it progresses from simple initial models, which are evaluated and revised, to a series of more complex and sophisticated intermediate models, in order to eventually reach the final target models. In the process of co-construction, cognitive dissonance is used to foster small changes in the models. Analogies are used to build on students’ existing knowledge to construct and revise their models (Clement, 2008b; Clement & Steinberg, 2002, 2008; Steinberg, 2008). The process of co-construction focuses on how teachers can co-construct models with their students by offering the students appropriate analogies and producing appropriate cognitive dissonance.

**Students generate models.** Some researchers are more concerned with how
students might generate their own models. In some research, model construction is facilitated by text, interactive multimedia, or students’ observation and experiments (Acher, Arca, & Sanmarti, 2007; Buckley, 2000; Buckley & Boulter, 2000; Gobert, 2000; Louca et al., 2011). Students need to generate their models and regulate their reasoning during their interaction with materials that are intended to provide students with pieces of related information. Teachers only play the role of discussion facilitators without intervening in students’ model construction, and guide students to develop appropriate scientific models. The results of these studies point out that when a group of students is merely offered pieces of information, only a few of them will be able to engage in the model-building process or develop scientific models.

Boulter (2000) encouraged students to construct models in a child-centered questioning discourse. The results showed that the teachers needed to guide students to construct the appropriate models and lead the arguments in certain ways. Without the support of the teacher, Louca et al. (2011) also found that students encountered a barrier when moving from descriptive models, describing how something happens over time, to causal models, describing how an agent affects a physical process.

However, when asked to generate, evaluate, and modify their models to explain scientific phenomena, students are more likely to self-generate models with more coherence or explanatory mechanisms (Bamberger & Davis, 2011; Cosgrove, 1995; Maia & Justi, 2009; Schwarz et al., 2009; Wong, 1993a, 1993b). Thus, these self-generated models can be employed to advance students’ conceptual understanding, rather than leaving them with static representations of their ideas (Coll & Lajium, 2011; Coll & Taylor, 2005; Wong, 1993a, 1993b). Accordingly, without designed activities and guided
reasoning or discussion, students seem to have problems monitoring their own reasoning, not to mention constructing consistent and coherent models.

*The approach of this study.* As illustrated in Figure 1, I designed this teaching experiment to engage students in self-developing explanatory models for magnetic phenomena through the designed activities and the metacognition facilitating tools (including journal writing, group discussion, and metaconceptual modeling criteria). In the activities, students control the processes and products of model construction. The instructor does not contribute new ideas or information to the students’ reasoning processes, but helps students to clarify their problems and ideas and to keep them on task.

Jonassen, Strobel, and Gottdenker (2005) proposed that constructing models is more productive than using models in learning, because solving or answering conceptual questions requires learners to construct mental models as a foundation for prediction, inference, reasoning, and experimentation. Moreover, when students construct their own models, they have ownership of the knowledge, which is vital for making sense of abstract concepts and constructing knowledge. Thus, in this research I did not offer students any explanatory models to understand unfamiliar phenomena. Instead, I required the students to construct their own models through the scaffolding activities.

Research usually shows that without guidance, student-generated models are not much like scientific models. In the earlier clinical interviews about students’ model development, even though students may have the ability to construct explanatory models without metaconceptual awareness, their models were not coherent, consistent, or sophisticated (Cheng & Brown, 2010). Therefore, in this research I guided students through the GEM cycles to develop a series of progressive models from their initial
models to more coherent, consistent, and sophisticated explanatory models with the assistance of metacognition facilitating tools intended to help students reflect and monitor their reasoning.

In the next section, I discuss how different theoretical frameworks explain students’ knowledge structure. Then I explain the multidimensional framework (Brown, 1993, 1995a, 1995b; Cheng & Brown, 2010) I chose as the theoretical framework to design and conduct this study as well as the interpretive framework to analyze students’ conscious and unconscious levels of knowledge.

**Theoretical Frameworks of Students’ Conceptual Structure**

Previous research on students’ conceptions has focused primarily on students’ “misconceptions” (Fredette & Clement, 1981; Horner & Rubba, 1979). The misconceptions position usually emphasizes problems with students’ pre-knowledge and neglects the productive properties of students’ conceptions that can be a starting point for students’ scientific thinking and construction of scientific explanations.

Several major perspectives have been used to explain the nature of students’ knowledge structure and the mechanisms of students’ conceptual development. The first perspective is “theory-like knowledge.” Researchers (e.g., Driver & Erickson, 1983; Gopnik & Wellman, 1994; McCloskey, 1983; Vosniadou & Brewer, 1992; Vosniadou, Vamvakoussi, & Skopeliti, 2008) regarded students’ conception as theory-like and considered students’ conception to be consistent and coherent, so they usually tried to identify the similarities between students’ mental models and those of medieval scientists.

Another perspective is *fragmented knowledge*, which is contrary to theory-like
knowledge. Researchers (diSessa, 1988, 1993, 2008; Yates et al, 1988) regarded students’ knowledge as piecemeal and fragmented and considered students’ conception as lacking coherence and consistency, so they often tried to break down students’ knowledge to the most elemental level.

The third perspectives is the multidimensional framework, which Brown (1993, 1995a, 1995b; Cheng & Brown, 2010) proposed to incorporate these two different perspectives into a broader perspective that focuses on conscious and unconscious levels of knowledge as well as a coherent versus fragmented conceptual structure.

Theory-like knowledge. “Theory theory” (Brewer, 2008; McCloskey, 1983; Carey, 1985, 2009; Vosniadou & Brewer, 1992, 1994; Vosniadou et al., 2008; Wellman & Gelman, 1992; Wise, 1988; Wiser & Smith, 2008) is a perspective that deems students’ intuitive conception as theory-like, coherent, and consistent instead of fragmented. Theory theorists argued that students depend on some coherent and domain-specific naïve theories to explain their observed phenomena in their daily life, so before children have formal science education, they already possess coherent, intrinsic ideas about the world (Carey, 1988, 2009; Gopnik & Wellman, 1994; McCloskey & Kargon, 1988).

Theory theorists often draw analogies between scientists and students because both of them construct their theories based on the evidence available for them to predict and explain the world (Carey, 1988; Gopnik, 2003; Wellman & Gelman, 1992), or they draw analogies between the paradigm shift in science history and students’ conceptual change (Carey, 1988; Wiser & Carey, 1983). Some theory theorists believe that the development of students’ naïve theory is similar to the process of scientific discovery or a paradigm shift in science, so they compare students’ conceptions with medieval scientists
and try to find the similarities between them (McCloskey, 1983; McCloskey & Kargon, 1988; Wiser, 1988). Recognizing the similarities between medieval scientists and students, theory theorists usually suggested that conflict is the main element that causes students’ conceptual growth from their naïve theory to scientific theory. Teachers should confront students’ conceptions with anomalous data or alternative theories, and eventually substitute students’ conceptions for formal scientific theory (Chin & Brewer, 1993).

Students’ conceptions about force and motion are a common example for illustrating how theory theory perspective interprets students’ conceptions. Theory theorists perceived that impetus theory is employed consistently by students to explain the motion of the object in different contexts, such as the motion of a ball rolling on a table or the trajectory of a dropping ball (McCloskey, 1983; McCloskey & Kargon, 1988). For example, McCloskey (1983) found similarity between students’ naïve theory of motion and medieval scientists’ impetus theory. Both of them use impetus to explain the moving of the objects. They view impetus as a kind of energy or force stored in the moving object, which can run out by friction or gravity. Therefore, naïve theory is regarded as a natural cognitive process and outcome from the interaction with the physical world.

Impetus theory can also be applied to understand how novices explain the scenario of tossing a ball. When an object is thrown upward, the force inside the object will be dispatched by the force of gravity, so the object will gradually slow down. Then, when the object is at the peak of its arc, these two forces are equal; when the object starts to fall down, gravity is stronger than or overcomes the force of the object (McCloskey,
Vosniadou (1994, 2002b, 2007; Vosniadou et al., 2008) proposed framework theory to explain the profound similarities between students’ conceptions and medieval scientists’ theories to account for the deeper rationale of students’ naïve theory and inspect how their framework theory constrained their reasoning. In accordance with Vosniadou’s (1994, 2002b) point of view, students’ ontological and epistemological presuppositions are under the organization of framework theory, which is an explanatory framework to organize observed phenomena and constrain knowledge construction.

Framework theory is different from scientific theory because novices use it unconsciously. However, framework theory itself is coherently and consistently applied to knowledge construction. The only way to enable students to shift from their naïve conception to scientific theory is to gradually revise and replace the presuppositions of their framework theory (Vosniadou, 1994, 2007; Vosniadou et al., 2008).

Students’ conceptions about force and motion are a common example for illustrating how framework theory can be used to interpret students’ conceptions. According to framework theory, students’ conceptions about the force of moving or stationary objects can be categorized as several internally consistent and theory-like (Ioannides & Vosniadou, 2002). Ioannides and Vosniadou (2002) found that younger students used the concept of internal force, which is the internal property inherent in objects such as weight, to explain the motion of the object. Older children used the external force of the object, which is the acquired property of moving objects because of the pushing or pulling by other agents, to explain the motion of the object. Intuitive framework theory, which is the ontological presupposition that force is regarded as the
property of objects and the epistemological presupposition that the motion of objects needs explanation with regard to a causal agent, is embedded in students’ ideas about internal and external force on the objects.

**Fragmented knowledge.** Knowledge-in-pieces theorists argue that students’ intuitive knowledge from daily life experience is a fragmented collection of independent ideas that do not have coherence or systematicity as theories have (diSessa, 1988, 1993, 2006, 2008; diSessa, Gillespie, & Esterly, 2004; diSessa & Wagner, 2005; Hammer, Elby, Scherr, & Redish, 2005; Linn, Eylon, & Davis, 2004; Minstrell, 2001; Taber & Garcia-Franco, 2010; Wagner, 2010).

diSessa (1988) coined the term *p-prims* to represent these intuitive fragmented phenomenological primitives that deconstruct the knowledge of mechanics to the most elemental pieces from everyday interactions with the world, such as pushing, pulling, and throwing. P-prims are spontaneously activated when individuals explain phenomena. Students employ these p-prims in “coordination classes,” which are a “systematic collection of strategies for reading a certain type of information out from the world” (diSessa & Sherin, 1998, p. 1155). In line with the constructivist view, p-prims (diSessa, 1993) and coordination classes (diSessa & Sherin, 1998) are regarded as the components of students’ conceptual resources that help students construct their explanations for scientific phenomena (Hammer, 2000; Hammer et al., 2005).

Based on the fragmented knowledge perspective, students have different conceptions from scientists because students organize or activate their p-prims differently, not because they have inadequate conceptions. For instance, Ohm’s p-prim, which states that more effort begets more effect and that more resistance begets less effect, is
appropriate when it is applied to the concept of electrical current. However, when one applies Ohm’s p-prim to the falling of an object, one would think that a heavier object falls faster than a lighter object.

Another example is the intuitive idea of balancing, which is also one kind of p-prim (diSessa, 1993). Although students seem to employ the idea of balancing spontaneously to inappropriately explain the balance of force when an object is at the peak of its trajectory after being thrown, it is an essential concept for explaining the conservation of energy or momentum (diSessa, 2006). So, there is no problem with these p-prims or with intuitive thinking, but students’ application of these concepts presents obvious problems. Accordingly, in the process of developing expertise, students may add new or activate existing p-prims by focusing on different features or structures of objects, reorganize the priority of their existing p-prims, or integrate conceptual resources instead of replacing existing ones (diSessa, 1988, 1993; diSessa & Sherin, 1998).

Students’ ideas about force and motion are an area that illustrates how researchers can employ the fragmented knowledge perspective to interpret students’ conceptions. The example of tossing a ball illustrates how p-prims can be employed to decompose the impetus theory and explain the force and motion of the ball. In tossing a ball, the action between the hand and ball is usually not contemplated by novices because they assume that the hand offers force as a mover, which is a p-prim. Novices cue the intuitive p-prims continuous motion requiring continuous force and dying away to explain how a diminished upward force causes the gradual slowing motion of the ball. Therefore, novices conclude that when the force inside the ball overcomes the force of gravity, the ball goes up. They also conclude that when these two forces equal, the ball balances at
peak. Finally when the force of the ball gradually *dies away*, the gravity *overcomes* the upward throwing force, and the ball falls downward (diSessa, 1993).

diSessa (1988, 1993) admitted that people sometimes used impetus theory to explain phenomena related to motion in some contexts, but impetus theory is not a widespread theory of motion across individuals and across different contexts. Impetus theory can only explain some problems in some contexts, such as tossing a ball, but not in other contexts such as dropping a ball. It is also difficult for students to have a strong commitment to any particular theory-like explanation. Furthermore, diSessa thought that impetus theory was not a fundamental theoretical foundation of intuitive physics because impetus theory needs to be decomposed to fundamental intuitive pieces. He claimed that the different combination of students’ p-prims that focused on different features of the situation cause students to have different explanations for the same problems. So impetus theory is not the smallest primitive elements to explain students’ alternative conceptions and reasoning and it also oversimplifies students’ conceptions and reasoning processes.

**Multidimensional framework.** Brown (1993) proposed a multidimensional framework to bring these different perspectives into a larger framework that focuses not only on conscious and unconscious levels of conceptions, but also coherent and fragmented conceptual structures. In this multidimensional framework, students’ conceptions can be viewed as deriving from different levels—verbal symbolic knowledge, conscious models (including explanatory models), implicit models, and core intuitions. Verbal symbolic knowledge and conscious models represent students’ conscious levels of knowledge; the implicit models and core intuitions represent students’ unconscious and entrenched levels of knowledge.
According to Brown’s (1993, 1995a, 1995b; Cheng & Brown, 2010) clarification of the multidimensional framework, the components of verbal symbolic knowledge are discrete and usually can be abstractly represented by a phrase, formula, or concept map, such as defining power as the energy per time or the mathematical formula of a circuit. The conscious models are composed of the images of observable situations and entities, and explanatory models, which visualize unobservable elements, to explain why observable phenomena (e.g., wire connecting batteries and light bulbs) occur.

Thus, an explanatory model is an imagistic model involving complex interactions between unseen elements. For example, according to conscious model students use for explaining how a battery turns on a light bulb, the battery transmits current into the wire and causes the flow of the current to trigger the light bulb. In this model, the battery is the source sending out the current, and the light is the consumer of the current. When the current goes through the light, the amount of the current is reduced. In this conscious model, an explanatory model helps students visualize unobservable flowing current to explain an observable electric circuit. Although this is not the consensus model of scientists, it is an explanatory model that explains an observable phenomenon (the lighting of a bulb) by drawing on the causal interactions of unseen elements.

By contrast, implicit models and core intuition are automatically and unconsciously employed by the students. Implicit models refer to students’ intuitive ontological assumptions and beliefs about the world, such as the notion of heat as a substance, the earth as flat, or an electrical current resembling a water flow. Core intuitions usually represent the causal relationships between elements and can be unconsciously activated in different domains. For example, the battery is an initiating
causal agent and can therefore make things happen. Students’ conscious levels of knowledge are usually influenced by or built on their unconscious levels of knowledge.

Students’ conceptions about force and motion illustrate how researchers can employ the multidimensional framework to interpret students’ conceptions. In order to explain the observable scenario of a moving ball, students may develop a conscious model, which includes a hypothesized explanatory model stating how the observable force is exerted on the ball by the hand, how the force stored inside the ball enables it to move upward, and how gravity from the earth overcomes the force in the ball to pull the ball downward. This conscious model is similar to the McCloskey’s impetus theory.

In this model, the integrated verbal symbolic knowledge is the information about the existence of gravity. The implicit model here represents students’ intuitive assumptions about the world from their experience, such as the idea that a moving object needs to have force to remain in motion, or that force is like a substance that can be imparted to or stored in the object. This intuitive assumption here is emphasized in Vosniadou’s framework theory. Here, core intuition represents students’ intuitive causal relationships, such as one object working as an initiating agent that exerts force on the other object, or forces cancelling or overcoming each other. These intuitive causal relationships are emphasized in diSessa’s p-prim idea.

The previous empirical study, which explored how students use different conceptual resources to develop their explanations, demonstrates how students may involve core intuitions, implicit models, and verbal symbolic knowledge in their reasoning, but also how they had difficulty developing coherent and sophisticated explanatory models (Cheng & Brown, 2010). Simply using only the implicit model (e.g.,
the same things stick together) or core intuition (e.g., the magnet works as initiating agent to act on other objects) did not allow students to develop explanatory models to account for the mechanism underlying magnetic phenomena.

When students involved not only their intuitive implicit model (one’s presuppositions or beliefs about the world) and core intuition (causal relationships between interactive elements) but also integrated and organized intuitive knowledge in a systematic and complex way to illustrate the interaction among the hypothesized elements, they were able to develop explanatory models for magnetic phenomena. The common example is that hypothesizing moving elements in the magnet or from the magnet to other objects allowed students to develop explanatory models to explain the different strength of different parts of the magnet and the attraction between the magnet and other objects.

However, even though students may develop explanatory models to explain certain magnetic phenomena, most still had problems revising these models into coherent and sophisticated explanatory models to account for all magnetic phenomena. It was found that if students can further integrate their verbal knowledge into their construction of explanatory models, they may develop more consistent, coherent, and sophisticated models. For example, in the previous study (Cheng & Brown, 2010), one student used the abstract idea of the wave-like current in the ocean passing over a long distance, to construct an explanatory model for the abstract idea of magnetism. By visualizing magnetism as wave-like energy passing across a longer distance, the student was able to explain how the magnet in the earth could influence the compass, instead of imagining a bubble-like energy encompassing the magnets, which only can influence the object for a
short distance.

Here, using verbal symbolic knowledge could help the student consider the form of energy in a more abstract form, e.g., wave-like instead of bubble-like, assisting her in making sense of the unfamiliar phenomena. Nevertheless, simply using abstract verbal symbolic knowledge does not help students to develop explanatory models. So, when students used the abstract term magnetism to explain all of the phenomena of magnetism without considering and organizing the causal relationships and assumptions about the nature of magnetism, they would fail to construct explanatory models.

**The theoretical frameworks adopted in this study.** The multidimensional framework (Brown, 1993, 1995a, 1995b; Cheng & Brown, 2010) underlying the design of this research informs my work in considering students’ conceptual resources in model construction. This framework is in line with constructivism, emphasizing the positive and productive aspect of prior knowledge in students’ learning. When students learn or construct their new knowledge, their reasoning involves their existing knowledge and intuition. Hence, activating or reorganizing the proper existing knowledge or intuition will help students to further construct more sophisticated knowledge.

Adopting the multidimensional framework provides me a more comprehensive interpretive framework to analyze and distinguish different levels of conceptual resource, instead of only focusing on one aspect of the conceptual resources. It also offers me a more dynamic view to examine how students involve, reorganized, and revise their different levels of knowledge systematically and coherently to construct explanatory models, as well as the dynamic relationships between the conscious and unconscious levels of knowledge (Brown & Hammer, 2008). The multidimensional framework helps
to clarify how model construction requires students to integrate pieces of information about the structures, functions, and interrelations between objects. Students’ conceptual resources can be interpreted and analyzed at the micro level in order to understand how students’ different levels of knowledge can influence or contribute to the construction of their explanatory models.

Owing to the problems in developing self-generated explanatory models, fostering students’ metacognition in their reasoning is perceived as a possible solution to these problems, as considering students’ metacognition determines whether students can regulate their own reasoning to develop coherent models. The following literature illustrates the importance of metacognition in model construction and reasoning.

**Metacognition**

Metacognition is one important factor influencing students’ reasoning. Researchers have argued that if students can monitor and control their own thinking, it may help them to involve and select appropriate conceptual resources in their reasoning processes to construct scientific models (Beeth, 1998; Clement & Steinberg, 2008; Grotzer & Mittlefehldt, 2012; Schwarz & White, 2005; Stewart et al., 2005; Verhoeff et al., 2008; White & Frederiksen, 2000; White et al., 2011; White et al., 2009).

Metacognition is recognized as an important aspect of expertise, and high-achieving students usually have greater metaconceptual awareness (Hartman, 2001). Some of students’ learning difficulties in connection with scientific concepts are due to a lack of metaconceptual awareness of entrenched presuppositions and beliefs. Students do not recognize the hypothetical properties of their beliefs and presumptions about the
world; they do not, consequently, examine these assumptions, but they believe their theories adequately convey the operations of the natural world (Vosniadou, 1994; 1999).

**Definition of metacognition.** Metacognition is generally defined as “thinking about thinking” (Flavell, 1979) and consists of two aspects: metacognitive knowledge (i.e., knowledge about cognition) and metacognitive skills (i.e., regulation of cognition) (Brown, 1987; Flavell, 1976). The theory of metacognition is studied and applied in different fields, including text comprehension (Garer, 1987; Pascarella & Pflaum, 1981; Schmitt, 1988), memory (Flavell, 1971; Nelson & Narens, 1994; Nelson, Narens, & Dunlosky, 2004), problem solving (Antonietti, Ignazi, & Perego, 2000; Ge, Chen, & Davis, 2005; Kauffman, Ge, Xie, & Chen, 2008), decision making (Meichenbaum, Burland, Gruson, & Camerson, 1985), and the control of learning (Baird, 1986; Case, Gunstone, & Lewis, 2001). Due to the different purposes of these studies, the meaning of metacognition shifts depending on the research conducted. These studies usually focused on how metacognition can enhance the learning processes and outcomes.

Some researchers emphasized the role of metacognition or employ metacognitive strategies in enhancing specific scientific reasoning, such as visualization (Gilbert, 2005, 2008), analogy (Mason, 1994), model construction (Hogan, 1999, 2001; Schwarz et al., 2009; White & Frederiksen, 1998), and conceptual change (Beeth, 1998; Georgiades, 2000; Hennessey, 1999, 2003). These researchers discussed metacognition by applying the concept to three areas: completing the task, learning, and reasoning. In this study, *metacognition* refers to learners’ abilities to monitor and control their own cognitive process for model building.

**Different levels of metacognition.** Metacognition brings individuals to conscious
awareness of their thinking, allowing them to reflect, monitor, evaluate, and control that thinking (Brown, 1987; Flavell, 1979). Nevertheless, Veenman (2005) argued that there are certain metacognitive activities that can be performed without much awareness. Metacognition regulates the cognitive process at different levels of consciousness (Efklides, 2008; Rouiller, 2005). Swartz and Perkins (1989) distinguished four levels of thought according to increasing levels of metacognition. The first level is referred to as unconscious or tacit thought, which is where decision-making without consideration occurs. The next three levels all deal with conscious thought. They referred to it as (a) conscious awareness of thinking, (b) strategic control of thinking for better outcomes, and (c) reflection on thinking to contemplate how to progress and improve.

In the process of model construction, metacognition can intuitively and spontaneously reside within the individual’s reasoning process. Expressing mental models may cause individuals to change their original models spontaneously (Gilbert et al., 1998a) and evaluating models may occur, in part, intuitively (Clement, 2008b). Therefore, some reasoning can happen unconsciously without intentional control. Although the reasoning process can occur spontaneously, the process can also be more precisely manipulated. Thus, students can develop more coherent, consistent, and sophisticated models (Grotzer & Mittlefehldt, 2012; Schwarz & White, 2005; Stewart et al., 2005).

Intuitive metacognition is not enough to lead students toward more scientific reasoning. In Cheng and Brown’s (2010) study, for instance, one of the students used the intuitive assumption “same thing[s] sticking together” to make sense of the phenomenon of magnetism. She consistently applied her explanations to different contexts; however
she did not control and evaluate her reasoning consciously enough. Her explanation was not sophisticated and coherent enough to explain all the phenomena. Accordingly, the strategies that can help students to externalize, monitor, and control their metacognition actively in their learning are necessary, thereby being advocated in this study.

**Metacognitive strategies in model construction.** How metacognition should be taught is perceived differently. In most of the literature, researchers only emphasized its importance without actually teaching it to students—such as through group discussion devoid of any metacognitive strategies (e.g., Clement & Steinberg, 2008; Verhoeff et al., 2008; Vosniadou, Ioannides, Dimitrakopoulou, & Papademetriou, 2001). However, some researchers thought that metacognition should be taught explicitly in the classroom (e.g., Beeth, 1998; Georgiades, 2000; Grotzer & Mittlefehldt, 2012; Schwarz & White, 2005; Stewart et al., 2005; White et al, 2011; White & Frederiksen, 2000, 2005; White et al., 2009; White & Gunstone, 1989). Researchers adopted two general approaches to enhance students’ metacognition in model construction: collaboration and prompts.

**Collaboration.** The researchers I discussed above adopted collaboration as an approach to facilitate students’ metacognition implicitly and explicitly. Collaboration is regarded as one of the methods to develop students’ metacognition in model construction (e.g., Coll, France, & Taylor, 2005; Hogan, 1999, 2001; Schwarz & White 2005; White & Frederiksen, 1998). Collaboration functions to encourage students’ metacognitive knowledge and skill in several ways.

Primarily, collaboration encourages students to externalize and reflect on individual ideas. Interaction with others helps students to articulate and evaluate their reasoning process, thereby enhancing their metacognitive skills (Hogan, 1999). Larkin
(2006) found that group interactions offer opportunities for students to clarify and test their own ideas and others’ ideas. Responses from group members prompted individuals to clarify and modify their own thinking. Group interactions helped students to become aware of their own and others’ thinking. Interacting with others provoked the need for students to reflect on their own thinking and provided opportunities to elaborate and practice their metacognitive strategies, as well as to get feedback on their own cognitive process. In short, collaboration with others facilitated awareness of the students’ own thinking processes (Wertsch, 1978).

In addition, collaborative group interactions actuate individual cognitive dissonance to trigger students to search for more satisfying explanations or more effective strategies (Brown & Palincsar, 1988; Hogan, 1999; Mercer, 2008). Some collaborative approaches, such as think aloud together (Hogan, 1999), were designed to encourage students to prompt each other to enhance their reasoning. Peer interactions can also be employed as a method to foster metacognitive regulation. They offer conditions for students to verbalize their thinking explicitly and consciously, so social interaction can increase the active confrontation necessary in order to raise the consciousness of their metacognitive regulations (Rouiller, 2005). Moreover, peer collaboration is beneficial to the tasks that demand provoking new insights, stimulating conceptual shifts, and promoting development of deep knowledge structure (Damon & Phelps, 1989). Collaboration can stimulate students to elaborate on and integrate knowledge in a new ways (Brown & Palincsar, 1988) and encourage students to build on each others’ ideas to co-construct knowledge (Crook, 1994).

Another function is the internalization of ability. Brown (1987) stated that through
interaction with others individuals would internalize the capability of the control of cognition, which is similar to Vygotsky’s (1978) perspective that the interpersonal nature of thought is gradually transformed to an intrapersonal one. According to this notion, individuals can internalize group reflective processes and further generalize and apply them in new contexts (White & Frederiksen, 1998). Thus, collaboration fosters a learning environment in which students can illustrate, defend, and reflect on their own thinking in order to be aware of, monitor, and evaluate their own and others’ thinking.

**Prompts.** Explicit approaches to promote metacognition also involve the use of prompts by teachers, peers, or in reflective journals. Some prompts are more general and just ask students to think about their thinking (e.g., Hennessey, 1999; Parker, 2006) or to examine the consistency between their data and developed models (e.g., Baek et al., 2011; Schwarz et al., 2009; Windschitl et al., 2008a, 2008b). Other prompts are more specific and are designed to assist students to reflect on their reasoning according to scientific criteria (e.g., Beeth, 1998; Grotzer & Mittlefehldt, 2012; Schwarz & White, 2005; Stewart et al., 2005; White et al., 2011; White & Frederiksen, 2005; White et al., 2009; White & Gunstone, 1989).

Even though prompting students to think scientifically is one of the common methods for promoting metacognition, the rationales for developing these specific prompts are different based on the perspectives and purposes. These prompts usually include various criteria to scaffold students’ evaluation of their ideas in terms of the process of scientific inquiry (White & Frederiksen, 1998, 2005; White & Gunstone, 1989), the standards of good models (Schwarz & White, 2005; Stewart et al., 2005; White, Collins, Frederiksen, 2011; White, Frederiksen, & Collins, 2009), and the status
of their notions (Beeth, 1998; Grotzer & Mittlefehldt, 2012).

Researchers developed these prompts based on different rationales. The first two kinds of prompts are developed based on the researchers’ assumptions about the characteristics of scientific models and inquiry process, in which students are expected to gradually revise their ideas toward scientific ideas. The last type of prompt, based on assumptions about the similarity between scientific revolution and students’ conceptual change, requires students to discard their ideas and accept scientific ones.

However, the rationale and the approaches of using the last kind of prompt are criticized by certain researchers. Beeth (1998) as well as Grotzer and Mittlefehldt (2012) encouraged students to evaluate their models for intelligibility and plausibility. This approach is derived from Posner, Strike, Hewson, and Gertzog’s (1982) conceptual framework based on the analogy between the scientific revolution and individual students’ conceptual evolution. Some researchers further applied this idea as an instructional strategy to assist students in discarding their models and accepting scientific models (Beeth, 1998; Grotzer & Mittlefehldt, 2012; Hewson & Hennessey, 1992; Hewson & Thorley, 1989). Researchers using this perspective view the structure of students’ naïve conceptions as theory-like and believe that students need to be confronted or convinced to drop their existing theory and accept the new theory.

dıSessa (2006) argued that Posner et al.’s (1982) framework only involved an epistemological perspective but did not involve psychological reality. Hence, his criticism was that this framework was not for the scheme of instruction to promote conceptual change. Introducing this framework explicitly in the curriculum was also inappropriate. Furthermore, if students’ idea were examined through the multidimensional framework
(Brown, 1993, 1995a, 1995b) (which offers an interpretation for students’ different levels of knowledge), this metacognitive strategy only supports students in monitoring their conscious level of knowledge to replace their existing theory with a new one. However, it does not encourage students to examine how they involve different levels of conceptual resource in their reasoning or analyze how they formulate their existing theories.

Therefore, in this study, I designed the metacognition facilitating tools (including journal writing, group discussion, and metaconceptual modeling criteria) to help students be aware, monitor, and evaluate their conscious and unconscious levels of knowledge in the multidimensional framework (Brown, 1993, 1995a, 1995b) in order to better use these tools to develop coherent and sophisticated explanatory models for magnetic phenomena.

**Prompt with metaconceptual modeling criteria in this study.** In this review of students’ models I highlight the important role of metacognitive strategies in enhancing students’ metacognition in model construction. When students are asked to think, verbalize, and argue their thinking explicitly and use scientific criteria to evaluate their inquiry processes or their models, it enhances students’ cognitive capacities with regard to their reasoning. Although the importance of metacognition has been verified in these studies, the mechanism of the metacognitive processes—which facilitates model building—has not been so thoroughly studied.

With the intention of reducing students’ intuitive or random shifting between different ideas or sticking to specific ideas without awareness, an approach to facilitating students’ cognitive process is necessary for students to monitor and control both the direction of building and the revision of their models. Asking students to only reflect on
their models or to record the progress of their own thinking is not enough to construct a coherent and sophisticated explanatory model. Hence, in this study, besides asking students to discuss and record their ideas, the following metaconceptual modeling criteria were developed to help students monitor, evaluate, and revise their models and control the changes. In order to support students in their construction of explanatory models by using different levels of conceptual resource, it is essential to facilitate their use of criteria for evaluating explanatory models, thereby not only representing and externalizing their notions, but also monitoring and controlling their reasoning processes.

By examining the process of scientists’ model construction (Clement, 1989, 1994; 2003; Nersessian, 1992, 1999, 2002, 2008) and students’ model construction (Cheng & Brown, 2010; Clement, 2008b; Rea-Ramirez et al., 2008; Williams & Clement, 2006), some criteria can be developed to help students construct coherent and sophisticated explanatory models in this study. Through reflection on the following criteria, students are expected not only to activate their existing related knowledge in order to construct explanatory models, but also to revise or modify their models through reflection. I proposed four criteria—visualization, explanatory power, predictive power, and consistency—as the metaconceptual modeling criteria for students to use in discussing, evaluating, and refining their models in the pilot study. Then, I chose two criteria—visualization and explanatory power—to implement in the main teaching experiments.

Visualization. Visualization is applied by scientists as a way to interpret and explain scientific phenomena and to offer insights in a significant aspects of scientific thinking (Al-Balushi, 2009; Gooding, 2004, 2006), but it is usually regarded as being
difficult for novices to understand and use to explain hidden and non-observable mechanisms at the microscopic level (Al-Balushi 2009; Chiou & Anderson, 2010; Gilbert, 2005, 2008; García-Franco & Taber, 2009; Hesse & Anderson, 1992).

The visualization of unseen causal entities and their causal relationships has been stressed as significant in the development of explanatory models (Clement, 1989, 2008a, 2008b; Gilbert 2005, 2008; Harlow, 2010). Clement (1989, 2008b) regarded explanatory models as hypothesized qualitative models to explain the causal relationship between the hidden structures under the systems. Explanatory models should have explanatory and predictive power for the phenomena in question. Merely presenting predictions based on analogies or extreme cases is not deemed as creating an explanatory model, because these predictions lack explanations for the causal mechanisms of events (Clement, 2008b). Hence, in order to construct explanatory models, students need to integrate their pieces of existing knowledge about the underlying structures and causal mechanisms to construct powerful explanatory models.

As Cheng and Brown (2010) found, students face some difficulties in using their own reasoning to construct explanatory models. Students may not feel the need to visualize the unseen elements and causal relationships underlying the phenomena to construct explanatory models; they would rather use abstract terms or intuition to explain all phenomena to avoid constructing their explanatory models. Moreover, Gilbert (2005, 2008) claimed that students have difficulty in explaining the phenomena in submicroscopic and symbolic levels. Students may identify macroscopic phenomena and symbolic levels of representations, but they do not have an understanding of the submicroscopic level.
Thus, it is necessary to prompt students to metacognitively consider the hidden and non-observable mechanisms underlying the phenomena. With a view toward constructing powerful explanatory models, students in this study are required to examine whether their models visualize unobservable elements in order to explain both observable phenomenon and the causal relationships or interactions among these elements.

*Predictive and explanatory power.* Models are judged by how well they explain observations and how well they predict new findings (American Association for the Advancement of Science, 1993; Norman, 1983; NRC, 2010; Stewart et al., 2005; Vosniadou, 2002a). Cheng and Brown (2010) found that most students use different and unrelated explanations to account for different phenomena. Even when students sometimes developed one explanatory model to explain a single phenomenon, these models were not applied to explain other phenomena. Also, no students used their existing models to predict new phenomena. These students, when asked to predict new phenomena, usually randomly guessed without drawing on their previously developed models. Thus, one of the criteria should include asking students to explicitly examine the predictive and the explanatory power of their models. According to this criterion, students are required to ask themselves whether this model could predict new phenomena and explain all available findings or could predict and explain more phenomena than other models.

*Consistency.* The consistency between ideas has also been proposed as a criterion for students to use to evaluate their model construction (Halloun 2004; Schwarz & White, 2005; Stewart et al., 2005). With the intention of specifically evaluating explanatory models, the consistency criterion is further defined as *internal consistency* to examine the
logical connection between the components in their models and external consistency to examine the consistency between their models and other ideas.

Children’s knowledge or explanations are regarded as lacking coherence and consistency by some researchers (diSessa et al., 2004; Rahayu & Tytler, 1999; Straatemeier, van der Maas, & Jansen, 2008). These studies also revealed that some students develop inconsistent and incoherent explanations for unfamiliar phenomenon without noticing or articulating these problems in their explanations (Cheng & Brown, 2010). Using the criterion of internal consistency prompts students to consider whether their ideas in the models are logically connected. Students are required to explicitly examine whether the components or ideas in their models logically connect or logically fit with each other without contradiction.

Using the criterion of external consistency prompts students to ponder whether their models are consistent with ideas that are external to their models. This criterion can enable students to reflect on their models to look for consistency and to help them incorporate their appropriate existing knowledge into their explanatory models. Students are required to explicitly inspect whether their models are consistent with prior knowledge and experience and their assumptions about the world. The reflective questions that students are required to employ to examine their model construction are in Table 1.
Table 1

*Reflective Questions to Facilitate Model Construction and Revision*

<table>
<thead>
<tr>
<th>Criteria for reflection of explanatory models</th>
<th>Reflective questions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Visualization</td>
<td>Can this model explain the hidden and non-observable mechanisms and the cause and effect underlying the observed phenomenon?</td>
</tr>
<tr>
<td>Predictive power</td>
<td>Can this model more accurately predict the phenomena?</td>
</tr>
<tr>
<td>Explanatory power</td>
<td>Can this model better explain all findings?</td>
</tr>
<tr>
<td>Internal and external consistency</td>
<td>Do the components in this model logically connect without contradiction? Is this model consistent with what you already know or experience and with your assumption about how the world works?</td>
</tr>
</tbody>
</table>

The way to employ the above metaconceptual modeling criteria goes beyond asking students to reason carefully and systematically. It tends to be more specific in encouraging students to evaluate their models by using these criteria and revising their models in order to meet these criteria. Teachers can employ these criteria in individual and group model construction to encourage students to become autonomous learners and to use these criteria spontaneously in their own reasoning.

In this research, my purpose for using these criteria as a metacognition facilitating tool is to introduce the students to the characteristics of explanatory models and to monitor and control their inquiry processes in order to construct coherent and sophisticated explanatory models. I do not expect students to give up existing knowledge or theories and to accept another new theory according to metaconceptual modeling criteria. These criteria tend to encourage students to use proper conceptual resources to construct and revise their models and to explain hidden and non-observable processes.
underlying magnetic phenomena.

Furthermore, I do not expect students to create scientific models as scientists but to construct explanatory models that may be close to scientific models or have the power to explain unfamiliar phenomena. Therefore, students may have the ability to explain unfamiliar events when they are learning new science topics in school.

Chinn and Malhotra (2002) compared simple forms of scientific inquiry as done in school and authentic scientific inquiry that scientists do and found discrepancies between the two. They suggested that students’ inquiry activities should include more features of authentic scientific inquiry. One of the differences in cognitive processes they identified is the development of theories. Scientists construct and revise theoretical models by hypothesizing underlying mechanism with unobservable entities, such as molecules or magnetic field. However, students’ inquiry tasks in school only focus on either observing empirical phenomena, or doing experiments to understand theories provided to them, instead of constructing underlying theoretical models. When theories are only presented to students, students do not obtain experience in constructing theoretical explanations. Therefore, the strategies adopted in this teaching experiment intend to offer students’ experiences of developing scientific explanations, which is considered a more complex and authentic scientific inquiry.

Using collaboration and prompts in this research. In this study, I adopted collaboration strategies and prompts with metaconceptual modeling criteria in order to facilitate students’ metacognition to construct explanatory models. White and Frederiksen (1998) proposed that reflective peers and self-assessment are two components that facilitate the students’ ability to understand complex phenomena. Students need to
participate in explicit reflective social processes so that they can observe how their own and others’ thinking in the process of inquiry and modeling are perceived from different perspectives. Through this social process, students should be able to internalize reflective skills, such as being systematic and inventive.

In light of the possible advantage of employing collaboration strategies and prompts in developing students’ reasoning, I have integrated these two components to facilitate students’ metacognition for model construction. Using collaboration and prompting together facilitates students’ thinking in a reflective way through questioning each other and themselves. In this research, I integrated collaboration at the stage of developing the best group explanations for magnetic phenomena and evaluating and revising their explanations based on the metaconceptual modeling criteria.

I employed the metacognition facilitating tools (including journal writing, group discussion, and metaconceptual modeling criteria) to promote students’ metacognition. These tools not only require students to think about their thinking process, but they also require students to reflect on their models in light of metaconceptual modeling criteria. The metacognitive journal requires students to record their own thinking processes and the reasons behind these processes and changes. The metaconceptual modeling criteria require students to reflect on their models according to these criteria for model construction and revision.

In summary, in this study, students’ model construction will be facilitated by encouraging students to involve their existing intuitive or learned knowledge to explain unfamiliar phenomena with the assistance of metacognition facilitating tools to actively monitor and control their cognitive reasoning process.
Chapter 3

Methodology

The Rationale of the Study Design

Cheng and Brown (2010) discovered the difficulties involved in third- and sixth-grade students using different levels of conceptual resources to construct explanatory models. They showed the disconnection between students’ abstract verbal symbolic knowledge and their intuition. Only one of the six students in the study could construct coherent and consistent explanatory models throughout several activities. One of the distinctions between this exemplary case and other cases is that this student could consciously involve her metacognition in her reasoning to spontaneously criticize and revise her explanatory models to account for magnetic phenomena.

Based on previous research about the positive impact of metacognition in model construction, in this research I hypothesized that encouraging students to explicitly use their metacognition may help them to control and monitor their cognitive processes so as to activate or reorganize appropriate conceptual resources to develop sophisticated and coherent explanatory models. The following section illustrates the methodological foundation of the design of this study.

Methodological perspective. In this research I adopted teaching experiment methodology, which is usually employed to investigate students’ learning processes and to develop instructional theories to explain and improve educational processes (Cobb, Confrey, diSessa, Lehrer, & Schauble, 2003; Design-Based Research Collaborative, 2003; diSessa & Cobb, 2004; Engelhardt, Corpuz, Ozimek, & Rebello, 2003). In the teaching
experiment, students’ knowledge-construction processes are facilitated by teachers or other instruments, such as software or model-eliciting activities. The main goal of the teaching experiment is to understand the nature of developing ideas as individuals or in groups (Lesh & Kelly, 2000). Teaching experiments involve more than describing the successful state of knowledge. They should explore the mechanisms and processes of the development, and the interaction among students or between students and teachers. They can also facilitate and investigate conceptual and ability development (Lesh & Kelly, 2000).

The teaching experiment derives from the clinical interview as an exploratory tool to investigate students’ knowledge and reasoning. It is also a conceptual tool for researchers to organize their scaffolding activities and interventions to encourage students to revise their conceptions (Engelhardt et al., 2003; Komorek & Duit, 2004; Steffe, Thompson, & von Glaserfeld, 2000). The teaching experiment can be used to explore students’ conceptual progress with intervention to change students’ conceptions, whereas the clinical interview is for exploring students’ current conceptions without the intention of changing them (Engelhardt et al., 2003; Steffe et al., 2000).

Moreover, the teaching experiment methodology is also a way to facilitate students’ reasoning at a meta-level. Komorek and Duit (2004) proposed that the questions posed by instructors can let students reflect on their own thinking at a metalevel, and the questions as well as the flexibility in the discussion among the students will stimulate them to discuss their reasoning at this meta-level so as to monitor their own and others’ reasoning. In the current study, the teaching experiment provided the context in which I investigated the dynamics of students’ knowledge construction when they interacted with
the material, other students, or the instructor, which helped me to explore the students’ reasoning at the meta-level and the micro-level.

Using clinical interviews, Cheng and Brown (2010) explored how students used their existing knowledge and intuition to make sense of abstract ideas of invisible magnetic forces and the difficulties of model construction. Their results showed that even though students employ their intuition or familiar knowledge to construct explanatory models, it is not guaranteed that students will construct a coherent, consistent, and sophisticated explanatory model. Thus, my objectives in this research using teaching were different. In the present study I aimed to understand how students developed and revised their explanatory models as well as monitoring and controlling their reasoning with the help of metacognition facilitating tools.

The rationale of the activities and strategies. The literature review in Chapter 2 provided the foundation for my design of this study. It offered the rationale of encouraging students to self-develop explanatory models to better explain scientific phenomena with the assistance of the metacognition facilitating tools (including journal writing, group discussion, and metaconceptual modeling criteria). It also justified my rationale of adopting the multidimensional framework (Brown, 1993, 1995a, 1995b; Cheng & Brown, 2010) as a theoretical framework to design and interpret this study.

In order to better develop explanatory models, I embedded the major patterns of model construction cycles—generation, evaluation, and modification—in the design of the activities. The predict-observe-explain (POE) approach, group discussion, and journal writing facilitated these cycles of model construction. On the basis of the multidimensional framework, I designed the sequences of the activities by considering
student intuition and existing knowledge in order to facilitate students’ cognitive process to construct explanatory models. Cheng and Brown (2010) showed that students appear to have problems in thinking about the causal relationships inside and outside of the magnets. Therefore, I developed the following activities to enable students to involve their intuition and existing knowledge to contemplate what is inside the magnets and connect that with the phenomena outside the magnets.

I expected students to obtain knowledge related to magnetism by participating in the activities and discussion with others, so I did not offer students information related to magnetism. My responsibilities were to guide students to follow the process of POE, record their thinking, and facilitate their metacognitive processes. Students needed to construct their explanatory models from their existing knowledge, including previously learned knowledge and experience, which may have helped them to generate analogies to explain unfamiliar phenomena. The discrepant events, such as the conflicts or discrepancies between students’ ideas, or among students’ prediction and observation, were intend for facilitating mental dissonance in order for students to be able to revise or change their models.

Although model building can help students engage in metacognitive processes (Jonassen et al., 2005), students’ metacognition should be scaffolded toward more scientific ways of thinking. In this study I hypothesize that if students reflect on their explanations by using scientific criteria, they will be able to employ appropriate conceptual resources to develop and revise their existing ideas to coherent and sophisticated explanatory models for magnetic phenomena. Therefore, I explicitly encouraged students in the fully scaffolded groups to reflect on their explanations with
metaconceptual modeling criteria; I asked students in the partially scaffolded group to reflect on their explanations, but did not offer them metaconceptual modeling criteria. Comparing scaffolding with and without metaconceptual modeling criteria allows me to inspect how reflection on scientific criteria enhanced students’ model building.

Pilot study. In the pilot study, the teaching experiment included five activities. I instructed students to reflect on their explanation by using four criteria—visualization, explanatory power, predictive power, and consistency. Owing to the high dropout rate after the third activity and the lack of continual engagement in a series of activities during afterschool time, I reduced the number of activities to three (M1: Two Magnets Activity, M2: Cutting Magnet Activity, and M3: Metal Bars Activity), and the number of criteria to two (visualization and explanatory power).

In the main study, I selected these three activities according to whether they could help students to activate useful conceptual resources to assist them in developing explanatory models. I arranged the M1: Two Magnets Activity as the first activity because in the pilot work it helped students to activate their previous experiences and ideas about how two magnets interact. In the pilot work, the M2: Cutting Magnet Activity helped students to hypothesize unseen elements to develop their models to account for observable phenomena. The M3: Metal Bars Activity helped students to develop or further apply their models to account for how the magnet acts on other materials. By contrast, in the two excluded activities, in which students first stroked metal bars and then the test tube containing iron filings or observed the pattern of iron filings over a bar magnet, students spent more time and energy in discussing the problems or discrepancies in their observation instead of devoting their efforts to developing their explanations.
In the main study, I selected these two criteria according to whether they could help students revise their ideas to generate more sophisticated and coherent explanatory models. I chose the criteria of visualization and explanatory power because students in the pilot study more often revised their explanations when considering these criteria than when considering the others. When reflecting on the criteria of predictive power and consistency, students usually claimed their explanations met these criteria without revising their ideas.

**Research Design**

The purpose of the research is to investigate the detailed processes of how promoting metaconceptual evaluation facilitates students’ model development to explain magnetic phenomena. This research is composed of two major intertwined parts. The first is the processes of students’ model construction. The second is how encouraging metacognition can facilitate these processes.

In this teaching experiment, students observed magnetic phenomena, kept metacognitive journals to record their explanations, and held facilitated discussions (both fully and partially scaffolded groups). During the group discussion, all students discussed their ideas with others, selected or developed group consensus explanations, and compared their current group explanations with their previous ones. In addition, only the fully scaffolded groups were explicitly encouraged to reflect on their explanations with specific metaconceptual modeling criteria. The teaching experiment was implemented as individual and small group activities instead of whole classroom activities in order to study individual reasoning processes. Figure 2 shows how the metacognition facilitating
tools were used by the fully and partially scaffolded groups.

<table>
<thead>
<tr>
<th>Metacognitive Journals</th>
<th>Group Discussion</th>
<th>Metaconceptual Modeling Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>Discussion with others</td>
<td>Selecting or developing a group consensus explanation</td>
<td>Comparing current group explanation with previous explanations</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Partially scaffolded groups</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Fully scaffolded groups</th>
</tr>
</thead>
</table>

*Figure 2.* This diagram shows the metacognition facilitating tools used in this study. Both partially and fully scaffolded groups were involved in the first four, while only fully scaffolded groups were explicitly required to use the metaconceptual modeling criteria of visualization and explanatory power.

The participants, the role of the researcher, the metacognition facilitating tools (including journal writing, group discussion, and metaconceptual modeling criteria), the pre- and post-instructional interviews, and the teaching experiment are illustrated in the following section.

**Participants.** I recruited 11 fifth grade students from public schools near a large Midwestern university. Based on students’ availability, I assigned them to two small groups in the fully scaffolded (FS) groups (Frank, Felix, and Freddie in the first FS group; Finn, Faye, and Fiona in the second FS group) and two small groups in the partially scaffolded (PS) groups (Pearl and Peggy in the first PS group; Paul, Patty, and Paige in the second PS group). I implemented the teaching experiment in small groups instead of in their regular classrooms in order to study individual reasoning processes.
I selected fifth grade students on the basis of three criteria. First, the design curriculum asks students to think about microscopic phenomena and their thinking processes, which are more appropriate for upper elementary school-aged children. Second, in the local district, fourth and seventh grade students learn topics related to magnetism in school, so fifth-grade students have observed some phenomena about magnetism and have existing knowledge about magnetism. The third was a practical reason: Fifth grade students in the local district are easier to recruit than other higher grades of students in the afterschool program.

In this study, students and parents received and signed consent letters to voluntarily participate in this research. The participating students filled out a self-report inventory, a Junior Metacognitive Awareness Inventory (in Appendix A) in the pre-interview, and their teacher filled out teacher ratings forms independently (in Appendix B). These two metacognitive instruments were designed by Sperling, Howard, Miller, and Murphy (2002) to assess students’ metacognition about their learning in general. I also asked students to evaluate their performance in science class as above average, average, or below average at the end of the pre-interview.

The participants in this study had diverse science backgrounds. First, owing to the problem of recruiting enough participants from the same school, the participants in these studies came from three different schools. Students in the two fully scaffolded groups (FS) and the first partially scaffolded (PS) groups came from the same school, so they were evaluated by the same teacher. Students in the second PS group were from two different schools, but they attended the same after-school program, so they were also evaluated by the same teacher. Second, although some students were recruited from the same school,
they were taught by different science teachers in fourth grade when they learned the unit about magnets. Table 2 uses symbols to indicate the different schools that students were recruited from and the teachers who evaluated students’ performance.

Table 2

Summary of Students’ Information

<table>
<thead>
<tr>
<th>Student</th>
<th>Group</th>
<th>Schools that students were recruited from</th>
<th>Teachers who evaluated students’ metacognition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Freddie</td>
<td>FS1</td>
<td>S1</td>
<td>A</td>
</tr>
<tr>
<td>Felix</td>
<td>FS1</td>
<td>S1</td>
<td>A</td>
</tr>
<tr>
<td>Frank</td>
<td>FS1</td>
<td>S1</td>
<td>A</td>
</tr>
<tr>
<td>Fiona</td>
<td>FS2</td>
<td>S1</td>
<td>A</td>
</tr>
<tr>
<td>Faye</td>
<td>FS2</td>
<td>S1</td>
<td>A</td>
</tr>
<tr>
<td>Finn</td>
<td>FS2</td>
<td>S1</td>
<td>A</td>
</tr>
<tr>
<td>Pearl</td>
<td>PS1</td>
<td>S1</td>
<td>A</td>
</tr>
<tr>
<td>Peggy</td>
<td>PS1</td>
<td>S1</td>
<td>A</td>
</tr>
<tr>
<td>Paige</td>
<td>PS2</td>
<td>S2</td>
<td>B</td>
</tr>
<tr>
<td>Patty</td>
<td>PS2</td>
<td>S3</td>
<td>B</td>
</tr>
<tr>
<td>Paul</td>
<td>PS2</td>
<td>S2</td>
<td>B</td>
</tr>
</tbody>
</table>

The role of instructor. In this research, I served in the roles of researcher and instructor to investigate and facilitate students’ learning simultaneously. I did not give direct information to students. For example, in this study, the ideas related to magnetism, such as scientific explanations or analogies, were not offered to the students. The information that students obtained should be derived from their observation and discussion in the activities, rather than from the instructor. Students needed to generate their explanations or explanatory models by themselves in their individual reasoning processes and group discussions. The goal of my intervention was to introduce and guide the procedures of the activities, as well as the journal writing and group discussions. The
instructional goal also included helping students externalize the process of their thinking and reasoning as well as reflect on their own reasoning.

I, as an instructor, initiated and directed activities. The responsibility of the instructor was to lead the activities and supervise the use of metacognition facilitating tools (including journal writing, group discussion, and metaconceptual modeling criteria). The instructor also posed questions that enabled students to clarify their thinking to others, such as asking students how they developed certain models or why they selected specific models, or questions that enabled students to reflect on their ideas, such as asking students whether their previous ideas were consistent with or related to their current ideas or whether they had revised their previous ideas.

Students were prompted by the instructor to be aware of their metacognitive processing and to contemplate the causal relationship to explain how and why magnets work, rather than only describing their observations. The students developed, generated, and revised the ideas. If students ran out of ideas to explain magnetism, the instructor encouraged them to employ their familiar knowledge or to think of something similar to explain unfamiliar phenomena. Students’ ideas were challenged by the other students’ ideas, the reflective questions in the journal, and the instructor.

The instructor offered specific guidance on the task and controlled the progress or agenda of the activities and discussion, thereby enabling students to focus on reasoning and the metacognitive process about model building and revision. Hence, students would not have to devote their time to figuring out the tasks, such as considering and discussing what should be done in the next steps, what should be observed in the activities, what should be recorded in the journal, and who should initiate the discussion.
**Metacognitive facilitating tools.** In this teaching experiment I adopted metacognition facilitating tools, which included metacognitive journals, group discussion, and the metaconceptual modeling criteria. Students in both the FS and PS groups needed to record their ideas in their metacognitive journals and have group discussion. Only students in the FS groups were required to reflect on their explanations by using metaconceptual modeling criteria. The purpose of using metacognitive facilitating tools is to promote students’ conscious monitoring and control of their cognitive process.

**The metacognitive journal.** Students used metacognitive journals to record the results of their predictions, observations, and explanations. Students also recorded their reasoning process about the related information they employed in their reasoning and the underlying reasons for the constructions and changes of their explanations. My goal with the metacognitive journal was to enable students to develop conceptual awareness and monitoring through reflecting on their individual ideas, the process of changes or revisions, and the reasons for developing these ideas and making these changes. The function of the journal was to record the progress of students’ conceptions and metaconceptual processes. See Appendix C for the contents of the journals.

**Group discussion.** Group discussion was integrated into the activities of the teaching experiment to promote students’ metacognition. In the design of the activities, group discussion occurred after the participants recorded their predictions, observations, and explanations. Students were encouraged to present and explain their own models and reasoning to other students and generate the best models collaboratively. In the second and third activities, they compared their current group models with the group models in the previous activities in order to select or construct the best models. Only students in the
FS groups were required to further reflect on their current group models and compare current and previous group models with metacognitive modeling criteria. Students in both groups needed to explain why the selected, newly developed, or revised models were better than others, and then use the group consensus explanation to reflect on their own at the end.

The group discussion may serve several functions in the research design. First, it may help students to externalize their thinking process, because students need to describe and draw pictures to explain their mental models to their partners. This is the first step for students to become aware of their thinking. Second, my goal of developing the best consensus explanations may prompt student to reflect on others’ ideas and their own ideas in order to eventually justify the best one. Third, the group discussion may facilitate the use of the metacognitive modeling criteria in discussing group consensus explanations through negotiation on how to use these criteria to examine their ideas. Fourth, the process of developing group models may also help students reflect on their own process of model building. So, not only can the group discussion encourage students to better use the metacognitive modeling criteria, but the function of the discussion itself can also facilitate the students’ metacognitive processes.

**Metaconceptual modeling criteria.** For the purpose of helping students to construct sophisticated and coherent explanatory models, I introduced the metacognitive modeling criteria of visualization and explanatory power only to students in the FS groups to reflect on their reasoning. I formulated these two criteria into more understandable questions for students to evaluate their model construction process. Table 3 lists these modified questions.
Table 3

Reflective Questions Employed by Students to Facilitate Their Model Construction and Revision

<table>
<thead>
<tr>
<th>Criteria for reflection of explanatory models</th>
<th>Meaning of the criteria</th>
<th>Reflective questions employed by students</th>
</tr>
</thead>
<tbody>
<tr>
<td>Visualization</td>
<td>Can this model explain the hidden and non-observable mechanisms and the cause and effect underlying the observed phenomenon?</td>
<td>Do I have a model (a still or moving picture about things that I can’t see but can explain what I observe)?</td>
</tr>
<tr>
<td>Explanatory power</td>
<td>Can this model better explain all findings?</td>
<td>Does this model explain my observations?</td>
</tr>
</tbody>
</table>

The criterion of visualization was introduced after the first activity (M1: Two Magnets Activity). In order to illustrate how scientists can visualize models to describe unobservable mechanism underlying the observable phenomena, I provided students the activity of guessing what might be inside the black box and the example of scientifically hypothesizing what might be inside the earth. This activity is illustrated in detail in the following black box activity. I then asked the students to reflect on their explanations by using the criterion of visualization, which was illustrated in Table 3.

The criterion of explanatory power was introduced at the latter part of the second activity (M2: Cutting Magnet Activity). After the metaconceptual modeling criteria were introduced, students continued using these criteria to evaluate models in the group discussion in order to select or develop the best models. The purpose of using the metaconceptual modeling criteria was to assist students in reflecting on their own and competing ideas. Reflection on these criteria intended to help students to be aware of, monitor, and assess their existing ideas in order to develop coherent sophisticated explanatory models rather than to convince them to renounce their own ideas and accept.
new models as some conceptual change research advocates (e.g., Beeth, 1998; Grotzer & Mittlefehldt, 2012).

**Interview.** Semistructured interviews were conducted before and after three sessions of teaching experiments for eliciting students’ initial ideas, and understanding students’ learning pathways and their reasoning processes. I conducted these interviews after school with individual students.

In the pre-instructional interview, students’ initial ideas and related learning experience about magnetism were elicited through their interaction with different kinds of materials before the teaching experiments. Students not only made predictions, observations, and explanations about which materials are magnets, but they also justified their identification of the magnets and gave further explanations about how magnets work. Next, they also needed to recall their previous learning experiences related to magnets. The individual interviews took about ten minutes before the teaching experiments. The pre-instructional interview protocol is included in Appendix D.

After the teaching experiments, individual semi-structured interviews were also conducted in order to understand students’ model construction as well as their reasoning processes. Stimulated recalls were also conducted in the beginning of the post-instructional interview. Researchers have long applied stimulated recall as an important method to study students’ cognitive processes (De Grave, Boshuizen, & Schmidt, 1996; O’Brien, 1993) and metacognitive processes (De Grave et al. 1996; Anderson, Nashon, & Thomas, 2009; McTavish, 2008). Through stimulated recalls, those reasoning and metacognitive processes that were not revealed in the observation of teaching experiments would be disclosed by the students.
In addition to some recorded video clips, some parts of students’ written metacognitive journals were selected in order for students to recall and clarify their reasoning processes. The selection of video clips and journals was based on trying to understand students’ reasoning, so the selected segments went over the parts of the experiment where the interviewer’s understanding of students’ reasoning processes was less clear. Students were asked to clarify what they were thinking when they were doing in these activities.

The interview questions also required students to examine the progression of their model construction and how they changed or revised their models. Next, the roles of the metaconceptual modeling criteria, the metacognitive journal, the group discussion, and the design of the activities in students’ reasoning were evaluated by the students. The influence of using these strategies and activities to help students’ reasoning and future learning was assessed by the students. The post-instructional interview took about 40 minutes for each student after the teaching experiments. The post-instructional interview protocol is included in Appendix E.

**Design of activities.** There were three activities in the teaching experiments in which students played with different materials that would help them to construct models to explain magnetism. The three main activities (M1: Two Magnets Activity, M2: Cutting Magnet Activity, and M3: Metal Bars Activity) in this research were not designed as a random collection of activities. Rather, these activities are interrelated. The design, considering the students’ response in the earlier clinical interviews (Cheng & Brown, 2010), intended to help students activate more appropriate intuition and existing knowledge in their reasoning and consider the microscopic phenomena inside and outside
the magnet, thereby enabling them to be aware of the gap between their intuition and abstract verbal symbolic knowledge learned from school.

In these activities, students in the FS and PS groups both followed the sequence of prediction, observation, and explanation in the activities. They made their own predictions and explanations before observing the phenomenon and to make individual explanations and modification after their observation. Then they needed to elaborate on individual ideas and discuss them with others in order to select or develop the best group consensus model. Finally, they compared their current group picture with other group pictures they previously developed.

At the end, students went back to reexamine their individual models. The only difference between the FS and PS groups was that the metaconceptual modeling criteria were introduced only to students in the FS groups. The criterion of visualization was first introduced and employed in the black box activity after the first activity, and the criterion of explanatory power was first introduced at the latter part of the second activity. Afterwards, students in the FS groups needed to continue reflecting on these criteria when they evaluated and compared group pictures in all subsequent activities.

In this research, the instructor informed students about the purpose of the study in the beginning in order to help them to construct explanatory models to account for unfamiliar phenomena without worrying whether they got right answer or not. The instructor told the students that the purpose of the study was to examine how they developed and changed their explanations for magnetic phenomena. Table 4 lists the dates and length of the activities of the first and second fully scaffolded group (FS1 and FS2) and the first and second partially scaffolded group (PS1 and PS2).
### Table 4

*Date and Time of Activities*

<table>
<thead>
<tr>
<th>Group</th>
<th>M1: Two Magnets Activity &amp; Black Box Activity which introduce the criterion of visualization</th>
<th>M2: Cutting Magnet Activity with reflection on the criteria of visualization and explanatory power</th>
<th>M3: Metal Bars Activity with reflection on criteria of visualization and explanatory power</th>
</tr>
</thead>
<tbody>
<tr>
<td>FS1</td>
<td>3/16/2010 (54 minutes)</td>
<td>3/17/2010 (54 minutes)</td>
<td>3/22/2010 (64 minutes)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Group</th>
<th>M1: Two Magnet Activity</th>
<th>M2: Cutting Magnet Activity</th>
<th>M3: Metal Bar Activity</th>
</tr>
</thead>
<tbody>
<tr>
<td>PS1</td>
<td>4/8/2010 (43 minutes)</td>
<td>4/9/2010 (57 minutes)</td>
<td>4/12/2010 (47 minutes)</td>
</tr>
</tbody>
</table>

**M1: Two magnets activity:** In the two magnets activity, the instructor showed students two bar magnets and asked them to write down and clarify their individual predictions and explanations about what would happen between two magnets, before playing with them. While playing with the two magnets, the students needed to describe and record their observations. After that, they wrote down their explanations for the attraction and repulsion between two magnets and compared their current explanations with previous explanations in the prediction.

Next, the students shared their ideas with others in order to select or develop the best explanation and convince each other why a certain explanation was better than...
others. They then drew and wrote their own explanations on a piece of paper to illustrate them to each other and the instructor. If students had problems selecting or developing the best explanation, the instructor asked them to vote for the best explanation and to clarify the reason underlying their vote. Finally, individual students needed to evaluate their group consensus explanation and consider whether they needed to revise their own explanations after the discussion.

In this activity I tried to make students aware of their pre-knowledge and assumptions about magnets and help them elicit their original intuitive ideas about initiating agents in the two ends of the magnet to explain how magnets work.

**Black box activity.** In the black box activity, the instructor first showed students a black box adapted from the tube activity in Lederman and Abd-El-Khalick’s (1998) paper, which is shown in Figure 3. The instructor pulled one end of a rope and asked students to observe the interaction between different ropes. Students were asked to imagine and draw what the rope may look like inside the tube shaped box and then design and test their own tube accordingly.

Next, the instructor showed students a picture of the internal structure of the earth to introduce an idea that although scientists cannot see what is inside the earth, they can make a picture of what they can’t see through the observed phenomena. The idea of visualization was introduced, and the students were asked to use this criterion to think about their own picture at the ends of first activity in order to develop the best explanation. After discussion, they reflected on their own explanations and considered whether they needed to make any changes.
Figure 3. A black box activity that was adapted from the tube activity in Lederman and Abd-El-Khalick’s (1998) paper.

**M2: Cutting magnet activity:** In the cutting magnet activity, the instructor showed students two compasses and asked them what was inside the compasses. In order for students to identify the magnetic properties, the instructor showed the attraction and repulsion between these two compass needles as well as between one needle and one bar magnet.

First, students recorded and stated their individual predictions and explanations about what would happen after breaking the compass needle in half, into smaller pieces, and into unobservable smaller pieces. During their observation, students needed to portray and record what happened after breaking the compass needle and using the other compass to test the two ends of the pieces of the compass needle. The instructor made sure students observed the coexistence of two poles of the cut pieces. After observation, students needed to write down their own explanations of what happened after breaking the compass needle in half and then into smaller pieces. They were asked to imagine what happened after breaking the needles into unobservable smaller pieces and to clarify the changes between their previous explanations and current explanations.
Next, the students shared their ideas with each other in order to select or develop the best model and convince each other why a certain model was better than the others. After developing the group consensus models, students reflected on the criterion of visualization, which was previously introduced in the black box activity. Then, the instructor introduced the criterion of explanatory power and asked students to evaluate their explanations by using the criterion of explanatory power. After reflecting on the metaconceptual modeling criteria, students compared their current model with the model they developed in the first activity. Finally, students reflected on their own models and considered whether they needed to revise their original models after the discussion.

In this activity, the compass needle is used as a substitute for regular bar magnets because the compass needle is easily split by students. The breaking magnet activity is designed to meet students’ intuitive desire to understand magnets by having them break down magnets to observe their internal structure. Some student mentioned this intuition in Cheng and Brown’s (2010) clinical interviews. In that research, students usually hypothesized that there should be something in the two ends of the magnets to attract other material to the two ends. The breaking magnet activity is designed to make students reconsider the structure inside the magnets.

**M3: Metal bars activity:** First, students were asked to distinguish the metal bars from the magnet by using the compass. In the metal bars activity, students needed to record and declare their predictions and explanations about which part of the magnet could attract more metal bars and what would happen to the magnet and the metal bars. During their observation, the instructor guided students to observe that two ends of the magnet attracted more metal bars than the middle part and to discover that the metal bars
have two different poles by testing them with the compass. Then, students needed to write down their own explanations about the interactions between the magnet and metal bars, as well as the changes between their explanations for their prediction and observation.

Next, the students shared their ideas with others in order to select or develop the best model and convince each other why a certain model was better than others. After developing the group consensus models, students reflected on the criteria of visualization and explanatory power and compared their current model with the first two models. Finally, students reflected on their own models and considered whether they needed to revise their original models after the discussion.

This activity intends to offer students the chance to consider how magnets work or influence other materials. It may enable students to apply their previous explanations inside and outside the magnet to explain how the magnet attracts metal bars. In the clinical interviews of previous studies (Cheng & Brown, 2010), more students developed explanatory models in the metal bars activity than in the other activities. However, most explanatory models they developed were tentative and incoherent. Hence, reflecting on the metaconceptual modeling criteria and reviewing previous pictures was an attempt to encourage students to revise their explanations to become coherent and sophisticated explanatory model for the all observed magnetic phenomena.

Data Collection

The quantitative data collected from surveys and self-evaluation provide information about students’ metacognition with regard to their learning and their science
performance in school. The quantitative information allows inspection of whether students in the FS and PS groups differed in terms of their metacognition and science learning in school before the teaching experiment.

The qualitative data collected in this study provided information about students’ cognitive and metacognitive process. In order to study the process of students’ model development and to explore how using metacognition facilitating tools assists these reasoning processes, I collected students’ writing and drawings in the journals and papers. I video recorded the teaching experiments and pre- and post-interview, including students’ verbal responses and discussion as well as their nonverbal expressions, such as hand gestures and drawings, which they employed to convey their meanings.

Credibility. Mental models cannot be directly studied and can only be reasoned from actions and speaking (Justi & Gilbert, 2000). Thus, researchers studying mental models usually look at expressed models with a view toward understanding human mental models. Therefore, how to make mental models close to expressed models is essential in the study of mental models. White (1998) emphasized that researchers should pay attention to the validity and reliability of instruments and observation about the metacognition because it is not a directly observable mental process.

In this study, for the purpose of studying students’ mental model and process, the discussion and metacognitive journals are used to help students to externalize and verbalize their thinking process and product. Their mental models can be studied and analyzed from their writing, drawing, and speaking. These methods provide better access to students’ thinking and reasoning. There are different ways to enhance credibility in qualitative research (Mertens, 2005); the method I adopted in this research is
triangulation.

**Triangulation.** Triangulation emphasizes the consistency of evidence across different sources or methods. When collecting the data, the following resources were collected and methods were employed to enhance the credibility of studying students’ cognitive and metacognitive process.

I first determined students’ pre- and post-instructional knowledge via interview before and after the whole teaching experiment. Also, I was able to verify their pre- and post-knowledge by the knowledge developed in different contexts. Students’ pre-knowledge was affirmed by their explanations for their predictions in the M1: Two Magnets Activity before they started the activities. Students’ post-knowledge was confirmed by their explanations for all observed magnetic phenomena at the end of M3: Metal Bars Activity. Moreover, their knowledge could be further verified by another method, e.g., the metacognitive journal the students used to record their initial and final explanations via writing and drawing.

Students’ individual processes of model construction can be investigated through multiples sources. I explored these reasoning processes by starting with pre-instructional interviews about the students’ preconceptions and previous learning experiences, keeping track of their individual ideas and their contribution to group discussion in the teaching experiments, and confirming with their post-instructional interviews about the product and process of their reasoning. Furthermore, these individual reasoning processes can also be validated by different methods. Besides their speaking and interaction in the videos, the writings and drawings in their individual journals and their group discussion papers helped me to monitor their individual ideas and the changes of these ideas.
How metacognition might be facilitated to enhance students’ model building can be investigated by observing how individuals and groups evaluated their ideas with or without using the metaconceptual modeling criteria. The aids of the metaconceptual modeling criteria, metacognitive journals, group discussion, and activities were also evaluated by students in their post-interview as to whether or not these designs facilitated their reasoning.

Data Analysis

In this study, quantitative analysis of surveys and students’ self-evaluation of their science performance provided information about whether students in the FS and PS groups had similar metacognition or science performance in the school before the teaching experiment. Qualitative analysis of students’ pre- and post-interviews as well as the teaching experiments provided information about the process of students’ model construction, their use of conceptual resources, and their metaconceptual evaluations influencing their cognitive processes described above.

Quantitative analysis. To identify any differences between students in the FS and PS groups in terms of their metacognition and science learning in schools before the start of the teaching experiments, nonparametric statistical tests were conducted to assess whether one of two independent samples had more values than the other. The Mann-Whitney U Test was selected for this study because its assumptions complied with the use of two independent samples and an ordinal scale of measurement. Three Mann-Whitney U Tests were employed to evaluate whether there were significant differences between the FS and PS groups in three aspects: self-evaluation of
metacognition (see Appendix A), teachers’ evaluation of students’ metacognition (see Appendix B), and students’ self-evaluation of science performance.

This study was not designed to investigate whether the students improved in their metaconceptual abilities or science learning abilities. The purpose of including the quantitative analysis of survey of students’ metacognition and self-evaluation of science performance was to obtain indications of students’ prior metaconceptual and science learning abilities in order to rule out the hypothesis that any difference in performance between FS and PS groups was because of differences in prior metaconceptual or science learning abilities.

**Qualitative analysis.** To answer the three main research questions about model building, conceptual resources utilization, and metacognition facilitation, this study adopted a qualitative data analysis to explore students’ cognitive processes and metacognitive processes. The fine-grained qualitative data analysis allowed me to further investigate how students’ metacognitive processes can influence their cognitive processes of employing different conceptual resources to develop and revise their models. This approach also helped me to identify different or similar emergent patterns of students’ explanations, conceptual resources, and metacognitive evaluation between FS and PS groups.

The Design-Based Research Collective (2003) suggested that the teaching experiment “relies on techniques used in other research paradigms, like thick descriptive datasets, systematic analysis of data with carefully defined measures, and consensus building within the field around interpretations of data” (p. 7). Therefore, in this study, the qualitative data analysis of students’ explanations and metacognition follows Chi’s
(1997) verbal analysis method to seek out and build the theory of students’ reasoning process.

First, students’ responses were screened and reduced them to explanations and metacognitive statements, which were segmented by activity features, such as prediction, observation, individual explanation, group discussion, reflection on the metaconceptual modeling criteria, and comparing pictures.

Next, the progression of students’ explanations was coded by considering existing literature about the levels of knowledge development (Chin & Brown, 2000; Krnel, Watson, & Glazar, 1998; Russ et al., 2008; Talanquer, 2010). Students’ utilization of conceptual resources underlying the development of explanatory ideas was interpreted through the multidimensional framework (Brown, 1993, 1995a, 1995b; Cheng & Brown, 2010). Students’ metaconceptual evaluations were identified by existing studies (Yuruk, 2007; Yuruk et al, 2009) and were categorized as different types of criteria according to emergent patterns.

Finally, according to the results of the coding, the patterns of students’ cognitive and metacognitive processes were identified by continually comparing the similarities and differences within and between groups. The quantitative-based qualitative approach (Chi, 1997) was adopted to further compare the frequencies of certain codes of students’ explanations and metacognition in order to use graphical representations to demonstrate the similarities and differences between FS and PS groups.

The following illustrates how students’ explanations, conceptual resources, and metacognition were analyzed.

**Analysis of development of explanations.** To answer the first research question
about how students developed and revised their explanations, students’ explanatory ideas were analyzed in terms of levels of sophistication and coherence. First, in order to investigate sophistication of students’ explanations, three levels of explanation emerged by considering existing categories or theoretical frameworks to illustrate the sophistication of knowledge (Chin & Brown, 2000; Krnel et al., 1998; Russ et al., 2008; Talanquer, 2010). These studies pointed out the development of the concept that a microscopic explanation is more sophisticated and developed than a macroscopic explanation, which is more advanced than a description of an observation. A dynamic model is more advanced than a static model.

The examples of three main levels of explanation in this study are illustrated in Table 5 from lower levels to higher levels of conceptual development: (a) Level 1: Description of observation. Students discuss the activity of the magnet, but do not involve any unseen components in their explanation; (b) Level 2-1 macro and Level 2-2 micro: Static level of explanation. Students explicitly discuss macroscopic unseen components (such as metal, lead, or special things inside the magnet) or microscopic unseen components (such as elements, electrons, atoms, molecules, or positive or negative minerals) in their explanations without referring to the activities or interactions between these unseen elements; and (c) Level 3-1 macro and Level 3-2 micro: Dynamic level of explanation: Students explicitly indicated the activities and interactions of unseen macroscopic or microscopic components in their explanation.
<table>
<thead>
<tr>
<th>Levels</th>
<th>Definition</th>
<th>Example of transcript</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level 1</td>
<td>Description of the activity of the magnet</td>
<td>Freddie: The magnet will have a force to pull it. Peggy: They (two magnets) will attract when N and S are put together because they are opposites and they will repel because these two are the same and they won’t connect.</td>
</tr>
<tr>
<td>Level 2-1 macro</td>
<td>Illustration of a static image of macroscopic unseen components (such as metal, lead, or special things inside the magnet)</td>
<td>Frank: I think that both ends attract the same amount of metal but the middle parts don’t attract. I think this because the magnetic material is on the inside and the sides (two ends). Freddie: Magnetite makes up magnets.</td>
</tr>
<tr>
<td>Level 2-2 micro</td>
<td>Illustration of a static image of microscopic unseen components (such as elements, electrons, atoms, molecules, or positive or negative minerals)</td>
<td>Paul: I think because there are molecules or stuff that somehow with the nature of other metals (in the magnet). Felix: I showed the particles of North and South and I put tons of about one thousand equals a whole entire of magnet and there’s a bunch of little particles together to make one giant magnet.</td>
</tr>
<tr>
<td>Level 3-1 macro</td>
<td>Illustration of the activities and interactions of unseen macroscopic components in their explanation</td>
<td>Frank: I put the stuff inside the magnet is going through it (metal bar) so I made the lines look like there was stuff inside the magnet. Pearl: I think when they are both North and North, they will push apart from each other and not attract because they are the same type of material on that side. So they don’t have anything that pulls them together.</td>
</tr>
<tr>
<td>Level 3-2 micro</td>
<td>Illustration of the activities and interactions of unseen microscopic components in their explanation</td>
<td>Frank: Because we didn’t put North and South on any of those (the elements inside the magnet). We did not put them (elements) connect or repelling away from each other (in the final picture of M1). Felix: They (particles) just flow away like the first time you see it. This will be here and this will stay as North/South and then the next second it is over here and stuff. So… it’ll keep floating around and they return to the North/South now and it’ll just keep floating around maybe fly back to.</td>
</tr>
</tbody>
</table>
Next, in order to investigate the coherence of students’ ideas, looking across the explanations for the different activities, these were categorized as coherent (the same explanatory ideas used for all phenomena), partially coherent (the same ideas for some but not others), or fragmented (different explanatory ideas for each phenomenon). The categorization of level and coherence of explanations allowed me to show the details as well as the patterns of revision and progression that students made. The similar and different ways of developing and revising explanatory ideas within and across groups were investigated.

**Analysis of conceptual resources.** To answer the second research question about how students used conceptual resources, students’ explanations were further interpreted based on the multidimensional framework (Brown, 1993, 1995a, 1995b; Cheng & Brown, 2010). It offers an interpretive framework to explore how students involve conscious knowledge (verbal symbolic knowledge and conscious model) and unconscious knowledge (implicit model and core intuition) in their model building. The similar and different ways of utilizing conceptual resources within and across groups were explored. Table 6 contains definitions and examples that illustrate how students’ conceptions of magnetism were interpreted according to the multidimensional framework.
Table 6

*Four Categories of Conceptual Resources*

<table>
<thead>
<tr>
<th>Levels</th>
<th>Definition</th>
<th>Example in this study</th>
</tr>
</thead>
<tbody>
<tr>
<td>Verbal symbolic</td>
<td>Consciously remembered verbal principles.</td>
<td>The attraction of repulsion between the N and S end of magnets and N-S particles.</td>
</tr>
<tr>
<td>knowledge</td>
<td></td>
<td>The N-S particles as initiating agents in the magnet go to the end of the magnet where metal bars stick to. These N-S particles react to the N-S particles in the metal bars to make the particles move to align with each other so metal bars would stick to the magnet.</td>
</tr>
</tbody>
</table>
| Conscious models     | Visualization of the image of the activities of unobservable elements (explanatory models) to explain why observed phenomena happen. | 1) The pieces of something should be the same as the whole things.  
2) Same outside $\rightarrow$ same inside. |
| Implicit model       | Tacit assumptions about a particular class of phenomena.                 | 1) Causal agency is attributed to the microscopic N-S particles in the magnet to act on N-S particles in the metal bars.  
2) More agency begets greater effects. |
| Core intuitions      | Intuitions about attributions of causal power or agency. Whenever objects interact causally, core intuitions will be involved. | 1) The pieces of something should be the same as the whole things.  
2) Same outside $\rightarrow$ same inside. |

**Analysis of metacognition.** To answer the third research question about how promoting students’ metaconceptual evaluation facilitates the process of developing explanations and utilizing conceptual resources, students’ metacognitive statements were identified and categorized according to existing categories, such as metaconceptual awareness, monitoring, and evaluation (Yuruk, 2007; Yuruk et al., 2009). Students’ metaconceptual evaluation was further categorized according to the metaconceptual modeling criteria (visualization and explanatory power) and other metaconceptual criteria raised spontaneously by students, such as level of detail of the model, understandability, etc. Finally, students’ model development and knowledge utilization were compared before
and after students’ reflection on their metaconceptual modeling criteria or self-generated criteria within the same groups as well as with and without introducing metaconceptual modeling criteria across different groups.
Chapter 4

Results of Students’ Explanations and Metaconceptual Evaluation

This chapter describes the progression of students’ self-developed explanations for certain phenomena (in this case, how a magnet works) and the criteria they consciously used to assess their explanations. Students’ self-evaluation of their knowledge is regarded as metaconceptual evaluation, which is one aspect of metacognition (Yuruk, 2007; Yuruk, Beeth, & Andersen, 2009). In this section, to answer the first research question, about the progression of students’ explanations, I present students’ explanations coded by the three main levels of explanation (as illustrated in the data analysis section of the methodology chapter), thereby obtaining the overall pattern of students’ explanation. To answer the second research question, about the conceptual resources involved in students’ different levels of explanation and the revisions of or changes to their explanations, I use a multidimensional framework (Brown, 1993, 1995a, 1995b; Cheng & Brown, 2010) to interpret the progression of students’ explanations in the three activities and their responses during pre- and post-interview.

To answer the third research question, about how promoting students’ metacognition influences the development, evaluation, and revision of their explanations, I present, first, how different groups of students employed the criteria to evaluate and then revise or change their explanations in three activities and, second, what they perceived as important criteria to evaluate and revise their explanations in the post-interviews. For the two fully scaffolded (FS) groups, I show how their explanations progressed once they were encouraged to use the metaconceptual modeling criteria of visualization and explanatory power. I also show how their self-generated criteria
influenced their explanations. In addition, their interpretations of the criteria of visualization and explanatory power and the meanings of their self-generated criteria are illustrated. For the two partially scaffolded (PS) groups, I show how students used their self-generated criteria to evaluate and modify their explanations during the activities. I also illustrate the self-generated criteria they used to evaluate their group and individual pictures.

Before addressing these three research questions explicitly, I will present and discuss the results of surveys about students’ self-evaluated metacognition, teachers’ evaluation of students’ metacognition in learning, and students’ self-evaluated science performance (Table 7). This table shows that there is no difference between students’ metacognition and science performance in the FS and PS groups before the activities. Next, the case of Frank, a participant in the first FS group, is presented in detail later to show how the multidimensional framework is involved in students’ varying levels of explanations. Frank’s case also shows how students use both learned criteria and self-generated criteria to reflect on their explanations and revise them accordingly. Moreover, Frank’s case provides a detailed look at the instructional sequence. Several important aspects emerge from Frank’s case, and these are identified in order to search for similar or different patterns in other students’ explanations and metaconceptual evaluations. The explanations and metaconceptual evaluations of other individual students are also summarized to show how and why their individual explanations and metaconceptual evaluations may be similar to or different from Frank’s. The comparison of these four small groups of students (i.e., two FS and two PS groups) will show the differences and the similarities between the progressions of their explanations and their
metaconceptual evaluations.

The focus of this analysis is individual students in groups; therefore, every student’s explanations and metaconceptual evaluations is from the pre- and post-interviews, as are their contributions to group activities. Nevertheless, identifying students’ individual explanations and metaconceptual evaluation in their group discussion is difficult, especially where students did not propose or clarify their own, individual idea. They may agree or disagree with some ideas or maintain or shift to some ideas without articulating their reasons for doing so or offering their metaconceptual evaluation. These difficulties are eased through the consideration of students’ drawing and writing in their individual journals and group pictures as well as their individual post-interviews, wherein they were asked to explore why they were thinking about specific ideas or why they supported or changed to certain ideas at that time. The analysis intends to capture the externalized aspects of their internal conceptual and metaconceptual processes and then to infer conceptual and metaconceptual processes through interpretive analysis.

**Students’ Metacognition of Their Learning and Students’ Evaluation of Their Performance in Science**

All students in the FS and PS groups filled out the Junior Metacognitive Awareness Inventory (Appendix A) in the pre-interview and their teachers filled out the Rating of Student Metacognition (Appendix B). Students were also asked to evaluate their performance in science class as above average, average, or below average at the end of the pre-interview. Both fully scaffolded groups (FS1, FS2) and the first partially scaffolded (PS1) group were from the same school, and the second partially scaffolded
(PS2) group was from another after-school program. Because of this, the PS2 group’s metacognition was evaluated by a different teacher than the other three groups. Table 7 shows students’ self-evaluation of their metacognition and teachers’ evaluation of students’ metacognition.

Table 7

*Evaluation of Students’ Metacognition and Science Performance*

<table>
<thead>
<tr>
<th>Student</th>
<th>Group</th>
<th>Self-evaluation of metacognition</th>
<th>Teachers’ evaluation of metacognition</th>
<th>Students’ self-evaluation of science performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Freddie</td>
<td>FS1</td>
<td>36</td>
<td>2</td>
<td>2 (Average)</td>
</tr>
<tr>
<td>Felix</td>
<td>FS1</td>
<td>28</td>
<td>4</td>
<td>3 (Above)</td>
</tr>
<tr>
<td>Frank</td>
<td>FS1</td>
<td>27</td>
<td>6</td>
<td>3 (Above)</td>
</tr>
<tr>
<td>Fiona</td>
<td>FS2</td>
<td>27</td>
<td>3</td>
<td>2 (Average)</td>
</tr>
<tr>
<td>Faye</td>
<td>FS2</td>
<td>29</td>
<td>4</td>
<td>3 (Above)</td>
</tr>
<tr>
<td>Finn</td>
<td>FS2</td>
<td>27</td>
<td>2</td>
<td>2 (Average)</td>
</tr>
<tr>
<td>Pearl</td>
<td>PS1</td>
<td>30</td>
<td>5</td>
<td>3 (Above)</td>
</tr>
<tr>
<td>Peggy</td>
<td>PS1</td>
<td>31</td>
<td>2</td>
<td>3 (Above)</td>
</tr>
<tr>
<td>Paige</td>
<td>PS2</td>
<td>29</td>
<td>6</td>
<td>3 (Above)</td>
</tr>
<tr>
<td>Patty</td>
<td>PS2</td>
<td>27</td>
<td>6</td>
<td>2 (Average)</td>
</tr>
<tr>
<td>Paul</td>
<td>PS2</td>
<td>32</td>
<td>5</td>
<td>3 (Above)</td>
</tr>
</tbody>
</table>

To determine if there is a significant difference between two different groups of students, three Mann-Whitney U Test were employed. According to Mann-Whitney U tests, there were no significant differences between students’ self-evaluated metacognition ($M_f = 29, M_p = 29.8, U = 21, p > 0.05$), teacher’s evaluation of students’ metacognition ($M_f = 3.5, M_p = 4.8, U = 22, p > 0.05$), and students’ science performance ($M_f = 2.5, M_p = 2.8, U = 19.5, p > 0.05$).

The metacognition assessed in Table 7 is different from the metacognition
investigated elsewhere in this study. Metacognition assessed in these two surveys refers to students’ learning in general, but the metacognition investigated elsewhere in this study refers to students’ metaconceptual evaluation of their explanations. While the data do not specifically show whether there is a significant difference in students’ metaconceptual evaluation, it does show that students in the FS and PS groups have no significantly different metacognition in their learning and their performance in science classes.

**Analysis of the First Fully Scaffolded Group**

Frank was selected for the focus of this analysis, because he participated in all three activities and was better at articulating his thoughts about why he supported or opposed certain ideas than other students. This section examines the progression of Frank’s explanations and metaconceptual evaluation while he was assisted in reflecting on individual or group explanations by using the criteria of visualization and explanatory power. The other two students, Freddie and Felix, are not the main focus in this case study, but their explanations and reasoning sometimes are included to show how their ideas may have influenced Frank’s explanations.

During the three activities, Frank was assertive about his ideas, so he was good at proposing his own ideas instead of just supporting ideas of others. When others had different ideas than he had, he would try to convince other students by articulating his reasons; alternatively, when he agreed with another student’s ideas, he would try to synthesize all of the ideas to come up with the best group picture.

At first, Frank started with a lower level of explanation—that metal would stick to
the magnet—and did not offer further explanations about the underlying behavior of magnets (Level 1; see data analysis section for illustration of different levels of explanation). Through using the criteria of visualization and explanatory power to assess his and others’ explanations, he finally developed a higher level of explanation, stating that microscopic N-S particles act on other particles or objects (Level 3-2 micro). Other students, except Fiona, in the FS groups, have similar patterns to Frank’s, which will be illustrated after the case study.

Coding students’ explanations in terms of three main levels help to present different levels of sophistication of their explanation, instead of simply judging the “correctness” of their models. Higher-level of explanations represent that students started to develop explanations that went beyond merely describing their observations or voicing intuitive ideas that magnets have force to pull other objects, without providing underlying reasons. Students started to develop explanations more closely resembling microscopic models that scientists develop to visualize the underlying mechanism for observed phenomena. This classification of explanations enables a better description of the process of students’ reasoning, and the progression of developing intermediate explanations between intuitive ideas and scientific explanations.

**Pre-interview.** On the first day, I began the individual pre-interview by asking Frank to predict which objects on the table are magnets and provide reasons for his selection. I asked Frank to pick up the objects that he predicted were magnets. Frank predicted the ones that other things would stick to as the magnets. Then Frank further articulated the differences between magnets and magnetic objects during his observation of objects on the table, as reflected in the following exchange:
These two [the square and the disc magnets] are magnets and these ones [which stick to the magnet, including a magnet ball, paper clips, a washer] are magnetic. [Separating different groups of objects on the table.]

Why?

Because they [which are magnetic] can be made into a temporary magnet. If they stay on a magnet long enough so they are just like North and South and they stick to other magnets.

So why are these magnetic and why are these two magnets? Are they different? Or are they the same?

These ones [the square and the disc magnets] have a North and South end. Magnets have North and South and…

And these [magnetic ones] do not have?

These don’t but you can make them into a temporary magnet.

Temporary. How do you make them as temporary?

Like if they stay on the magnet long enough they can sometimes stick to this stuff.

During Frank’s observing and playing with the objects on the table, he distinguished magnetic objects from magnets. Although there was no North and South symbol on these objects, Frank recalled that magnets have a North (N) and South (S) end, but magnetic objects do not have N and S ends and can be made into temporary magnets by attaching them to the magnets. In other words, Frank already had some existing ideas about the N
and S end of the magnet and magnetized objects before participating in the activities in
this study.

Next, I asked Frank to explain his idea about how magnets work to act on other
materials and to draw his explanation on the paper; the following discussion ensued:

[00:03:32]

32. Frank: I think there’s like little stuff in the metal [box] and then when you
get the magnet to it then it goes straight and sticks [drawing metal stuff like lines stick to the magnet].

33. I: So these are metals and this is a magnet [pointing to the drawing].

34. Frank: Yes this is metal and this is the magnet and when you put the magnet
to the metal, all the stuff inside the metal [box] goes straight and sticks.

35. I: Can you explain why this metal would stick to the magnet?

36. Frank: I don’t know.

Later on, Frank referred the little stuff as moving metal lines that he had seen inside a box.
He had observed these metal lines would be pulled toward the magnets without further
clarification of why these metal lines would stick to the magnet. Since this explanation
did not hypothesize anything inside the magnet and the magnet as a direct initiating agent
to pull other objects, I categorized this explanation as a Level 1 explanation.

Although Frank started from lower-level of explanations, his later explanations
were revised, and his explanation progressed during the three activities. Other students in
the FS groups presented explanations that followed a similar progressive pattern to
Frank’s. The idea about moving metal lines may influence Frank’s explanations about
moving material lines, elements, or particles inside the magnets or metal bars in the following three activities and the post-interview. This raises questions regarding whether students’ ideas, learned knowledge, or experience potentially influences how they develop their explanations, which will be discussed in a later section about the interpretation from the multidimensional framework. Figure 4 shows Frank’s drawing in the pre-interview about how the magnet pulls metal objects.

![Figure 4](image-url)

*Figure 4.* Frank’s drawing in the pre-interview about how the magnet pulls metal objects.

Finally, I asked Frank about his learning experience about magnets. Frank could recall “magnetic stuff” in the earth, compasses’ being like little magnets, and learning about magnets in the 4th grade, as well as from the science channel, all of which influenced what he drew on the picture in the interview. From the interpretation of the multidimensional framework, even though Frank did not refer to the abstract verbal symbolic knowledge in the pre-interview to explain the behavior of magnets, he could remember that magnets have N and S ends when distinguishing the magnets from magnetic objects.

Comparing Frank’s explanations and learning experiences in the pre-interview with others’, one can find that Frank did not bring up more verbal symbolic knowledge
than other students in the FS groups, who mentioned the following: using electricity to make magnets; the attraction and repulsion between the N and S ends or the positive and negative sides of the magnets; and the force field of the magnet. However, in the end, Frank and most students in the FS groups developed more coherent and higher-level of explanations than the students in the PS groups. Hence, it is essential to explore the different conceptual resources that students involve to develop and revise their explanations in order to understand how Frank and most students in the FS groups could develop coherent and higher-level of explanations at the end, while students in the PS groups did not. The following data analysis section about multidimensional framework investigates whether employing different conceptual resources may influence how students develop explanatory models.

**Activity M1: Two magnets.**

**Overview.** The second day, Frank, Freddie, and Felix, in the first FS group, made their individual predictions, group observations, and their individual explanations for what happened between two ends of the magnets. Then, they together devised the best group picture to account for the attraction and repulsion between two magnets. After the instructor introduced the black box activity and the criterion of visualization, they employed the criterion of visualization to reflect on their group picture. I now proceed to look in more detail at these interactions.

**Prediction.** In this session, I began by giving students their journals and showing them the two bar magnets and asking them to write down their prediction about what would happen between two N ends of the magnet and between the N and S end of the magnet, as well as why this may happen. They spent about three minutes writing their
predictions and explanations for their predictions. In the following conversation, all students have the same prediction about the attraction between two unlike poles and the repulsion between two like poles, but based on different explanations. Frank volunteered to propose his ideas first:

[00:05:35]

47. Frank: I’ll go first. I put the magnets [that] will push away from each other, and I showed a picture [about the explanation for his prediction] of them pushing away from each other. If you switch one magnet, and I put there [his picture in his journal] “switch” and they will attract and I put them together and I think this is because of some of the minerals in the magnets.

In line 47, Frank was the first one to hypothesize that magnets work “because of some of the minerals in the magnets.” Since Frank did not indicate the activities of these elements, his explanation is classified as Level 2-2 micro. According to the multidimensional conceptual framework, I interpreted Frank as the first student to propose a simple image about “mineral” elements inside the magnet, which seems to involve only a simple image that there should be something special inside the magnet to enable magnets work.

On the other hand, Freddie and Felix started with lower-level of explanations by referring only to the relationship between two magnets. Their explanations, therefore, are both categorized as Level 1 explanations. Freddie used his understanding about the relationships between the positive and negative sides to explain the attraction and repulsion between two magnets. Felix employed a simple analogy to clarify the relationships between two N or two S ends of the magnet: he stated that the two ends are
like the relationships between a bully and a nice kid, so they do not go together. On the other hand, the relationships between the N and S are like two bullies or two nice kids. Since they are alike, they go together.

Later on, Frank spontaneously commented on Felix’s explanation as very understandable, but he did not shift to Felix’s explanation in the following activity. Here, Frank employed a self-generated criterion of understandability to evaluate Felix’s explanation, but this evaluation does not prompt him to revise his explanation. However, later, Frank revised his explanations according to his other, self-generated criteria. Hence, whether Frank and other students revise their explanations based on the self-generated criterion of understandability in other instances or on other, self-generated criteria in the activities will be continuously inspected in this study. How students employed these different self-generated criteria will be compared whether students revised or did not revise their explanations. This comparison will answer whether certain self-generated criteria would prompt them to revise or change their explanations.

**Observation and explanation after observation.** While playing with these two magnets together, students found and commented that what they observed is the same as what they predicted, so they explained that that is why they did not change their explanation after their observation of two magnets.

In the group discussion after their observation, although Frank agreed with Freddie’s ideas about the positive and negative sides of the magnet, he said that there should be some special materials inside the magnet to make them work. Regarding Freddie’s positive and negative idea, Frank distinguished this idea as merely a generalization of the observation to describe “what a magnet does,” which did not explain
the underlying reasoning about why magnets work. He suggested, “Should I draw the material things like the lines because we have to explain why we think it does that?” and others agreed with this idea. Frank proposed the positive and negative mineral elements or material lines in the magnet as an explanation for the attraction and repulsion between two magnets. Thus, Frank combined the positive and negative side explanation that Freddie previously suggested with his own idea that there are special mineral elements inside the magnet.

According to an interpretation enabled by the multidimensional framework, Freddie appeared to use abstract verbal symbolic knowledge about the attraction and repulsion between the positive and negative sides to explain what happens between two magnets. As Freddie stated, “You could say it is like a battery. It had positive-positive, and it wouldn’t work.” The relationship between positive and negative may derive from verbal symbolic knowledge about the positive and negative sign on the battery.

Thereupon, Frank further developed a “material line” explanation.

[00:21:42]

221. Frank: You could explain the material in it like lines, like if it is a positive and a positive the lines will push away like they’re going away from it and so they go away from each other. But if you put positive to negative they’re like straighten up like army. They are all straight in lines and then they connect. That is what I think.

Frank was the first one to propose interactive moving elements inside the magnet. Due to the illustration of the activities of these microscopic elements inside the magnet, this explanation is categorized as Level 3-2 micro. According to the multidimensional
framework, this explanation is interpreted as an explanatory model that involves verbal symbolic knowledge; in this case, knowledge about the relationship between positive and negative ends, as proposed by Freddie. Frank’s explanatory model involves the core intuition that microscopic elements in the magnet as initiating agents react to other microscopic elements in the other magnet. Comparing Frank with other students in the FS and PS groups reveals that students consider the activities of microscopic elements inside the magnet to be essential to coherent explanatory models. The above students’ explanations show that merely describing the interaction between two magnets using the relationship between positive and negative or employing anthropomorphism did not enable them to develop explanatory models. I will further explore the barriers students face when attempting to developing coherent explanatory models later in the section of the analysis of the multidimensional framework of students’ explanations.

In terms of metaconceptual evaluation, the above paragraphs reflect that, before introducing black box activity and the criterion of visualization, Frank was able to spontaneously articulate his own criteria to evaluate others and his own explanations. Frank thought that Freddie’s idea that two positive and two negative would push each other away or one positive and negative would connect only describes “what a magnet does,” but does not explain why a magnet does and why this happens between two magnets, which is categorized as Level 1 explanation. Hence, Frank visualized unobservable, moving material lines inside magnets to explain the attraction and repulsion between two magnets; as a result, his explanation is categorized as Level 3-2 micro. I defined this self-generated criterion as the evaluation of “the nature of explanation,” which may lead Frank to visualize the material lines inside the magnet.
This analysis raises the question of whether other students in the FS and PS groups would develop similar self-generated criteria to Frank’s, and, if so, how these self-generated criteria may influence how they develop or revise their explanations. Figure 5 shows Freddie’s explanation of the positive and negative sides of the magnet and Frank’s “material line” explanatory model about why a magnet can attract other objects during their group discussion.

<table>
<thead>
<tr>
<th>Freddie</th>
<th>Frank</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image" alt="Freddie's explanation" /></td>
<td><img src="image" alt="Frank's explanation" /></td>
</tr>
</tbody>
</table>

*Figure 5. Freddie’s and Frank’s explanations in the group discussion of the first activity.*

The following discussion also shows how Frank evaluated others’ ideas. Although Felix agreed with the “material line” explanatory model, he proposed a different explanation, that there should be something like “positive and negative stuff,” which can be interchanged inside the magnet, so two magnets can stick together. In response, Frank argued that Felix’s idea is similar to the idea of static electricity. Felix, however, thought he was not talking about the static electricity in the magnet.

[00:25:55]

267. Felix: Because I am thinking that it just got something [...] because I don’t think they do that. I think some of these interchange with some of these [the stuff in the negative and positives sides]. So some plus would be in here and some negative would be in here that makes them and so the thing that makes them—
268. Frank: But they would neutralize.

269. Felix: I am saying like when they come together that is because this is trying to trade out with some of these.

270. Freddie: That is all a magnet thing so. [...] When you make a magnet, it has negative and positive.

271-283. [...] 

284. Frank: The only thing I disagree with Felix’s is that if the positive goes to a negative magnet, one of those magnets would neutralize.

285. Freddie: That is how magnets made. You have positive and negative in it.

286. Frank: No, I mean like if your static electricity if you shock somebody, you cannot walk up to somebody else and shock them again. You have to rub your feet on the carpet again or something because you are neutralized. They each neutralize because there is the right amount of positive and negative.

The above transcription portrays how Frank evaluated Freddie’s idea. The self-generated criterion that Frank used to evaluate the explanations is the consistency with other ideas or experiences. First, Frank thought that Felix’s idea was not consistent with his ideas about neutralization between positive and negative electricity. Frank questioned Felix’s idea about the interchangeable positive and negative electricity inside the magnet. Frank claimed (in line 268 and 284) that if these negatives and positives work like static electricity, there would be no way for them to interchange to stick each other, because these two would neutralize each other. Second, Frank also considered that Felix’s idea about interchangeable positive and negative static electricity is not consistent
with his experience about rubbing feet on the carpet and touching somebody else (in line 286).

This self-generated criterion of the consistency with other ideas or experiences was also employed by other students in the activities. By using the criteria of the consistency with other ideas or experiences, students would support or oppose a new idea based on whether or not that idea was consistent with other ideas or experiences. Here, Frank only employed this criterion to evaluate others’ ideas without the result of revising of his own idea or enabling others to revise their ideas. This self-generated criterion will be subsequently investigated in order to inspect whether Frank and other students employed this criterion to oppose, support, or revise their explanations. Figure 6 shows Felix’s explanation about moving positive and negative elements inside the magnets.

Figure 6. Felix’s explanation in the group discussion of the first activity

In the above group discussion, Frank proposed the “material line” explanation, which was agreed upon by Freddie. Felix proposed the “positive and negative stuff” explanation, which was not supported by the other two students. In other words, before introducing the criterion of visualization, all students already had developed or agreed with a Level 3-2 micro explanation, stating the properties and activities of the microscopic elements inside the magnet, regardless of their disagreement about whether these microscopic elements should be moving elements that pulled and pushed each other or interchangeable positive and negative elements that chained each other.
After students developed the group picture to explain attraction and repulsion between two magnets, I asked them to record their own explanation and to clarify whether their own current explanations are the same as their previous explanations from their original observation. Then, we moved on to do the black box activity in order to introduce the criterion of visualization later.

The black box activity and introduction of the criterion of visualization. I showed students one black box. I pulled the ropes of the box and asked them to guess what might be inside the box. All students creatively guess what might be inside the box, such as a magnet, a pulley, or two magnets tied to the yarn. Frank also proposed a different idea, saying, “Or it could be simply just two pieces of ropes. When you pull it like connected like these and when you pull it, it goes like this.” Then, without opening the box, I gave students paper rolls and two strings for them to make a box that looked like what they guessed the black box looked like.

While students were making their own boxes, students pulled and observed the ropes of the black box in order to figure out how to tie their ropes inside their own boxes. They tried different arrangements of their ropes, starting with one string and finding no success. Then, they put two ropes across each other, parallel with each other, or tied into a big circle in the middle of their own boxes. After they found that the ropes of their boxes did not move consistently as the ropes of the black box did, they tried to revise the arrangement of their ropes inside their boxes. Finally, Frank proposed to twist two ropes together inside the box and found that his box worked more closely to the black box than other students’ boxes. After the black box activity, they were asked to think of an example where scientists need to devise pictures of the inside of something without being able to
see inside. Students did not provide any example, but Felix perceived what he did was to make “an educated guess and a hypothesis.”

Since students did not provide any example, I showed them a picture of the inside of the earth and asked them whether anyone has been to the inside of the earth. Students illustrated how scientists can make this picture without being able to see the inside of the earth by providing the example of observing a volcano and lava, which enable scientists to know the structure of the earth, such as the core and mantle, and to know that the core might be hot. Frank also asserted that by observing sediment rock, scientists can reason about the different layers of the earth, and by putting all these observations together, scientists can come up with this picture.

I pointed out the similarity between the picture scientists made to explain the inside of the earth through their observation of some phenomena and the boxes that students made to imagine the inside of the black box through their observation of pulling the ropes. I related this process of creating images that a person cannot see but can explain what that person observed as visualization. At the end, students were asked to read the criterion of visualization, which states whether they have a still or moving picture about things that they cannot see that can explain what they observe. Felix related this criterion to what they did in the activities: “Like that [earth picture] is a still picture and that [the black box] is more like a moving picture since we can see them.”

**Reflection on the explanations by using the criterion of visualization.** After learning the black box activity and the criterion of visualization, all students judged that their explanations met the criterion of visualization without future articulation. They considered that they already hypothesized what might be inside the magnet. Nevertheless,
assessing their pictures by using the criterion of visualization made Felix recognize that his explanation about “interchanged positive and negative stuff” could not explain the repulsion between two magnets, so he started supporting Frank’s idea instead. Here, reflection on their explanations by using the criterion of visualization seemed to enable Felix to further examine his own ideas and be aware of the limited explanatory power of his explanation, although the criterion of explanatory power had not been introduced at this time.

On the other hand, Frank did not comment on Felix’s evaluation of the limited explanatory power of Felix’s idea and still used his self-generated criteria of the consistency with other ideas or experiences to evaluate Felix’s explanation. Frank claimed, “Since they [static electricity] jumped to it and it will just be like a spark, [but] you cannot see the spark and sometimes you put two magnets and the stuff coming together on your fingers, [but] you do not feel the shock.” Frank stated that according to Felix’s idea about the interchangeable positive and negative electricity, they should be able to see the spark or feel the shock when two magnets put close to each other, which is not consistent with his experience of putting two magnets together.

It seems that assessing their explanations by employing the criterion of visualization did not help Frank and Freddie to revise their explanations, but it helped Felix to be aware of the limitation of the explanatory power of his explanation and then support Frank’s idea instead. This raises two questions: (a) How using the criterion of visualization may help students evaluate and revise their ideas, and (b) when students may think their pictures meet the criterion of visualization without revising their explanations. Hence, in the following activities, students’ responses to the evaluation of
their explanations by using the criterion of visualization will be examined in order to explore when using this criterion would make students revise their ideas and how they revise them.

**Activity M2: Cutting magnets.**

**Overview.** The second day, students made their individual predictions, group observations, and their individual explanations for what happened while cutting a magnet into the smallest possible pieces, and they finally came up with the best group picture together to account for the co-existence of N and S ends on the smallest pieces. Next, students employed the criterion of visualization to reflect on their group picture. After the instructor introduced the criterion of explanatory power, students started to employ the criterion of explanatory power to reflect on their group picture. Finally, they compared their current group picture in M2 with their previous picture in the M1: Two Magnets Activity. I now go on to look in more detail at these interactions.

I began by demonstrating the big compass to students for the purpose of allowing students to identify the magnetic properties of the magnet. Students recognized this object as a compass and asserted that the arrow of the compasses would point to the North direction. Frank mentioned the information that he watched on the science channel: “Like there’s stuff in the earth and like the compass is also a magnet, so it’s like the earth is one big piece of metal, and it makes it point North.” I gave students another big compass and a bar magnet for them to test the two ends of compass arrow. They identified the North and South ends of the compass’s arrow and observed the attraction and repulsion between two compass arrows or between one bar magnet and one compass arrow. I pointed out that the compass arrow is like a small magnet, so we could cut this
small magnet instead of using a big bar magnet due to the technical difficulty.

**Prediction.** After that, I asked students to predict what would happen if they cut the magnet in half, in quarters, and then into the smallest pieces and recorded their explanation for their prediction. Frank made the prediction that the smallest pieces still have N and S on the two ends of the magnet, which is also agreed by the other student, Felix, because they thought the smallest pieces would be “like the shreds of the whole entire magnet.” Frank clarified, “I think if you have them [the smallest pieces] in the right order, they do what Felix said [to stick together], or they’ll all push away from each other.” Frank illustrated what he drew in the journal, which is showed in the following Figure 7.

In this picture, Frank drew the small circles as the smallest cut pieces of magnet also like small magnets, so they would attract or repel from each other. In the above prediction, given that this explanation was talking about the co-existence of N and S on the small pieces of the magnet instead of hypothesizing materials or elements inside the magnet, this explanation is categorized as Level 1. According to the interpretation from multidimensional framework, Frank and Felix’s explanations seemed to involve the implicit model that the pieces of something should be the same as the whole thing. Therefore, the smallest cut pieces are the small version of the big magnet, so these small pieces should behave like magnets.
Observation and explanation after observation. During their observation of cutting the magnet, students took turns to cut the compass arrow in half and one-fourth pieces. Then, they used the small compasses to test the two ends of the cut pieces of the magnet. They discovered the co-existence of N and S on each of the pieces of the magnet and recorded their observations in the group picture. All students were asked to write down their explanations for their observations of the co-existence of N and S on each of the pieces.

After the observation stage of the activity, Frank re-stated his own observation about the co-existence of N and S on each of the pieces. “I think this would happen because all of the magnets, no matter how small have a North and South magnetism.” On the other hand, Felix was the first one to propose the idea that a magnet is made out of a bunch of magnetic particles with N and S on them (N-S particles), which may later influence Frank’s explanation:

[00:27:14]

281. Felix: I put that I think they do because they are made of like North and South particles. There’s a bunch of particles, like magnet particles that are North and South. I showed the particles of North and South,
and I put tons of about one thousand equals a whole entire of magnet, and there’s a bunch of little particles together to make one giant magnet.

In the group discussion, they pondered whether the co-existence of N and S is related to the earth’s axis, which was proposed by Freddie, and finally agreed that a magnet would be made up of magnetic particles: Frank was the first one to start indicating N and S on the microscopic particles, which they drew by using a magnifying glass to enlarge the elements. Before, they only drew circles to represent elements or particles without indicating N and S on them. Inasmuch as they only mentioned about microscopic elements inside the magnet without referring to the activities of these elements, this group explanation is categorized as Level 2-2 micro. In other words, Frank’s explanations progressed from Level 1 to Level 2-2 micro during this group discussion.

According to the multidimensional framework, this agreed-upon group explanation seems to involve a simple image about many microscopic N-S particles in one magnet, which may be based on the same implicit model that *the pieces of something should be the same as the whole thing*. Hence, they may also hypothesize the co-existence of N and S ends on the particles as small magnets that can constitute a big magnet. It seems that this implicit model is employed to help them visualize microscopic elements. Thus, I will inspect this implicit model further to examine whether students apply it to explain other magnetic phenomena and whether this implicit model is utilized by other groups of students. Figure 8 shows the group picture before students evaluated it using the criteria of visualization and explanatory power. In the following picture, the
dots they drew were the particles inside the rock. The diamond shape is the compass magnet they can carve out of the rock. Then a magnifying glass was drawn above the rock to show the magnified N-S particles.

![Diagram of a compass magnet and magnifying glass](image.png)

*Figure 8.* The group picture before students evaluated their group picture by using the criteria of visualization and explanatory power in the second activity.

**Reflection on the explanations by using the criterion of visualization.** Before using the criteria to evaluate their explanation, all three of the students developed and agreed to the group explanation that putting magnetic particles together would become a magnet. While discussing visualization, all of them agreed that this group explanation met the criterion of visualization. As Frank illustrated, “We drew a bunch of big dots [the big circle has N and S in them]….And then we drew that it makes up the big rock. A big magnetic rock.” In other words, they considered drawing big dots making up a big magnet, thereby assisting them to visualize what happened inside the magnet. This is similar to what happened when students employed the criterion of visualization to reflect on their explanations in the M1 activity: Two Magnets Activity. Students perceived that drawing microscopic “material lines” or “N-S particles” met the criterion of visualization. The hypothesis that students regarded microscopic elements as meeting the criterion of
visualization will continue to be examined in the next activity.

Reflection on the explanations by using the criterion of explanatory power.

Next, the criterion of explanatory power was first introduced to students by asking them to read the definition of criteria on the poster and to contemplate whether their picture can explain most or all of their observations. During the discussion of explanatory power for the current observation, they all concluded that their group picture met the criterion of explanatory power: As Frank expressed, “We did show visualization, we did what we think is inside the magnet, we even drew the magnifying glass.” In other words, since students here already visualized N-S elements before examining their explanation using the criteria of explanatory power, they considered that they already explained what was inside the magnet, which accounted for their current observation, so that there was no need to revise their explanation.

When they were asked whether their group picture could explain how the elements or particles interacted, Frank started to draw to clarify the interaction and organization of these elements. He referred to the attraction between N and S of the elements and the repulsion between two N and two S ends of the elements as the formative parts of in the structure of the magnet: “North and South but then this one goes away because it’s South and North and then it connects into a North and the South. Another South and a North so they all connect.” Frank further clarified the interaction of these elements in the bar magnet and explained that the alignment of these N-S elements is consistent with the N and S of the magnet:

[00:47:05]

484. Frank: Because when they all connect, they end up making this and the
North are facing this way, and the South are facing this way, because a North would go onto a South, and then it would connect, but they’ll be a South on the other end so like North would be this way, and South would be this way, because they end up like forming this way and this way.

In the above explanation, Frank drew his idea on the group picture and illustrated that the different arrangements may make elements connect or push each other away. The N of particles would face the same way; the S of particle would face the other way. Owing to the same order of these elements, the N and S ends of the particles would connect with each other. Since Frank began to mention the activities of these microscopic elements, this explanation is classified as Level 3-2 micro. It seems that the reflection on the explanatory power of the explanations to account for what happens between N-S elements prompts students’ explanation to progress from Level 2-2 micro to Level 3-2 micro.

According to the multidimensional framework, this explanation is interpreted as an explanatory model because it considers N-S elements and the interaction and arrangement of these elements inside the magnet. In this explanatory model, Frank applied the same implicit model, that *the pieces of something should be the same as the whole thing*, as the above Level 2-2 micro explanation, which includes a simple image that a big magnet is composed by N-S elements just like small magnets. This explanatory model also further involves the core intuition that these N-S elements became initiating agents to act on other N-S elements in the magnet. In addition, verbal symbolic knowledge that the attraction and repulsion between N and S end, which was originally
employed to describe the interactions between two magnets, appeared to be further applied to interaction between microscopic N-S elements.

The above discussion of explanatory power for explaining what happened between these elements encouraged Frank to illustrate explicitly the relationship between these N-S elements and to further apply verbal symbolic knowledge about the attraction of repulsion between N and S ends from observable magnets to unseen N-S elements. Figure 9 shows Frank’s above explanation about the arrangement and interaction of N-S elements inside the magnet, which was supported by Felix and Freddie during group discussion.

Figure 9. Frank’s explanation which was supported by Felix and Freddie while discussing the criterion of explanatory power in the second activity.

When they were asked whether their group picture could explain the previously observed phenomenon in M1, Frank claimed that their group picture could also explain the attraction or repulsion between two magnets by using their current picture of the molecular level; Freddie and Felix also agreed with this explanation:

[00:49:32]

484. Frank: Because all the North are facing this way and since they try to connect like they did at the molecular level. They will try to
connect again except they just push away. Because if you put them together North and South and a few years of heat they'd become a giant or bigger magnet.

Thus, Frank maintained that the attraction between two ends of the two magnets were similar to the attraction and repulsion between two ends of the N-S particles. If these magnet-like particles or magnets were put together at the same order, they would become bigger magnets. Because he still referred to the activities of these microscopic elements, his explanation is classified as Level 3-2 micro as well. In terms of the multidimensional framework, Frank applied the same explanatory model for what happened between two magnets. This idea is different from how he explained the attraction and repulsion between two magnets in M1, in which he included unknown elements pushing and pulling each other. Here, reflecting on whether their explanations had the explanatory power to account for their previous observations may have helped students to apply their explanations to the previously observed phenomenon. Thus, I will further investigate whether the criteria of explanatory power can help students to apply their explanations or revise their explanations to account for other phenomena.

**Comparing group pictures.** At the end, all students were asked to compare their current group picture in the M2: Cutting Magnet Activity with the last group picture in the M1: Two Magnets Activity. There were able to spontaneously used criteria similar to the learned criteria to evaluate group pictures and select the final group picture of M2 as the best one. Frank seemed to spontaneously use criteria similar to the criterion of visualization to evaluate these two pictures. According to what Frank articulated in the discussion of criteria and the post-interview, he usually referred to better visualization as
the picture that better showed the inside of the magnet, so drawing N-S particles is better than drawing unknown elements. Here, he also noted, “We put little lines [in the first final picture] and now we actually have North/South particles melting into each other and going away from each other.”

During the reflection on the explanatory power of their group picture, Frank referred to better explanatory power as his reason for preferring the picture to include certain elements, such as moving N-S particles, which provide underlying reasons to better account for all of his observations. Frank offered two interpretations for what the criterion of explanatory power means. The first interpretation is the “nature of explanation” which is previously mentioned as one of Frank’s self-generated criteria in M1: Two Magnets Activity. Here, Frank reflected on the final group picture of the M1: Two Magnets activity: “Not as much [explanatory]. I mean it explains it as a generalization but I don’t think it gets the big picture like this [the final group picture of the M2: Cutting Magnet Activity].” He indicated that the final group picture of M1 was a generalization of the observation, but it did not have a picture to explain what actually happens inside a magnet, as the final group picture of M2 did.

The second interpretation is that the visualization of N-S elements leads to the picture having more explanatory power. Frank thought that the final group picture of M2 could explain cutting magnets better than the final group picture of M1, because he indicated, “We didn’t put North and South on any of those [the elements inside the magnet] [in the final picture of M1]. We did not put them connect or repelling away from each other [in the final picture of M1].” Here, the criteria of visualization and explanatory power seem to be interrelated or to facilitate each other. Hence, this raises questions
about whether students had similar understandings about the criterion of explanatory power and whether they thought that better visualization of hypothesized elements would lead to better explanatory power. This question will be further explored in the following M3: Metal Bars Activity and in the post-interview, and will be discussed in the section dedicated to the analysis of students’ metaconceptual evaluation.

**Overview.** Four days later, only Freddie and Frank participated in the third activity. They made individual predictions, group observations, and individual explanations about which part of the magnet could attract more metal bars and what would happen between the magnet and the metal bars. Then they created a group picture to account for their observation. During their group discussion, students were asked to employ the criteria of visualization and explanatory power to reflect on their group’s picture and, eventually, to compare their current group picture in M3 with their previous group picture in the M1: Two Magnets Activity and the M2: Cutting Magnet Activity. After comparing all the group pictures in these three activities, students developed their pictures to explain all their observations. They were asked to do so by evaluating their group pictures according to the criteria of visualization and explanatory power. I now go on to look in more detail at these interactions.

I started by showing students a small metal bar and asking them to guess what it was. Students tried to put it on the metal part of the desk and found these two metal objects did not attach to each other. Furthermore, there was no N and S symbol on the metal bar. As a result, they predicted this metal object as simply a metal, instead of a magnet. Then I gave them a small compass to allow them to test the object. They found that the arrow of the compass did not react to the metal, so they confirmed
prediction that the object was only a metal. Next, I showed them the bar magnet and asked them to test two ends of the bar magnet. Frank called the bar magnet a “magnetic metal.”

Prediction. After students distinguished the metal bar from the bar magnet, I asked them to predict which part of the magnet could attract more metal bars. Based on the same reason, both of them predicted that the metal bars would stick to any place on the magnet. As Frank said, “I think it can stick to any side, because it is just a piece of metal, so it doesn’t have a North or South sides, so it would repel.” Without consideration of the structure or different parts of the magnet, this explanation is categorized as Level 1. According to the multidimensional framework, the magnet is regarded an initiating agent to act on the metal bar. In the rest of the activity, Frank continuously revised the causal agency in order to better explain observed phenomena.

Observation and explanation after observation. During their observation, they discovered that two ends of the magnet can hold four metal bars, but none of the metal bars could stick to the middle part of the magnet. I put the magnet and metal bars on the table and asked them whether the metal bars would still stick to each other if I removed the magnet. Frank tried to remove the metal bars from each other and found these metal bars still attached to each other after the magnet was removed. Both students claimed these metal bars became temporary magnets. I gave them the small compass to test two ends of these metal bars, and they confirmed that these metal bars had become temporary magnets.

After their observation about what happened between the magnet and metal bars, they found that their prediction was different from their observation, so they started to
generate explanations to account for the different parts of the magnet. Frank claimed that there were magnetic materials inside the magnet, and that there was a “casing [container]” in the middle part of the magnet, so there was no magnetic force in the middle part. Since the “magnetecy,” as he coined it, went through the metal bars, they would stick to the magnet.

[00:21:11]

186. Frank: I think that both ends attract the same amount of metal, but the middle parts don’t attract. I think this because the magnetic material is on the inside and the sides, I think, the middle parts are like a casing, and then this is actually the stuff inside, but I am not sure. So the sides are more of like the stuff on the inside than the casing here….It [casing] is like a container, and these sides [the middle parts] are the stuff inside the container, and so they are magnetic, but I am not sure, and then I put [down the explanations in his journal] metal would stick to each other on the magnet. I think like this because the magnetecy goes to through the metal. So it will stick.

Freddie stated that Frank’s idea was similar to his. He posited that two ends were stronger than the middle part of the magnet, so the metal bars would stick to the two ends, and the magnetic force would go through these metal bars, thereby sticking to the magnet.

Frank and Freddie shared the same idea that there is no (or, at least, less) force in the middle part of the magnet, so metal bars would be pulled toward the two ends, and
that there must have been something being transferred from the magnet to the metal bars to make them stick to the magnet. In terms of the multidimensional framework, the first idea may have been developed based on the core intuition that more force would pull more objects and less force would pull fewer objects. Therefore, there must have been less or no force in the middle part of the magnet, so the middle part could not pull other objects. The second idea may be developed based on the implicit model that force is substance, so there must have been force-like physical substance going through the metal bars to make them stick to the magnet. Later, this intuitive core intuition and implicit model would be extended to explain macroscopic or microscopic, hypothesized entities they developed. I will examine other groups of students below, to discuss whether they used similar conceptual resources to those Frank and Freddie used to explain the same magnetic phenomena. Figure 10 shows Frank and Freddie’s group’s explanation before they employed the criteria of visualization and explanatory power to evaluate their explanations.

Figure 10. The group explanation before students employed the criteria of visualization and explanatory power to evaluate their explanations in the third activity.

Reflection on the explanations by using the criterion of visualization. After students developed their group picture, I asked them to evaluate their picture by using the criteria of visualization and explanatory power. This is the first time that students used the criteria to evaluate their explanation in the M3: Metal Bars Activity. Frank thought that their group picture did meet the criteria of visualization without revision of their
group picture. Then they drew another group picture to illustrate what they visualized inside the magnet and metal bars in the following Figure 11.

Here, their explanation is fragmented in two different parts. One part depicts how metal bars stick to the two ends of the magnet because of “magnetite” inside the magnet, and the “casing” or less magnetite makes the middle part of the magnet not work. The other part depicts how metal bars can stick to the magnet either because the “stuff” in the magnet reacts to the metal bars or because “stuff” in the magnet transfers into the metal bars, making the metal bars into a half-magnet. There is no connection between the ideas of magnetite and moving stuff inside the magnet.

Their first period of reflection on the criterion of visualization did not appear to help them revise their explanations, because their perceived hypothesized macroscopic elements met the criteria of visualization. However, it helped them to further clarify why their picture met this criterion by talking about the activity of the macroscopic “stuff” they hypothesized inside the magnet. Thus, part of their explanation moved from the previous Level 2-1 macro to Level 3-1 macro, but it did not make them connect these disconnected ideas.

Issues are raised here about whether employing the criteria of visualization and explanatory power would help students to develop more coherent explanations. A more “coherent” explanation is defined as employing the same elements to explain different observed phenomena or make connections between different elements proposed to account for different observed phenomena. A more “fragmented” explanation is defined as employing different elements or ideas to explain different observed phenomena, without articulating the relationships between different elements or ideas they proposed. I
will explore this in additional detail through the rest of the activity and further inspect it by examining other groups of student explanations. Figure 11 shows the group picture the FS1 students drew during the discussion of visualization. The two blackened dots represent the “stuff” inside the magnet.

![Figure 11](image)

*Figure 11. The group picture during the discussion of visualization in the third activity.*

*Reflection on the explanations by using the criterion of explanatory power.* In the discussion of explanatory power, students were asked to evaluate whether their pictures have the power to explain their observations in this and the previous activities. Frank pointed out that their current group picture could explain the M2: Cutting Magnet Activity and the M3: Metal Bars Activity, but could not explain the M1: Metal Bars Activity. He asserted, “The only thing that I don’t think it explains is how it attracts and repels… I think it is explanatory except that it doesn’t explain that [attraction and repulsion].” He applied his above macroscopic level of group explanation of M3 to explain the co-existence of N and S ends on small magnets in M2, which was also supported by Freddie. Frank clarified that when the magnet was cut, there was no cover on it to block the power out from the magnetite inside the magnet, so the middle part would become magnetic. Since this explanation provides a simple image of macroscopic magnetite in the magnet, without referring to the activities of the magnetite, it is categorized as Level 2-1 macro.
On the other hand, in order to account for M1, Freddie suggested a microscopic level of explanation: “We could draw like what we did on the one page in order to explain these particles going towards each other.” He proposed and drew the moving particles inside the magnet:

366. Freddie: This is North and North, and it shows how the particles are going away which the particles are running away, so the magnet says …they would probably go…They like retreat, but if you put North and South. It goes close to each other again, so they can pull each other together, and that’s why I drew particles going towards the magnet.

The above discussion of the limitation of explanatory power for explaining the M1: Two Magnets Activity made Freddie propose the activities of the microscopic particles inside the magnet; therefore, this explanation is categorized as Level 3-2 micro. Furthermore, Freddie and Frank considered that these different levels of explanation, which account for different magnet phenomena, helped each other. Figure 12 shows Freddie’s explanation involving moving particles to explain attraction and repulsion between two magnets.
Here, their first period of reflection, on the criterion of explanatory power in the M3: Metal Bars Activity, encouraged students to assess how their group picture can explain different magnetic phenomena, but reflecting on this criterion did not result in their using the same ideas or elements to explain all of their observations. Instead, these fragmented explanations are similar to the group explanations developed by the students in the PS groups, who also employed different ideas or elements to explain different magnetic phenomena. This brings up the questions about when the criteria of visualization and explanatory power only help students to clarify their explanations and when these criteria facilitate the revision of their explanations.

*Comparing group pictures.* I asked students to compare current and previous group pictures and select the best one from among their previous final group pictures of the M1: Two Magnets Activity and the M2: Cutting Magnet Activity and their current group picture of the M3: Metal Bars Activity. Frank spontaneously used criteria similar to explanatory power to justify the current group picture of M3 as the best picture:
390. Frank: I think these two [the current group picture of M3, Figure 11, and the final picture of M2, Figure 9] help to explain each other, except this one [the final picture of M1, Figure 5] is more about just how they go together….This one [the final picture of M1, Figure 5] here explains how they go together or repel. I think these two [the final picture of M2 and the current group picture of M3] explain what’s inside, but this one [the current group picture of M3] explains it more, because there is the bar [metal bar], and this one [Freddie’s current picture about attraction and repulsion between two magnets, Figure 12] is the same as this one [the final picture of M1] because it explains how they go together and repel.

The above justification of the best picture shows that Frank considered that the final picture of M1 only showed how two magnets attract or repel each other. However, the current group picture of M3 and the final picture of M2 were complementary, because these two explained what is inside the magnet, but the current group picture of M3 explained more, because it also explained how a magnet attracts metal bars. Yet, at this time, no one questioned the different levels of explanation and how they used different explanations to account for different phenomena without connection between these ideas.

**Reflection on the Explanations by Using the Criteria of Visualization and Explanatory Power.** After comparing their previous and current group pictures, students were asked to develop the best picture to explain all observations. At this time, in order to consolidate their ideas, Freddie then asked Frank whether their group picture was talking
about microscopic particles, which he proposed, or macroscopic magnetite, which Frank proposed (in line 429). Frank did not respond to Freddie’s question at that time, and he shifted the discussion to the shape of magnetite instead (from lines 430 to 440):

[00:55:27]

429. Freddie: Yes. I just have a question to Frank. Are those little particles microscopic? Are you talking about magnetite?

430. Frank: No, because you can cut it open and you see them. It wouldn’t be there’s nothing there.

431. I: Do you mean there is nothing there?

432. Frank: No, you cut it open and you can actually see the stuff.

433. I: How about you Freddie?

434. Freddie: Except if you say it is grains, Frank, like grain. Unless you put the magnet like this it would pour out?

435. Frank: No, it’s not powder. It’s like a rock.

436. Freddie: Oh, then I agree with that.

437. I: How about you? Do you have different ideas because you think it should more looks like grain?

438. Freddie: No.

439. I: No? How about you?

440. Frank: No, I think it looks like rock.

After they were asked to examine their picture by thinking about the criterion of visualization again, Frank considered that their group picture met the criterion of visualization and started drawing and articulating the relationships between particles and
magnetite in their final group picture. Frank clarified the relationships between particles and magnetite: “There’s rock and inside the rock are little particle things like atoms.” Frank illustrated the structure of magnets as microscopic elements inside the macroscopic magnetite of the magnet that act on other elements in other magnets or metal bars.

After Frank and Freddie distinguished the difference between microscopic and macroscopic structures and articulated the relationship between them, I asked the students to reflect on their group picture by using the criterion of explanatory power again, contemplating whether their previously chosen best group picture could explain their observations from different activities. Frank consistently employed the idea of there being microscopic elements or particles, instead of macroscopic magnetite, inside the magnet and metal bars to coherently explain the M1: Two Magnets Activity, the M2: Cutting Magnet Activity, and the M3: Metal Bars Activity, which was also supported by Freddie.

Here, the second reflection on the criterion of visualization enabled students to articulate different levels of explanation, and the second reflection on the criterion of explanatory power helped students to employ the activities of the microscopic N-S elements allowing them to coherently explain all of their observations in M1, M2, and M3. Yet, as mentioned above, the first reflection on the criterion of visualization only helped them to articulate the activities of macroscopic elements they hypothesized inside the magnet, and the first reflection on the criterion of explanatory power only helped them to be aware of the limited explanatory power of their current macroscopic explanation. This raises the questions: When do the criteria of visualization and explanatory power facilitate students to revise their explanations, and when do these
criteria not help them do so? This will be further explored in the subsequent section about how employing these learned criteria may encourage students in the FS groups to revise their explanation.

Ultimately, Frank employed coherent explanations at Level 3-2 micro, which involve the activities of microscopic elements inside the magnet to account for all magnetic phenomena. While explaining the attraction and repulsion between two magnets in M1, Frank clarified that these microscopic elements inside would stay away from each other when two N ends of the magnet faced each other; conversely, when the N end of the magnet faced the S end of the magnet, these elements would go together. To explain the co-existence of the N and S end of the cut magnets in M2, Frank stated that when the magnet is cut, the exposed part would become the other magnetic end of the elements.

To explain why two ends of the magnet would attract metal bars in a chain in M3, Frank expressed that the elements inside the two ends of the magnet react to the microscopic elements inside the metal bar, thereby making the metal bar a magnet, which would then react to and attract other following metal bars. He illustrated the microscopic elements in the magnet and metal bar as below:

[01:00:42]

487. Frank: Because this stuff [referring to the microscopic elements in the two ends of the magnet] reacts to the metal …so it makes the stuff [microscopic elements] inside the metal all weird, so it makes it [metal bar] into a magnet. And then it can attract this metal and then the same thing happens and it can attract this metal.

Figure 13 shows the final group picture of M3, which was proposed by Frank.
While Frank drew microscopic elements inside the magnet, at this time Frank did not indicate N and S on each element inside the magnet and metal bar, so he did not clearly articulate the relationship between N and S end of the particles. This problem was later pointed out by Frank in the post-interview when he compared his individual final pictures in the post-interview and this final group picture of M3.

Figure 13. The final group picture of M3, which was proposed by Frank.

The aforementioned progression of Franks’ explanation raises questions. The first question is whether other students made a similar progression to Frank’s when they were asked to reflect on their explanations using the criteria of visualization and explanatory power. The second question is whether using the criterion of visualization assisted other students in developing macroscopic or microscopic explanations. The third question is whether using the criterion of explanatory power assisted other students to be aware of the limitation of their current explanations and to employ microscopic explanation to coherently account for observed phenomena as Frank did.

Post-Interview. One or two days later, all students were interviewed individually, following the semi-structure interview protocol. At the beginning, every student reviewed what he or she had done in the previous group pictures and then drew his or her best
picture to explain the observed magnetic phenomena. In order to explore how students evaluated their pictures after these activities, they were asked to compare their individual final drawings with other group pictures. After that, they were asked to review what they wrote in the journal and what they were doing or thinking in the video. At the end, they were encouraged to talk about their experience using the criteria, journal, and group discussion in these activities, as well as their learning experiences about magnets. I will now consider Frank’s final explanation and metaconceptual evaluation in more detail.

Explanation for M1, M2, M3. Two days later, I interviewed Frank. I started by showing him the final group pictures in the previous three activities and asking him to recall what they drew in the previous activities. After Frank reviewed all previous final group pictures, I asked, “Now let’s draw a picture of a magnet which can explain what we have observed before in these three activities.” Frank drew the structure of the magnet and articulated his own drawing in Figure 14: “Those are the particles inside the magnetite that makes it magnetic.” Frank referred to the N-S particles: “It has to be like North [end of the particles] faces North [end of the magnet] and South [end of the particles] faces South [end of the magnet].” He also drew a container in the middle part of the magnet: “Because it has a container there so even if it [the middle part of the magnet] did have the same amount [of the particles], it [the container] would block it out.”
In this individual drawing in the post-interview, Frank explained the structure of the magnet by saying that there are N-S particles inside the magnetite making magnets magnetic. The N parts of the particles face the N end of the magnet. The S parts of the particles face the S end of the magnet. There is a “container” in the middle part of the magnet, so this container blocks the power from the middle part of the particles. Frank used moving N-S particles in the magnet and metal bars to account coherently for all of their observations. Since Frank used the activities of microscopic particles to explain their observations in different activities, all of these explanations are categorized as Level 3-2 micro in the M1: Two Magnets Activity, the M2: Cutting Magnet Activity, and the M3: Metal Bars Activity and represented in Figure 15.

When using his own picture to explain the M1: Two Magnets Activity, Frank drew and explained how the particles in the magnets would make two magnets attract and repel each other:

[00:17:19]

106. Frank: I think they will attract because all the South ones [the S of the particles] were the ones facing South [the South end of the magnet].
They [the particles] will go and stick to the sides like I say over here [about how metal bars stick to the magnet] and they like to form together and then stick, and when you take it off, it’ll [the particles] go back, and then when you put back there all the North ones [the particles in the N end of the magnet] like they sort of float away. Since the momentum of them is going, sort of pushes the magnet too.

According to his idea, this explanation shows that all the S parts of the particles inside face the S end of the magnet, and vice versa. The N and S end of the magnet would attract because these particles would move and stick to the end of the magnet. When the N and S end are moved away, the particles would go back to where they were. On the other hand, the N and N end would push each other away because the particles in the N end of the magnet float away, and the momentum of this moving would push the magnets.

When using his own picture to explain the M2: Cutting Magnet Activity, Frank maintained that when you cut any place of the magnet, N and S would co-exist on each of the pieces, because “all the particles are still facing North and South so it will still have North and South.” In other words, all N of the particles are still facing the N end of the magnet, and all S of the particles are still facing the S end of the magnet. The S end of the particles would stick to the N end of the particles.

When using his own picture to explain the M3: Metal Bars Activity, Frank claimed that the N-S particles in the magnet go to the end of the magnet where metal bars adhere. These N-S particles would react to the N-S particles in the metal bars, making the
particles move to align so that they would stick:

[00:11:29]

62. Frank: That’s what I think or just all the particles around here [in the magnet near the metal bar] would go there [to the end of the magnet where metal bars stick]… and then they react to the metal and make this [the metal bar] into a magnet too….And then so it makes those things [particles inside the metal bars] go and stick here, and then it is sort of a reaction make a little…It [the particles in the metal bars] would be North and South because they’d have to stick.

Afterward, this metal bar becomes a magnet, reacting, in turn, to the next metal bars. The longer the metal bar chain, the weaker the reaction. There is a container in the middle part of the magnet, which blocks the power from the middle part of the particles, so the metal bars would not stick to it.

According to the multidimensional framework, Frank’s theses explanations account for different phenomena involving similar conceptual resources. First, these explanations all refer to the interaction between N-S particles, so they all involve coherent explanatory models. Second, in these explanatory models, causal agency is attributed to the microscopic N-S particles in the magnet and other objects reacting to the magnet. Moreover, another core intuition, that more force would pull more objects and less force would pull fewer objects, is also employed to explain why the middle part the of the magnet is different from the two ends of the magnet. Third, these explanatory models all contain verbal symbolic knowledge about the attraction and repulsion between N and S ends to explain what happens between two magnets and N-S particles. Fourth,
the same implicit model that the pieces of something should be the same as the whole things is utilized to hypothesize the composition of magnets. Moreover, the implicit model, same outside→ same inside, is also used to clarify why metal bars would eventually behave like magnets, because what is inside the metal bar is similar to what is inside the magnet. In a subsequent section, I will examine whether the different conceptual resources Frank used are employed by students in the other FS and PS groups, as well. Figure 15 shows the above interpretation of Frank’s explanations in the post-interview according the multidimensional framework. This figure shows how Frank developed three coherent explanatory models to explain M1: Two Magnets Activity, M2: Cutting Magnet Activity, and M3: Metal Bars Activity.
The attraction of repulsion between the N and S end of magnet and N-S particles

Verbal symbolic knowledge

Specific Situation

M1: Two Magnets
M2: Cutting Magnet
M3: Metal Bars

Explanatory model

Implicit model

The pieces of something should be the same as the whole thing

Same outside → same inside

Core intuition

N-S particles-N-S particles-magnet or metal bar

More agency begets greater effects

Figure 15. The interpretation of Frank’s explanations in the post-interview.
Regarding metaconceptual evaluation, Frank spontaneously employed criteria similar to the criterion of explanatory power to evaluate the pictures before being asked to do so. When asked to compare all group pictures with his final individual picture, Frank deemed his final picture as the best because it could explain most of his observations:

[00:19:05]

116. Frank: Because I think it just explains more. I mean because it shows no matter how you cut it, the particles are facing North and South, and it explains what happens inside the metal bar, at least what we think happens inside the metal bar, and it explains what we think is happening inside the magnets, when you put the different faces towards it, and it explains why the magnet doesn’t stick to the middle and sides.

Frank additionally applied the criterion of explanatory power to compare and evaluate his final picture and the final group picture in the M3: Metal Bars Activity. Frank stated, “I just think it [his own final drawing] explains more, because you would just do a bunch of scribbles [in the metal bars] through out there [in the final group picture of M3].” Frank claimed that his final picture, in which he drew moving N-S particles, explains what happens between the magnet and metal bars better than the final picture of M3, in which they only drew scribbles to explain what happens between the magnet and the metal bars. On the basis of what Frank stated during the discussion of criteria in the activities and the post-interview, he attributed better explanatory power to the picture showing moving N-S particles because it provided underlying reasons to account for all of his observations.
After being asked again to use the criterion of visualization to examine the pictures in the post-interview, Frank also thought that his own picture had better visualization:

[00:20:41]

124. Frank: I think this one [Frank’s individual final drawing] has better visualization because it shows the different shapes of particles [N-S particles], and it shows what happened when you cut it, and it shows the magnet, and it shows the metal bars and stuff like that [what is inside the magnet and metal bars]...We didn’t put North or South or anything [in the particles of the M3: Metal Bars Activity].

During the discussion of criteria in the activities and the post-interview, Frank usually related better visualization to the picture that shows better what is inside the magnets and metal bars; thus drawing N-S particles in the magnet has better visualization than drawing unknown elements inside the magnet and metal bars. The influence of using these two criteria and the interaction between these two will be further analyzed in the students’ metaconceptual evaluation section.

**Students’ Self-Developed Explanations**

The above examples illustrate how Frank developed his explanations, and how he reflected on his explanations, by using the criteria of visualization and explanatory power as self-generated criteria. In this section I will examine all students’ explanations in detail. I summarize the pathways of individual students’ articulated explanations in Appendix F. Because of the difficulty keeping track of individual students’ explanations in a group, I
have perceived students as possessing any explanations they agreed to at that time, unless they proposed additional ideas or different ideas, or opposed the ideas that other proposed.

In this section, I analyze the various levels of sophistication and coherence of students’ explanations in the FS and PS groups in order to get a wider perspective on students’ explanations in pre-interviews, during the three activities, and in post-interviews. However, this primary analysis is necessarily cursory and does not provide detailed analysis of how students developed and revised their different levels of knowledge in their explanations. Rather, the following section provides a more detailed layer of analysis, using the multidimensional framework to make sense of how students used a variety of conceptual resources to develop and revise these explanations. Finally, I present a section on students’ self-developed explanations, examining how students employed the criteria of visualization and explanatory power as well as self-generated criteria to evaluate and revise their explanations. In the process, I reveal the correlations between students’ self-generated explanations and their metaconceptual evaluations.

**Different levels of students’ explanation.** The above example of Frank in the first FS group shows that he progressed from lower to higher levels of explanation and moved from more fragmented to more coherent explanations. In this section, the trajectory of other students’ explanations is tracked through their explanations in the pre- and post-interviews as well as their explanations in the activities. Of the students in the two FS groups, all students except Fiona made similar progress to Frank’s. However, students in the two PS groups had difficulty progressing to higher-level of explanations or coherent explanations.
This presentation of students’ explanations in the FS and PS groups will explore three findings. I will look first, at how students’ explanations moved from lower levels to higher levels in the FS groups, but stayed at similar levels in the PS groups. Second, I will consider under what conditions students’ explanations moved from lower to higher levels in the FS and PS groups. Third, I will discuss how students’ explanations reached more coherent states in the FS groups and stayed at more fragmented states in the PS groups.

In order to show the progression of students’ explanations, diagrams of individual explanations in different groups and in different activities are drawn in Figures 16, 17, 18, and 19. When the diagrams show that students’ explanations progressed from Level 1 to Level 3-2 micro in the same section, students actually did not go through Level 2-1 macro, 2-2 micro, and 3-1 macro. In other words, students’ explanations moved from Level 1 directly to Level 3-2, unless there is a dot in the line to show students did not move directly between these two levels, such as Faye’s explanations in the second FS group in the M1: Two Magnets Activity moving from 1, to 2-2 micro, and then to 3-2 micro in Figure 17. In addition, these diagrams only show students’ articulated explanations or show the explanations that students supported but did not include unarticulated explanations. Therefore, some segments are missing, which represents that students did not articulate their explanations or support other explanations at that time.

In order to show students’ coherent versus fragmented explanations, the diagrams of individuals’ explanations to account for current and previous observed phenomena at the M2, M3, and post-interview stages are recorded for each of the four groups in Tables 8, 9, 10, and 11, respectively. Here a more “coherent” explanation is defined as one that
uses the same elements to explain different observed phenomena, and a more
“fragmented” explanation is defined as one that uses different elements in which the ideas
are not clearly connected to an earlier idea. There are some difficulties deciding whether
individual students had coherent or fragmented explanations for various observed
phenomena in M2 and M3, because individual students may not have explicitly
articulated their personal explanations for certain phenomena during group discussion.

**The first fully scaffolded group.** The pattern of the progression of the first FS
group is that three students’ explanations moved from lower levels of explanation, such
as Level 1 or 2-1 macro in the pre-interview, to Level 3-2 micro at the end of every
activity, with those students offering coherent, Level 3-2 micro explanations in the
post-interview. The progressions of Frank’s, Felix’s, and Freddie’s explanations are
shown in Figure 16. The coherence versus fragmentation of their explanations is shown
in Table 8.
Figure 16. Different levels of explanation of the first FS group. IE = Individual Explanation; P = Prediction; GE = Group Explanation; V = Evaluation of the Explanation by Using the Criterion of Visualization; EPM2 = Evaluation of the Explanation by Using the Criterion of Explanatory Power to Account for M2; EPbt = Evaluation of the Explanation by Using the Criterion of Explanatory Power to Account for What Happen between the Elements; EPM1= Evaluation of the Explanation by Using the Criterion of Explanatory Power to Account for M1; VEP = Evaluation of the Explanation by Using the Criteria of Visualization and Explanatory Power in Order to Develop the Best Group Picture; EM1: Explanation for M1; EM2: Explanation for M2; EM3: Explanation for M3.
Table 8

Coherent Versus Fragmented Explanations in the First FS Group

<table>
<thead>
<tr>
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<th>M2: Two Magnets Activity (Explain M1 &amp; M2)</th>
<th>M3: Metal Bars Activity (Explain M1, M2, &amp; M3)</th>
<th>Post-interview (Explain M1, M2, &amp; M3)</th>
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<tbody>
<tr>
<td>Frank</td>
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<tr>
<td>Felix</td>
<td>Unclear (C or F)</td>
<td>No participation</td>
<td>C</td>
</tr>
<tr>
<td>Freddie</td>
<td>Unclear (C or F)</td>
<td>C</td>
<td>C</td>
</tr>
</tbody>
</table>

Notes. F (Fragmented) = Used different ideas or elements to explain each of the different observed phenomena; PC (Partially Coherent) = Used the same elements and connected ideas to explain some observed phenomena, but not all. C (Coherent) = Used the same elements and connected ideas to explain all observed phenomena.

Frank. Figure 16 displays that in the pre-interview, Frank offered a Level 1 explanation. In the post-interview, he offered a Level 3-2 micro explanation to account for all of his observations in the M1: Two Magnets Activity, the M2: Cutting Magnet Activity, and the M3: Metal Bars Activity. In the same activities, Frank’s explanations usually moved from Level 1 or 2-2 micro and finally reached Level 3-2 micro at the end of every activity. In terms of the evolution of levels of explanation, Frank usually made significant progress in group discussions before being asked to use the criteria to evaluate explanations in M1 and M2, while using the criterion of explanatory power to evaluate his or group pictures in M2 and M3, or after making observations in M3.

Table 8 demonstrates that in the M2, M3, and post-interview, Frank employed coherent explanations involving N-S particles to explain all of his current and previous observations. Although case study of Frank shows that he had employed fragmented explanations to explain different phenomena in the middle of M3, such as positing microscopic particles to explain M1 and macroscopic magnetite to explain M2 and M3,
Frank could eventually coherently employ microscopic particles to explain all observations by considering the criteria of visualization and explanatory power at the end of M3.

**Felix.** Figure 17 shows that in the pre-interview, Felix offered a Level 2-1 macro explanation. In the post-interview, Felix offered a Level 3-2 explanation to explain his observations in the M1: Two Magnets Activity, the M2: Cutting Magnet activity, and the M3: Metal Bars Activity. In the same activity, Felix’s explanation usually started at Level 1 and reached Level 3-2 micro or Level 2-2 micro by the end of activities. Although Felix did not show his support or articulate a Level 3-2 micro explanation in M2 and did not participate in M3, in the post-interview Felix could consistently use Level 3-2 micro explanations to account for M1, M2, and M3. In terms of the evolution of levels of explanation, Felix usually made significant progress in group discussion before being asked to use the criteria to evaluate their explanations in M1, or after making observations in M2. Table 8 displays that in the post-interview, Felix was able to employ N-S particles to explain coherently all of his observations, while he did not articulate how N-S particles could explain M1 in the M2 activity.

**Freddie.** Figure 16 also shows that in the pre-interview Freddie offered a Level 1 explanation. In the post-interview, he offered Level 3-2 explanations to account for all of his observations in the M1: Two Magnets Activity, the M2: Cutting Magnet Activity, and the M3: Metal Bars Activity. In the same activities, Freddie made a progression similar to Frank’s in M1 and M3, moving from Level 1 at the beginning to Level 3-2 micro at the end of every activity. This may be because even though Freddie sometimes had different ideas than Frank, Freddie would eventually agree with Frank’s ideas during the group
discussion. In terms of the evolution of levels of explanation, Freddie usually made significant progress, similar to Frank’s, in group discussions, before being asked to use the criteria to evaluate group explanations in M1, M2, and M3, or when using the criterion of explanatory power to evaluate pictures in M2 and M3. Table 8 shows that Freddie also employed the idea of microscopic particles to explain all of his observations in M3 and the post-interview, but he did not articulate how N-S particles could explain M1 in the M2 activity.

Although Felix and Freddie may have progressed in a manner similar to Frank’s when analyzing their levels of explanation, they developed different ideas in the post-interview. For example, Freddie agreed with Frank’s and Felix’s ideas about N-S particles during the M2: Cutting Magnet Activity, but he proposed ideas involving N particles and S particles in the post-interview, because he thought N particles and S particles could not go together. If these particles attempted to connect, they would become neutralized. Nevertheless, Freddie did not propose this idea during the M2 activity. Further analysis will be presented in the next section to interpret students’ explanations according to the multidimensional framework; this will elucidate how students employed different conceptual resources to develop different explanations.

**The second fully scaffolded group.** The pattern of the progression of the second FS group is that three students’ explanations moved from lower levels of explanation, such as Level 1 or 2-1 macro in the pre-interview, to gradually to reach Level 3-2 micro at the end of activities, except Fiona. In the post-interview, they employed Level 3-2 micro or Level 2-2 micro explanations to account for their previous observations. The progressions of students’ explanations in the second FS group are recorded in Figure 17.
The coherence versus fragmentation of their explanations is showed in the following Table 9.

Table 9.

<table>
<thead>
<tr>
<th>Levels of Explanations</th>
</tr>
</thead>
<tbody>
<tr>
<td>3-2micro</td>
</tr>
<tr>
<td>IE</td>
</tr>
</tbody>
</table>

M1: Two magnets

M2: Cutting magnets

M3: Metal bars

Post-interview

Figure 17. Different levels of explanation of the second FS group. IE = Individual Explanation; P = Prediction; GE = Group Explanation; V = Evaluation of the Explanation by Using the Criterion of Visualization; EPM2 = Evaluation of the Explanation by Using the Criterion of Explanatory Power to Account for M2; EPbt = Evaluation of the Explanation by Using the Criterion of Explanatory Power for to Account for What Happen between the Elements; EPM1 = Evaluation of the Explanation by Using the Criterion of Explanatory Power to Account for M1; EPM3 = Evaluation of the Explanation by Using the Criterion of Explanatory Power to Account for M3; EM1 = Explanation for M1; EM2 = Explanation for M2; EM3 = Explanation for M3.
Table 9

**Coherent Versus Fragmented Explanations in the Second FS Group**

<table>
<thead>
<tr>
<th>Activity</th>
<th>M2: Two Magnets Activity (Explain M1 &amp; M2)</th>
<th>M3: Metal Bars Activity (Explain M1, M2, &amp; M3)</th>
<th>Post-interview (Explain M1, M2, &amp; M3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Finn</td>
<td>Unclear (C or F)</td>
<td>Unclear (C or PC)</td>
<td>C</td>
</tr>
<tr>
<td>Faye</td>
<td>C</td>
<td>Unclear (C or PC)</td>
<td>C</td>
</tr>
<tr>
<td>Fiona</td>
<td>C</td>
<td>Unclear (F or PC)</td>
<td>C</td>
</tr>
</tbody>
</table>

*Notes.* F (Fragmented) = Used different ideas or elements to explain each of the different observed phenomena; PC (Partially Coherent) = Used the same elements and connected ideas to explain some observed phenomena, but not all. C (Coherent) = Used the same elements and connected ideas to explain all observed phenomena.

*Finn:* Figure 17 reflects that Finn offered Level 1 explanation in the pre-interview. In the post-interview, he offered Level 3-2 micro explanations for the M1: Two Magnets Activity and the M3: Metal Bars Activity and offered a Level 2-2 micro explanation for the M2: Cutting Magnet Activity without articulating the interaction of these elements inside the magnet. In the same activities, Finn’s explanations usually moved from Level 1 or 2-1 macro to Level 3-2 micro or 2-2 micro at the end of the activity. However, at the end of M3, Finn supported Faye’s Level 3-2 micro explanation and Fiona’s Level 1 explanation, so his explanations at this time are categorized as these Level 1 and Level 3-2 micro explanations, respectively. In terms of the evolution of levels of explanation, Finn usually made substantial progress while employing the criterion of visualization to reflect on the group explanation in M1, in the group discussion in M2 before being asked to use the criteria to reflect on explanations, and after observation in the M3. Table 9 shows that although Finn did not express clearly how his current explanations can also explain other observed phenomena in M2 and M3, he could finally develop coherent
explanations involving microscopic N-S elements to explain all of his observations in the post-interview.

**Faye.** As reflected in Figure 17, Faye expressed a Level 2-1 macro explanation in the pre-interview. In the post-interview, she expressed Level 3-2 micro explanations for the M1: Two Magnets Activity and the M3: Metal Bars Activity and a Level 2-2 micro explanation for the M2: Cutting Magnet Activity without articulating of the interaction of these elements inside the magnet. In the same activities, Faye’s explanations usually moved from Level 1 or 2-1 macro to Level 3-2 micro at the end of the activity. Nevertheless, at the end of M3, Faye supported Fiona’s Level 1 explanation and her own Level 3-2 micro explanation, so her explanations at this time are categorized as Level 1 and Level 3-2 explanations, respectively. In terms of the evolution of levels of explanation, Faye usually made substantial progress while employing the criterion of visualization to reflect on the group explanation in M1, while using the criterion of explanatory power to explain previous observations in M2, and in the group discussions in M2 and M3 before being asked to employ the criteria to reflect on explanations. Table 9 indicates that Faye finally employed coherent explanations involving microscopic N-S elements to account for all of her observations in M2, M3, and the post-interview.

**Fiona.** Fiona was different from other students in the FS groups. As reflected in Figure 17, Fiona offered a Level 1 explanation in the pre-interview. In the post-interview, she declared Level 2-2 micro explanations for the M1: Two Magnets Activity, the M2: Cutting Magnet Activity, and the M3: Metal Bars Activity without articulating the interaction of these elements inside the magnet. In the same activities, Fiona’s explanations usually moved from Level 1 or 2-2 micro to Level 1, Level 2-2 micro, or
Level 3-2 micro at the end of an activity. Compared with other students in the FS groups, Fiona seemed to have difficulty developing Level 3-2 micro explanations. This difficulty may be associated with an inability to apply the criteria of visualization and explanatory power, because Fiona was the only student who had difficulty articulating these two criteria in the post-interview. This difficulty will be discussed later. In terms of evolution of levels of explanation, Fiona usually made substantial progress when employing the criterion of visualization to reflect on the group explanation in M1, as well as when reflecting on the criterion of explanatory power during the group discussion without being asked to reflect on their explanations.

Table 9 shows that Fiona was able to employ N-S elements to explain coherently the observed phenomena in M2, but she had problems providing coherent explanations to explain all observations at the end of M3—she utilized microscopic elements to explain M1, but utilized magnetism or waves going through the metal bars to make the metal bars connect with the magnet to explain M3, while she did not articulate her explanation for M2. In the post-interview, while being asked to explain M1, M2, and M3, Fiona mentioned the N-S elements in the magnet or metal bars, without articulating the activities of these elements to support her statements about why two ends of magnet have the same or different force, why the magnet would give force to metal bars, or why the two ends have a stronger pull than the middle part of the magnet. Although there is no connection between these elements and the behavior of the magnet, her explanation is categorized as exhibiting “coherence,” since she mentioned a simple image of N-S elements in the explanations for M1, M2, and M3.

Even though Fiona had generated N-S elements just as most students in the FS
groups had, she had problems developing the same kind of Level 3-2 micro explanations they did. This problem may be due to her lack of consideration of the activities of N-S elements. In other words, she only employed N-S elements to explain the structure of the magnet, but not the behavior of the magnet. Another possible underlying reason for this problem may be associated with Fiona’s lack of understanding of the criteria of visualization and explanatory power. These difficulties will be presented at the section about students’ different metaconceptual evaluations.

**Summary of the fully scaffolded groups.** In terms of different levels of explanation, all students in the FS groups progressed from lower levels of explanation (Level 1 or Level 2-1 macro) to higher levels of explanation (mostly Level 3-2 macro) at the end of the activities and in the post-interview, except Fiona, who only developed Level 2-2 micro instead of Level 3-2 micro explanations in the post-interview. The similarity among these students in the FS groups is that no one in the pre-interview provided a microscopic level of explanation, but in the post-interview, most of them adopted microscopic N-S particles or elements to explain the magnetic phenomena, with the exception of Freddie. The exceptions that Fiona’s and Freddie’s explanations present will be further investigated in the section on multidimensional framework and metaconceptual evolution.

Figure 16 and Figure 17 show that students in the FS groups usually make major progress mostly while using the criteria of visualization and explanatory power to reflect on their explanations, during their group discussion to develop the best group picture before they were explicitly asked to employed the criteria to reflect on their explanations, or while developing their individual explanations after their group observation. Moreover,
all students in the FS groups could eventually develop coherent explanations to account for all of their observations after the three activities. In the post-interview, they employed microscopic models to explain coherently their observations in M1, M2, and M3. Even though they presented some fragmented ideas during the activities, such as what Freddie and Frank did in M3, or what Fiona did in M3, they could eventually articulate coherent explanations through employing the learned criteria to reflect on their explanations.

In the above summary about the progression of students’ explanations, it is clear that there is a similarity regarding when students started to develop N-S elements during the activities in FS groups. In the M1: Two Magnets Activity, students only developed microscopic elements or particles, but in the M2: Cutting Magnet Activity, they started to develop explanations of microscopic N-S particles or elements during group discussion or when using the criterion of visualization to evaluate their group pictures. However, in the M3: Metal Bars Activity, students did not refer to microscopic N-S elements until they were asked to reflect on the criteria of visualization and explanatory power together in order to develop the best picture, or until they found their explanation could not cover their observations in M2 and tried to come up with the best pictures to explain all observations.

**The first partially scaffolded group.** The pattern of progression of the first PS group is that the explanations of the two students in this group either moved slightly from lower to higher levels of explanation or stayed at the same level. They provided Level 2-1 macro explanations in the pre-interview and gradually reached Level 3-1 macro or Level 2-1 macro at the end of activities. In the post-interviews, they employed explanations at Level 3-1 macro or Level 1 to explain their previous observations. The progressions of
students’ explanations in the first PS group are recorded in Figure 18, in which the horizontal axis is different from the ones in the FS groups, since students were not asked to reflect on their explanations by using the criteria of visualization and explanatory power. The coherence versus fragmentation of their explanations is showed in the following Table 10.
Levels of explanations

Figure 18. Different levels of explanation of the first PS group. IE = Individual Explanation; P = Prediction; GE = Group Explanation; BE = The Best Group Explanation after Comparing All Group Pictures; BEM2 = The Best Group Explanation to Account for M2 after Comparing All Group Pictures; BEM1 = The Best Group Explanation to Account for M1 after Comparing All Group Pictures; EM1= Explanation for M1; EM2=Explanation for M2; EM3=Explanation for M3.
Table 10

**Coherent Versus Fragmented Explanations in the First PS Group**

<table>
<thead>
<tr>
<th>Activity</th>
<th>M2: Two Magnets Activity (Explain M1 &amp; M2)</th>
<th>M3: Metal Bars Activity (Explain M1, M2, &amp; M3)</th>
<th>Post-interview (Explain M1, M2, &amp; M3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pearl</td>
<td>F</td>
<td>PC</td>
<td>F</td>
</tr>
<tr>
<td>Peggy</td>
<td>F</td>
<td>PC</td>
<td>F</td>
</tr>
</tbody>
</table>

*Notes.* F (Fragmented) = Used different ideas or elements to explain each of the different observed phenomena; PC (Partially Coherent) = Used the same elements and connected ideas to explain some observed phenomena, but not all. C (Coherent) = Used the same elements and connected ideas to explain all observed phenomena.

*Pearl.* Figure 18 reflects that in the pre-interview Pearl offered a Level 2-1 macro explanation. In the post-interview, Pearl used a Level 3-1 macro explanation to account for the M1: Two Magnets Activity, and used Level 1 explanations to account for the M2: Cutting Magnet Activity and the M3 Metal Bars Activity. In those latter activities, Pearl did not move beyond articulating her own observations or providing macroscopic levels of explanation without hypothesizing microscopic elements as students in the FS groups did. In terms of the evolution of levels of explanation, Pearl usually made some progress while developing the best group picture after comparing their current group pictures with previous group pictures in M2 and M3.

Table 10 records that Pearl usually employed fragmented explanations in the activities and the post-interview. There is one exception, at the end of M3, when Pearl shifted to a more partially coherent explanation, because Peggy suggested that they should include energy ideas in M3 and M2, because only energy could explain how magnets work. Yet, in the post-interview, for explaining the M1: Two Magnets Activity,
she employed a Level 3-1 macro explanation that the attraction and repulsion between the metal and the iron end of the magnet explains the attraction and repulsion between two magnets. To explain the M2: Cutting Magnet Activity observations, she provided a Level 1 explanation, that the co-existence of the N and S ends of the magnet is because these pieces should have N and S side, so they can attract or push each other away. For explaining the M3: Metal Bars Activity, she offered a Level 1 explanation that energy at the two ends would travel from the magnet to metal bars so that the metal bars would stick to the magnet. Pearl’s explanations in the post-interview are similar to those she articulated in the individual activities. She simply combined these different levels of explanation and disconnected elements or ideas together in the post-interview without attempting to revise of these explanations to coherently explain all of her observations.

**Peggy.** Figure 18 shows that, similar to Pearl, Peggy offered a Level 2-1 macro explanation in the pre-interview, She offered a Level 3-1 macro explanation to account for the M1: Two Magnets Activity, and used Level 1 explanations to account for the M2: Cutting Magnet Activity and the M3 Metal Bars Activity in the post-interview. Compared to Pearl, Peggy usually showed a similar progression in the interviews and activities, except in M1, in which Peggy’s explanations progressed from Level 1 to Level 3-1 macro during group discussion for deciding the best group picture, whereas Pearl stayed at Level 3-1 macro. Like Pearl, Peggy either rearticulated her original observations or provided only macroscopic levels of explanation, without hypothesizing microscopic elements, as students in the FS groups did. In terms of the evolution of levels of explanation, Peggy usually made some progress while discussing the best picture in the group in M1 and while developing the best group picture after comparing the current
group picture with previous group pictures in M2 and M3. Table 10 reveals that, again like Pearl, Peggy employed fragmented explanations in most of the activities and the post-interview.

**The second partially scaffolded group.** The overall pattern of progression of the second PS group is that these three students—Paul, Patty, and Paige—may not always move from lower to higher levels of explanation. They provided Level 1 or Level 2-2 micro explanations in the pre-interview, gradually reached Level 3-2 micro, Level 2-2 micro, or Level 1 at the end of the activity, and then employed various levels of explanation to account for their previous observations in the post-interview. Paul and Patty were the only two students who offered Level 2-2 micro explanations including molecules in the magnet in the pre-interview, which is higher than other students in the FS and PS groups. The progression of students’ explanations in the second PS group is recorded in Figure 19, in which the horizontal axis is different from those in the FS groups, since students are not asked to reflect on their explanations by using the criteria of visualization and explanatory power. The coherence versus fragmentation of their explanations is shown in Table 11.
Figure 19. Different levels of explanation of the second PS group. IE = Individual Explanation; P = Prediction; GE = Group Explanation; BEM1 = The Best Group Explanation for Accounting for M1 after Comparing All Group Pictures; BEM2 = The Best Group Explanation for Accounting for M2 after Comparing All Group Pictures; BEM = The Best Group Explanation for Accounting for More Molecules in Two Ends after Comparing All Group Pictures; BEM3 = The Best Group Explanation for Accounting for M3 after Comparing All Group Pictures; EM1 = Explanation for M1; EM2 = Explanation for M2; EM3: Explanation for M3.
Table 11

Coherent Versus Fragmented Explanations in the Second PS Group

<table>
<thead>
<tr>
<th></th>
<th>M2: Two Magnets Activity (Explain M1 &amp; M2)</th>
<th>M3: Metal Bars Activity (Explain M1, M2, &amp; M3)</th>
<th>Post-interview (Explain M1, M2, &amp; M3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Paul</td>
<td>F</td>
<td>F</td>
<td>F</td>
</tr>
<tr>
<td>Laura</td>
<td>F</td>
<td>F</td>
<td>F</td>
</tr>
<tr>
<td>Paige</td>
<td>F</td>
<td>F</td>
<td>F</td>
</tr>
</tbody>
</table>

Notes. F (Fragmented) = Used different ideas or elements to explain each of the different observed phenomena; PC (Partially Coherent) = Used the same elements and connected ideas to explain some observed phenomena, but not all. C (Coherent) = Used the same elements and connected ideas to explain all observed phenomena.

Paul. Figure 19 demonstrates that in the pre-interview, Paul offered a Level 2-2 micro explanation. In the post-interview, Paul provided Level 3-2 micro explanations to account for the M1: Two Magnets Activity and the M3: Metal Bars Activity, and provided a Level 1 explanation to account for the M2: Cutting Magnet Activity. Paul already had an existing idea about microscopic molecules before the activities, so in the end he could finally articulate and employ the activities of different microscopic elements to explain M1 and M3, but did not employ microscopic elements to explain M2 during the activities or in the post-interview. In terms of the evolution of levels of explanation, Paul usually made some progress during the group discussion in M1 and M3, while developing the best group picture to account for M1 after comparing all group pictures in M2, or while developing their individual explanations after group observation in M3.

Table 11 reflects that Paul employed fragmented explanations to account for different phenomena in the activities and in the post-interview. For explaining the M1: Two Magnets Activity, Paul employed a model of interaction between molecules to
explain the attraction and repulsion between two magnets, at Level 3-2 micro. For explaining the M2: Cutting Magnet Activity, Paul claimed that air causes the cut pieces become small magnets, at Level 1. For explaining the M3: Metal Bars Activity, he again used a molecular model to explain the two strong ends of the magnet and voiced a model about magnetic charges passing through the metal bars to explain why metal bars would stick to the magnet. As with those of other students in the PS groups, Paul’s explanations in the post-interview are similar to what he articulated in the activities. He merely restated his original explanations reflecting these different levels and disconnected elements or ideas in the post-interview without revising any of these explanations in an attempt to explain all observations coherently. Hence, although Paul developed a Level 3-2 micro explanation to account for M1 and M3, his explanations, which used molecules, air, and charges to account for different magnetic phenomena, are defined as fragmented because he used different, unconnected ideas to explain different phenomena.

Patty. Figure 19 reflects that in the pre-interview, Patty offered a Level 2-2 micro explanation. In the post-interview, Patty provided a Level 2-2 micro explanation for the M1: Two Magnets Activity, a Level 1 explanation for the M2: Cutting Magnet Activity, and a Level 3-2 micro explanation for the M3: Metal Bars Activity. Like Paul, Patty already had existing ideas about microscopic molecules before the activities, so in the end she could involve different microscopic elements to explain M1 and M3, but not to explain M2 during the activities or in the post-interview. In terms of the evolution of levels of explanation, Patty usually made some progress during group discussion in M1, while developing the best group picture to account for M1 after comparing all group pictures in M2, or while developing her individual explanation after group observation in
As Table 11 reflects, Patty employed fragmented explanations to account for different phenomena in the activities and in the post-interview. For explaining the M1: Two Magnets Activity, Patty employed a Level 2-2 micro explanation, that molecules in the magnet explain the attraction and repulsion between two magnets. For explaining the M2: Cutting Magnet Activity, Patty claimed a Level 1 explanation, that “they [cut small pieces] will become their own magnets because one magnet can only have two poles.” For explaining the M3: Metal Bars Activity, Patty used more magnetic charges to explain two strong ends of the magnet and flowing magnetic charges to explain how metal bars adhere to the magnet. As with other students in the PS groups, Patty’s explanations in the post-interview are similar to what she articulated in the activities. She merely restated these different levels of explanation and disconnected elements or ideas in the post-interview without revising them in an attempt to explain all observations coherently. Therefore, even though Patty developed a Level 3-2 micro explanation to account for M3, her explanation used different elements to account for different magnetic phenomena and are, therefore, fragmented, without connection between them.

*Paige.* Figure 19 displays that in the pre-interview Paige offered a Level 1 explanation. In the post-interview, Paige provided a Level 2-2 micro explanation to account for the M1: Two Magnets Activity and Level 1 explanations to account for the M2: Cutting Magnet Activity and the M3: Metal Bars Activity. Unlike Paul and Patty, Paige did not provide explanations about microscopic elements before the activities, but she provided a simple image of microscopic elements to explain M1, but not M2 and M3 in the activities or in the post-interview. In terms of evolution of levels of explanation,
Paige usually made some progress, along lines similar to Patty’s.

Table 11 reflects that Paige employed fragmented explanations to account for different phenomena in the activities and in the post-interview. To explain the M1: Two Magnets Activity, Paige employed molecules to explain the attraction and repulsion between two magnets, at Level 2-2 micro. For explaining in the M2: Cutting Magnet Activity, Paige asserted a Level 1 explanation that the co-existence of N and S ends of the pieces is possible because these pieces should always have two ends. For explaining the M3: Metal Bars Activity, Paige offered a Level 1 explanation in which the magnet functions as a power source to charge the metal bars, so the power would travel through the magnet and metal bars. As with other students in the PS groups, Paige’s explanations in the post-interview are similar to what she articulated in the activities. She simply restated answers reflecting different levels and combined disconnected elements or ideas in the post-interview without revising them to try to explain all observations coherently. Paige retained fragmented, lower levels of explanation to account for different magnetic phenomena after the activities.

Summary of the partially scaffolded group. In terms of different levels of explanation, students in the PS groups progressed from Level 1, 2-1 macro, or 2-2 micro to Levels 1, 2-2 micro, 3-1 macro, or 3-2 micro. In other words, compared to their explanations in the pre-interview, these students’ explanations improve only slightly in the post-interview, where they reflect a mixture of higher and lower levels of explanation. They provided different, fragmented ideas, or different levels of explanation, to account for different phenomena, without articulating the relationship between these ideas.

The similarity among these students in the PS groups is that, when students could
make only a Level 2-1 macro or Level 1 explanation without referring to microscopic elements in the pre-interview, they were unlikely to develop microscopic levels of explanation. Paige is the single exception to this. For example, Pearl and Peggy, in the first PS group, only incorporate the idea of macroscopic element in the pre-interview; during the activities and post-interview, they did not hypothesize microscopic elements to explain magnetic phenomena. However, Paige, in the second PS group, did not propose microscopic elements in the pre-interview, but she finally incorporated the idea of microscopic elements in the activities and in the post-interview through the group discussion with Paul and Patty, who themselves proposed microscopic levels (2-2 micro or 3-2 micro) of explanation in the pre- and post-interview and during the activities. On the other hand, Paul and Patty, who offered Level 2-2 micro explanations of a simple image of molecules inside the magnet in the pre-interview, developed Level 3-2 micro explanations to articulate the relationship between these molecules or charges to explain M1 and M3 during the activities or in the post-interview.

Figure 18 and Figure 19 demonstrate that students in the PS groups usually made some progress mostly while developing the best group explanations before and after comparing group pictures, or while developing their individual explanations after their group observation. Furthermore, all students in the PS groups employed fragmented and unconnected explanations or different levels of explanation to explain M1, M2, and M3 observations in most of the activities and the post-interview. Nevertheless, for students in the PS groups, developing higher, Level 3-2 micro explanations did not necessary mean that students employed coherent explanations, because students sometimes used different, unrelated micro elements to explain different phenomena. For instance, using a model of
moving molecules to explain the attraction and repulsion between two magnets but using a model of flowing magnetic charges from the magnet to the metal bars to explain why metal bar would stick to the two ends of the magnet. While developing the best group picture by comparing pictures during the activities, they usually put these fragmented ideas in different pictures into one group picture, without articulating the relationships between these ideas and without revising their current and their previous pictures. In other words, it appears that students in the PS groups developed fragmented explanations, maybe because they did not feel the need to develop one explanation to account for all of their observations.

The comparison of students’ explanations in the fully and partially scaffolded groups. The above analysis of students’ explanations by using three main levels of explanation discloses that students’ explanations in the FS groups shared similar trajectories. So did the students’ explanations in the PS groups. The above findings show that students in the FS groups made more progress in terms of levels of explanation and had higher degrees of coherence of explanation than students in the PS groups. With regard to the levels of their explanation, students in the FS groups progressed from describing their observations, or macroscopic levels of explanation, to developing microscopic levels of explanation. However, other students, in the PS groups, usually had difficulty developing microscopic levels of explanation, except for Paul and Patty, who had already provided the microscopic level of explanation in the pre-interview.

Considering the overall progression in terms of levels of explanation, student in the FS and PS groups all made significant progress during group discussion, whether they were asked to employ the metaconceptual modeling criteria to reflect on their explanations.
or not. As I have diagrammed in Figure 16, 17, 18, and 19, group discussion makes students share their information, so students usually would either combine their ideas or use one idea to confront each another, usually with the result of achieving higher levels of explanation. However, because this study focuses on individual students’ thinking, group discussion is beyond my current scope; nevertheless, it is an important area for future research to explore.

The comparison of different group pictures functions differently between the two different kinds of groups. For the students in the FS groups, comparing pictures enabled them to justify which group picture is better by employing and articulating their own criteria or the learned criteria, thereby helping them to revise ideas while developing a new best picture at the end. For the students in the PS groups, comparing pictures enabled students to develop the best picture by including different ideas from different pictures without revising of those ideas.

Concerning the coherence or fragmentation of explanations, most students in the FS groups, by reflecting on their explanations using the learned criteria, revised their explanations into more coherent explanations by using microscopic N-S elements to account for all of their observations. In contrast, all students in the PS groups developed fragmented explanations by positing different explanations, such as molecules, power sources, air, and magnetic charges to explain different magnetic phenomena, without making connections between these ideas or revising these ideas.

Figures 16 to 19 and Tables 8 to 11 record the pathways of development of students’ explanations in terms of level and coherence. The diagram in Figure 20 further summarizes the differences between students’ explanations in the FS and PS groups at the
end of the M2: Two Magnets Activity and M3: Metal Bars Activity, as well as in the post-interview. If the level or coherence of students’ explanations were not clear because students did not articulate their ideas, their explanations were not recorded in this diagram.

For the FS groups, most students proposed the activities of N-S microscopic elements to explain all magnetic phenomena after M2, so their explanations were categorized as Level 3-2 micro, coherent explanations. However, some explanations were classified as Level 2-2 micro and coherent in M2 and post-interview. Some students only proposed a simple image of microscopic N-S elements inside the magnet, without clarifying the activities or interaction between these elements to explain the dipole of the cut pieces of the magnet in M2.

On the other hand, for the PS groups, students proposed different elements and levels of explanation for different magnetic phenomena in the same activities and in the post-interview; therefore, their explanations were not only classified as fragmented, but were scattered across different levels of explanation. For example, at the end of the M2: Cutting Magnet activity, after comparing the current group picture from M2 and the previous group picture from the M1: Two Magnets Activity, Patty (P4) used unrelated and different levels of explanation to develop the best explanation for the different magnetic phenomena observed in M1 and M2. She employed a simple image of molecules inside the magnet, at Level 2-2 micro, to explain the attraction and repulsion between two magnets in M1 and used her observation about dipoles of small cut magnets, at Level 1, to explain M2.

At the end of the M3: Metal Bars Activity, after comparing previous and current
group pictures from different activities, Patty agreed to add a Level 1 explanation, about the magnet’s charging the metal bars to explain how metal bars stick to it, into their previously developed final group explanation in M2. Thus, her explanations are still categorized as Level 1 and Level 2-2 micro at the end of M3, because she claimed that using disparate ideas to account for different magnetic phenomena would develop the best single picture.

In the post-interview, after reviewing all group pictures in M1, M2, and M3, Patty drew her own best picture to account for magnetic phenomena. In order to explain three different magnetic phenomena, she offered different levels and fragmented explanations, which were similar to the final group explanations of the M3 activity. She still used a Level 2-1 micro explanation about a simple image of molecules for M1 and used a Level 1 explanation about dipole of cut, small magnets for M2. Nevertheless, for M3, she further articulated how the activity of magnetic charges makes the metal bar stick to the magnet, so her explanation is categorized as Level 3-2 micro, instead of only regarding the magnet as a battery-charging metal bar, as the previous final group picture in the M3 activity. Hence, her explanations are categorized as fitting into three different levels, Level 1, Level 2-2 micro, and Level 3-2 micro.

In summation, the development of students’ explanations in the FS groups reflects a revision process, so those students ultimately developed coherent, higher-level explanations. In contrast, the development of students’ explanations in the PS groups involved adding different ideas together without revision, so those students ultimately presented fragmented explanations spanning different levels. In the next section, the progressions of students’ explanations will be inspected in further detail, to explore how
students’ metaconceptual evaluation influenced how they employed different conceptual resources to develop higher- versus lower-level or coherent versus fragmented explanations.
Figure 20. Different levels and coherence of explanations of FS and PS groups. Fully scaffolded groups (F1 = Frank, F2 = Felix, F3 = Freddie, F4 = Finn, F5 = Faye, F6 = Fiona); Partially scaffolded groups (P1 = Pearl, P2 = Peggy, P3 = Paul, P4 = Patty, P5 = Paige)
The Multidimensional Framework of Students’ Explanations

In this section, I will interpret students’ explanations by utilizing the multidimensional framework (Brown, 1993, 1995a, 1995b; Cheng & Brown, 2010), exploring the conceptual resources they involved in their self-developed explanations and how they revised or changed them.

When and how students developed explanatory models. In the previous, data analysis part of the methodology chapter, students’ explanations at Level 3-1 macro and Level 3-2 micro referred to the activities of hypothesized, unseen elements inside the magnet, so Level 3 explanations are interpreted as involving explanatory models in their explanations.

In the pre-interview and at the prediction stage of the activities, most students usually based their answers either on unconscious levels of knowledge (such as the intuition that a magnet is a direct initiating agent acting on other objects, and the implicit models assuming that force is a property of the magnet), or on conscious levels of knowledge (such as verbal symbolic knowledge about attraction and repulsion between like or unlike poles of the magnet). Only two students, Pearl and Paul, in the PS groups, provided explanatory models about the interactions between two different types of material in the two ends of the magnet or the interactions between moving molecules inside the magnet at the prediction stage in the M1: Two Magnets Activity.

Figures 16 to 19 and Tables 8 to 11 revealed that, except for Fiona, students in the FS groups did eventually develop coherent explanatory models in the activities and the post-interview. Although several students in the PS groups sometimes also developed explanatory models to explain certain magnetic phenomena, their explanatory models are...
different from the ones developed by students in the FS groups. This difference is interpreted using different conceptual resources in the multidimensional framework. In the next section, about students’ different levels of conceptual resource, I will show how different groups of students activate or apply different conceptual resources to develop or revise their explanations.

**How students involve core intuition and implicit models to develop explanations.** This section describes how students employ or revise certain core intuitions or implicit models in order to explain magnetic phenomena. Doing different activities or learned, metaconceptual modeling criteria may promote students to utilize different conceptual resources in their explanations.

**Core intuitions.** According to the multidimensional framework, core intuitions deal with students’ attributions of causal power or agency. In this study, all students in the FS and PS groups reasoned about using ideas of causal agency, whether they developed higher levels of explanation or not. In particular, the following agentive ideas were present for all students: 1) all students posited causal entities, including observable magnets, unobservable macroscopic entities, or unobservable microscopic entities, as initiating agents, initiated agents, and affected responders; 2) they all employed Ohm’s p-prim (diSessa, 1993), that more agency begets greater effects. This core intuition was consistently employed by students to explain different parts of the magnet, whether they eventually developed higher levels of explanation or not.

On the other hand, students in the FS and PS groups have different pathways in revising the attribution of causal agency. For the FS groups, most students revised their causal agents, moving from attributing agency to the magnet itself or unseen macroscopic
entities inside the magnet, to attributing agency to unseen microscopic N-S entities inside the magnet. However, the PS groups tended to continue to attribute agency to the same entities with which they started.

Figures 16 to 19 display the two different progressions. Figures 16 to 17 show the progression of students’ explanations in the FS groups. These diagrams illustrate that students in FS groups revised the causal agents from observable magnets to become unobservable microscopic elements at the end. Figures 18 to 19 manifest the progression of students’ explanations in the PS groups. These diagrams indicate that students in the PS groups posited various observable and unobservable causal agents to explain different magnetic phenomena at the end, adding these new explanations onto the explanations they had offered at the beginning. Even though the diagram of PS groups also shows some progressions in terms of levels of explanation, this is because students added higher-level of causal agents but still kept their original, lower levels of causal agent, too.

For the FS groups, there were different ways to revise the attribution of causal agency in the activities. This is detailed in Figure 21, in which the arrow shows the direction that students revised the causal agents. The symbols (e.g., FS1-M2) represent when this revision happens. The figure also indicates when and how students revised their causal agents, with or without being asked to reflect on the modeling criteria. The vertical dimension represents different levels of visualization including observational, macroscopic, and microscopic levels. The horizontal dimension represents the explanatory power of the elements they proposed. If certain causal agents were employed by students to explain more magnetic phenomena, these causal agents are regarded as having more explanatory power than others. Figure 21 illustrates that students considered
their explanations to have more explanatory power if they used N-S elements as causal agents than using other causal agents, such as monopoles N and S elements, microscopic N-S elements, macroscopic element, and magnets themselves. Most students agreed that attributing causal agency to N-S elements allowed them to explain all magnetic phenomena. Attributing causal agency to other microscopic or macroscopic elements allowed them to explain only certain magnetic phenomena. Attributing causal agency to observable magnets only allowed them to describe their observations, instead of providing an underlying mechanism for magnetic phenomena.

There are three ways the causal agents were revised by students. Figure 21 displays that the first is that students revised their causal agents from being the observable magnets to other levels of causal agent, such as macroscopic elements, microscopic unknown elements, or microscopic N-S elements. The second is that students revised their causal agents from macroscopic elements to microscopic unknown elements. These two kinds of revision are clearly indicated in Figures 16 and 17, about revision across different levels of explanation. The third kind of revision stayed within the same microscopic level: Students revised causal agents from microscopic, unknown elements or monopole elements to microscopic N-S elements. Given that this revision stays within the same microscopic level (as is reflected on the top level of Figure 21), the progression could not be shown in terms of different levels of explanation in Figures 16 and 17.

Most of the time, these revisions were not direct revisions from observable magnets to microscopic N-S elements in one step. Rather, these revisions were a sequential process progressing from lower levels of causal agent to higher levels of
causal agent and from causal agents having less explanatory power to causal agents having more explanatory power. For example, in the M2: Cutting Magnet Activity of the second FS group, students began with considering that the cut pieces of the magnet are still magnets. Then, they started to hypothesize microscopic unknown elements in the magnet during group discussion. Through reflection on the criterion of visualization, they revised their causal agents from the microscopic “smart” elements to microscopic N-S elements. During reflection on the criterion of explanatory power, they assessed that one of the competing ideas involving monopole N and S elements as causal agents could not explain their current observation, so they finally agreed that the microscopic N-S elements have causal agency.
Figure 21. The revision of the attribution of causal agency in the FS groups. FS1-M1 = The first FS group in the M1: Two Magnets Activity; FS2-M1 = The second FS group in the M1: Two Magnets Activity; FS1-M2 = The first FS group in the M2: Cutting Activity; FS2-MS = The second FS group in the M2: Cutting Activity; FS1-M3 = The first FS group in the M3: Metal Bars Activity; FS2-M3 = The second FS group in the M3: Metal Bars Activity; V = Reflection on the criterion of visualization; EP = Reflection on the criterion of explanatory power.

In the PS groups, students often did not revise the causal agents they proposed in
the earlier activities. Instead, they added the different causal agents they proposed in each activity together in their later explanations to explain different magnetic phenomena. Figure 22 reflects that, in students’ explanations in the PS groups, the levels of visualization and explanatory power of causal agents remained the same. This diagram reflects that for these students, attributing causal agency to magnets allowed them to explain more magnetic phenomena than attributing causal agency to macroscopic and microscopic elements, which were only employed by them to account for one specific magnetic phenomenon. For instance, Paul, Patty, and Paige in the second PS group proposed different causal agents in their explanations to account for different phenomena. In M1, they used an idea of moving molecules to explain the attraction and repulsion between two magnets. In M2, they described the reason that the cut pieces of magnet have two poles is that air causes these pieces to become magnets. In M3, they illustrated that the magnet charged the metal bars or that moving charges traveled from the magnet to the metal bars to enable the metal bars stick to the ends of the magnet. However, in order to explain all of their observations, they put these different causal agents together in their final explanations without revision of these different causal agents.
**Figure 22.** The combination of the attribution of causal agency in the PS groups

*Implicit models.* According to the multidimensional framework, implicit models deal with students’ tacit assumptions about a particular class of phenomena. In this study, each activity drew out similar implicit models from students, whether they were in FS and PS groups or whether they developed higher levels of explanation or not. However, different activities drew out different implicit models.

First, in the M1: Two Magnets Activity, the common implicit model employed by students is that *like things would go together*. Most students in the FS and PS groups, except Frank and Freddie, tended to employ either the implicit model that like things would go together based on their experience or the verbal symbolic knowledge that different things would go together based on the different symbols which represent different ends of magnets attracting each other. Thereby, they may use “like” versus “dislike” or “same” versus “different” to explain why two magnets or microscopic...
elements would attract and repel each other. This implicit model about like things going together was employed by several students to refer to the relationships between two magnets or to the relationships between the microscopic elements in two magnets.

For example, in the beginning of M1, Felix equated what happens between two N and two S ends of a magnet to what happens between a bully and a nice kid who do not like each other and would therefore not go together, and what happens between a N and a S end to what happens between two bullies or two nice kids because they like each other and therefore would go together. After Felix developed explanatory models including microscopic N-S particles in the post-interview, he still involved an implicit model about like things going together to explain what happens between these particles.

[00:55:38]

Felix: So if you have a North and a North, you have the particles. [Continues to draw] and there’s North on this side, just in them. And so it’s like these already know who these people are – they are North. They see it as like an old person “We already know who you are, so we do not really care, so can you go away, please.” And so it pushes them away and if you have like [Continues to draw] the North and the South, the particles,…the South is like “Hey, we don’t know the North stuffs.” So they are like “Come on enter here.” So they kind of pull together.

Yet, in this study, the implicit model about like things going together is employed less by students than the verbal symbolic knowledge about different things going together, because most students could constantly refer to the symbols on the magnets. Hence, most students usually referred to two different ends of the magnet as having different forces,
macroscopic elements, or microscopic elements, so the N and S end of the magnet would go together.

Second, in the M2: Cutting Magnet Activity, the most common implicit model employed by students is that the pieces of something should be the same as the whole thing. Most students in the FS and PS groups provided explanations that the smallest cut pieces should be smaller versions of the bar magnet (that is, the same as the big magnet), which is based on an implicit model assuming that the pieces of something should be the same as the whole thing. Nevertheless, how students in FS and PS groups applied this implicit model is different. In the FS groups, students applied this implicit model not only to explain what happened in their observations about the observable cut pieces of magnet, but also to explain their hypothesis about unobservable microscopic elements. Accordingly, most students in the FS groups developed explanatory models that the bar magnet should be composed by interactive microscopic N-S elements or particles. For example, before reflecting on the metaconceptual modeling criteria, students in the second FS group hypothesized that there are “smart” microscopic elements inside the magnet. After their reflection on the criterion of visualization, however, they hypothesized that there are microscopic N-S elements inside the magnet.

Contrarily, students in the PS groups, without developing any explanatory model, regarded the cut smallest pieces of the magnet as just smaller magnets, because of the shrinking of the magnet, the influence of air, or the smallest cut pieces always having two ends. They tried to make sense of their observations by pondering other possible reasons rather than by visualizing unseen elements or further applying this implicit model to account for other unseen elements they hypothesized in other activities.
In other words, although students in the FS and PS groups developed their explanations based on the same implicit model, in the end, students in the FS groups were able to apply this implicit model to visualize unseen N-S microscopic elements inside the magnet to develop explanatory models, but students in the PS groups still maintained their original implicit models without further revision or application. How students’ metaconceptual modeling criteria helps students in the FS groups to apply the implicit model that the pieces of something should be the same as the whole thing, thereby visualizing microscopic N-S elements, will be illustrated in the section of metaconceptual evaluation.

Third, in the M3: Metal Bars Activity, the implicit model employed by all students is that force is substance; most students in the FS also applied the implicit model same outside → same inside. At the beginning, students in the FS and PS groups perceived that force is a substance possessed by magnets, or that force works like substance moving from a magnet to other objects. In M3, all students provided explanations that there should be something, such as magnetic force, energy, or magnetic charges, going from the magnet to the metal bars to make them stick to the magnet. These explanations seem to involve the intuitive implicit model stating that force behaves like a substance moving from the magnet to the metal bars. A similar intuitive idea was also referenced by some students in the pre-interview, who stated that there is a force in the magnet or the magnet has a force, so the magnet would pull other objects. These explanations also involve the intuitive implicit model that force is like a substance possessed by the magnet.

Nevertheless, this implicit model that force is substance was later overcome in the
post-interview by Frank and Felix in the FS groups by their further applying verbal symbolic knowledge about the attraction and repulsion between the N and S end of magnets from their observation to account for interactions between unseen N-S particles in both magnet and metal bars. They employed the idea that the interactive N-S particles in the magnet would react to the N-S particles in the metal bars without referencing something going through the metal bars to explain why metal bars would stick to the magnets in a chain. How employing certain verbal symbolic knowledge helps students explain what happens between these elements will be analyzed in the verbal symbolic knowledge section.

The other common implicit model is same outside→ same inside, which was employed by most students in the FS groups to explain the M3: Metal Bars Activity in the post-interview, because they had visualized what happens inside the magnet and started pondering whether the elements inside the metal bars are the same as or different from magnets. Half of the students in the FS groups, Frank, Felix, and Fiona, focused on the similarity between magnets and metal bars, because the metal bars would become magnets, having both N and S ends, after being attached to the magnet. Thus, they hypothesized that the elements inside the metal bars should be the same as the microscopic N-S elements in the magnet. However, how they explained what happens between these elements is not the same. Only Frank and Felix could employ the verbal symbolic knowledge about the relationships between and N and S end to explain what happen between these elements. On the other hand, the other half of the students in the FS groups focused on the difference between the magnet and metal bars, so they assumed that different outside→ different inside. Thus, they claimed that metal bar is different
from the magnet, so the elements in these two are different, and there should be something going from the magnet to the metal bars, so the metal bars would stick to the magnet regardless of the structure of the metal bars.

**How students involved verbal symbolic knowledge to develop explanations.**

According to the multidimensional framework, verbal symbolic knowledge deals with students’ consciously remembered verbal principles. There are two main kinds of verbal symbolic knowledge that were most often mentioned during the activities and interviews by students in the FS and PS groups: first, the attraction or repulsion between N and S ends of the magnet and, second, the interaction between positive and negative ends.

For the first kind of common verbal symbolic knowledge, both FS and PS groups used appropriate verbal symbolic knowledge about N-S attraction and N-N and S-S repulsion to explain what happens between two observable magnets. However, only the FS groups extended this verbal symbolic knowledge to help them think about unobservable, microscopic N-S elements within the magnets, since they visualized these microscopic elements as small magnets. This abstract, verbal symbolic knowledge was further extended by Frank and Felix to explain the interaction between the N-S particles in the magnet and metal bars, as well as between the magnet and metal bars as a whole. Felix clarified how these particles move: “This will stay as North/South and then the next second it is over here and stuff. So North [two north face each other] and it’ll keep floating around, and they return to the North/South now.” Applying this verbal symbolic knowledge to account for the interaction between magnets and particles allowed them to explain coherently all of their observations in different activities. It also enabled them to perceive that force can act over a distance through a series of interactions between
microscopic elements, so as to escape from the above implicit model assuming that *force is substance*. Figure 23 shows Felix’s individual final drawing, which indicates the interaction between N-S particles in the post-interview.

![Figure 23: Felix’s individual final drawing in the post-interview.](image)

With regard to the second kind of common verbal symbolic knowledge, a majority of students in both FS and PS groups initially used the verbal symbolic knowledge about the attraction and repulsion between positives and negatives in their attempts to make sense of the attraction and repulsion between two ends of the magnets at either an observational level or a microscopic level. In the beginning, students used the idea of positive and negative to refer to different sides of the magnet. After students proposed microscopic elements inside the magnet during their group discussion in the M1: Two Magnets Activity, they started referring to these elements as positive and negative minerals, elements, molecules, or charges.

Nevertheless, in the PS groups, this verbal symbolic knowledge was not discussed.
in the later activities. In the FS groups, all but one student moved from this idea to employ an idea involving interactive, microscopic N-S elements to account for all observed magnetic phenomena. One FS student, Freddie, retained the positive and negative idea, maintaining that magnetism and electricity were the same phenomenon in the post-interview. As a result, his final model was influenced by the verbal symbolic knowledge about electricity. He regarded that N-S elements cannot exist, and therefore there should be monopole N and S elements inside the magnet, since N and S elements cannot co-exist on the same elements, or they will neutralize. In detail, in the post-interview, Freddie employed the relationship between positive and negative to explain what happens to N particles and S particles inside the magnet to account for the M1: Two Magnets Activity.

[00:12:07]

Freddie: Because North and South is positive and negative like a battery and North to North is positive/positive so if you put positive with positive it will go away because North particles will only attract to something that is South particles or something similar. And South particles will do something like this and North particles are something similar.

In order to explain the M2: Cutting Magnet Activity in the post-interview, Freddie also applied the verbal symbolic knowledge about neutralization between positive and negative charges to explain why the co-existence of N and S on the same particles is a temporary state, because “if they stay like that it would be neutral…it wouldn’t be very magnetic,” so the particles should stay as separated N particles and S particles. Furthermore, in order to explain the M3: Metal Bars Activity in the post-interview,
Freddie also perceived a magnetic force traveling like electricity from the magnet to the metal bars. In brief, Freddie used verbal symbolic knowledge from another domain, static electricity or electricity, to help him to explain what happens to the magnet, which may also help him to develop explanatory models to some extent. However, Freddie did not point out the distinctions between these different domains or examine the inconsistency between these ideas.

The reason several students perceived magnetism to be the same as electricity may be because of their previous learning experience about electricity, as they elucidated in the interviews and activities. For example, Paul and Paige related the N and S of the magnet to what they learned about positive and negative electricity. Freddie and Paige stated that the idea about positive and negative came from their learning experiences about positive and negative on the battery. In the M1: Two Magnets Activity, Freddie recalled his previous learning experience

[00:17:44]

Freddie: My class did an experiment and we took a battery that had positive – positive. One is positive - negative and then another battery is positive and negative but we need to find out how they are reacted with plus-plus or minus-minus or plus-minus.

Felix, in the different science classes from Freddie in the 4th grade, mentioned his different learning experience: “I learned something different. I just learned that we had magnets and some said North and South and some said plus-minus.” In contrast, two students explicitly distinguished the difference between magnetism and electricity. Patty in the PS groups disagreed with her group member who utilized the positive and negative
idea to explain how magnets work by asserting, “I thought positive and negative was only on batteries.” Frank in the FS groups distinguished the differences between static electricity and two ends of the magnet and articulated his learning experience about static electricity.

Figure 24 diagrams a comparison of how Freddie and Frank involved conceptual resources to develop their explanations for the M3: Metal Bars Activity in the post-interview. At the end, Freddie and Frank involved different verbal symbolic knowledge. Freddie employed verbal symbolic knowledge about positives and negatives to hypothesize the existence of monopole N elements and S elements inside the magnet. Frank employed verbal symbolic knowledge about the attraction and repulsion between the N and S ends to illustrate what happens between two magnets and between microscopic N-S elements inside magnets. As described in the previous section about implicit models, Freddie employed the implicit model \textit{force is substance} to explain how force moves from the magnetic particles to the metal bar. Frank did not employ this implicit model in the post-interview, because he used the aforementioned verbal symbolic knowledge to account for the interaction between N-S elements in the magnet and metal bars instead, thereby enabling him to escape from the constraint of this implicit model. At the core intuition level, Freddie attributed causal agency to monopole N and S elements, but Frank attributed causal agency to N-S elements. However, both of them employed Ohm’s p-prim (diSessa, 1993)—that more agency begets greater effects—to illustrate that there could be more elements or power in the two ends of the magnet, so metal bars would stick to the two ends but not the middle.
Figure 24. The comparison of how Freddie and Frank involved different or similar conceptual resources to develop their explanations for the M3: Metal Bars Activity in the post-interview.
Barriers to developing higher-level and coherent explanatory models. All students except Fiona in the FS groups developed higher-level, coherent explanatory models to explain all of their observations at the end the study, even though no student had developed an explanatory model at the beginning of the activities. In contrast to the FS groups, all students in the PS groups had problems developing coherent explanatory models at the end of the study. In the beginning of the activities, Pearl and Paul in the PS groups were able to develop explanatory models involving unseen macroscopic or microscopic elements inside the magnet for the prediction of what happened between two magnets in M1. However, at the end of the activities and in the post-interviews, students in the PS groups had difficulty developing coherent explanatory models to account for all the observed magnetic phenomena. They tended to develop one macroscopic or microscopic explanatory model to explain only one phenomenon and use other, unrelated explanatory models or other, lower levels of explanation, without developing any single explanatory model that would account for all phenomena. In other words, even though they could develop one explanatory model to explain one magnetic phenomenon, they did not use or revise this explanatory model to account for other magnetic phenomena. Based on the comparison of students’ explanations in the FS and PS groups (see Figure 20), there are some possible reasons that may explain why students in the PS groups and Fiona in the FS groups had difficulty developing coherent explanatory models.

No involvement of the activities of microscopic elements inside the magnet.

When students did not involve interacting, microscopic elements inside the magnet in their process of model revision, they did not develop coherent explanatory models. Similarly, when students involved solely macroscopic elements in their explanations, they
had difficulty developing coherent explanatory models. This difficulty was articulated by
Frank in the FS groups during his reflection on the criterion of explanatory power. In the
M3: Metal Bars Activity, Frank posited macroscopic elements, unknown “stuff,” or
magnetite inside the magnet to explain the M2: Cutting Magnet Activity and the M3:
Metal Bars Activity, and then pointed out that this explanation could not explain the M1:
Two Magnets Activity, which was later explained by Freddie by utilizing moving
microscopic particles. Hence, when they were asked to develop the best group picture by
considering the criteria of visualization and explanatory power, they employed the
activities of the microscopic N-S elements to explain all of their observations in M1, M2,
and M3.

On the other hand, Pearl and Peggy in the first PS groups employed a
macroscopic component, that there was same or different material in two ends of the
magnet, as a causal agent to develop one explanatory model to account for the attraction
and repulsion between two magnets in M1. Nevertheless, neither applied this
macroscopic explanatory model to explain other magnetic phenomena, nor did they
articulate the limitation of their macroscopic explanatory model. They posited an idea of
weaker magnets to explain the smallest cut pieces of the magnet in M2 and an idea of
flowing energy from the magnet to the metal bars to explain why metal bars stick to the
two ends of the magnet in M3. Thus, basing ideas on macroscopic elements in the magnet
allowed students to explain only certain phenomena, and these students had difficulty
explaining all of their observations with one model.

Furthermore, when students provided only a simple image of microscopic
elements without considering the activities of these elements, they had difficulty
developing coherent explanatory models, because of the disconnection between the simple image of the hypothesized elements and the complex behavior of magnets. Fiona was the only student in the FS groups having problems developing explanatory models for her observations. During the activities, she had no problem proposing the N-S particles inside the magnet, as other students in the FS groups had done, to explain all of her observations, but she had difficulty talking about the activities of N-S particles in the magnet and metal bars in the post-interview. She mentioned, “They [the behavior of magnets] are probably to do with the elements inside,” but she did not know how to use hypothesized elements to explain the behavior of magnets.

Adding different elements into explanations to account for different magnetic phenomena without revision. When students simply added different elements (macro or micro) to existing models (i.e., concatenation rather than revision), they did not construct higher-level and coherent explanatory models. Students in PS groups usually added different elements together, thereby allowing them to utilize different elements to account for different magnetic phenomena, rather than revising these elements in order to explain all observations. Even though some students in the PS groups were able to employ certain microscopic elements to explain certain magnetic phenomenon, they used other different kinds of microscopic elements to explain other phenomena. Hence, their explanatory models could only account for one phenomenon or limited magnetic phenomena and were regarded as fragmented or less coherent explanations to account for all of their observations.

For example, in the post-interview, although Paul and Patty in the PS groups were able to posit an idea of molecules to explain the attraction and repulsion between two
magnets in M1, they hypothesized that there were different microscopic elements, moving magnetic charges from the magnet to the metal bars, to explain why metal bars would stick to the two ends of the magnet in M3. They did not apply any of their hypotheses of microscopic elements to explain the cut pieces of the magnet in M2. Instead, they perceived that the cut pieces should either be influenced by air or always have two poles. In cases when they recognized the differences between molecules and charges, they were unable to clarify the relationship between these two during the activities and in the post-interview. Accordingly, accumulating different ideas without revising them to improve explanatory power of any one explanation may be one of the students’ obstacles to developing coherent and sophisticated explanatory models in the PS groups.

According to the above analysis based on the multidimensional framework, most students in the FS groups develop higher-level and coherent explanatory models by doing the following: performing a series of revisions of the attribution of causal agency, and applying appropriate implicit models and verbal symbolic knowledge from their observational level to hypothesized microscopic level. In contrast, students in the PS groups did not develop higher-level and coherent explanatory models without revision of the attribution of causal agency. Neither did they further apply their implicit model and verbal symbolic knowledge from their observation to hypothesized microscopic elements. Thus, the following section presents the analysis of how using the criteria of visualization and explanatory power promoted students in the FS groups to develop higher-level and coherent explanatory models involving the activities of microscopic N-S elements to account for all magnetic phenomena.
Students’ Metaconceptual Evaluation

Students in the FS groups were assisted in reflecting on their explanations by using the metaconceptual modeling criteria of visualization and explanatory power, but students in the PS groups were not, so students in the PS groups rarely generated the criteria like visualization and explanatory power to evaluate their explanations during the activities. They also did not revise their explanations according to these two criteria. The differences between these two different groups were that students in the FS groups evaluated and revised their explanations mostly following the elicited scientific criteria of visualization and explanatory power, whereas students in the PS groups evaluated and accumulated their explanations (concatenation) mostly following their self-generated criterion of the need for more detail in the model.

How students in FS groups evaluated and revised their explanations. Students in the FS groups evaluated and revised their explanations mostly following the criteria of visualization and explanatory power. Through reflection on their explanations using the metaconceptual modeling criteria, most students in the FS groups gradually developed, evaluated, and revised their explanations to the highest level and coherence. These reflections on the scientific criteria also encourage students to activate and apply appropriate conceptual resources to construct coherent explanatory models to account for all magnetic phenomena.

Table 12 illustrates how the FS groups evaluated and revised their explanations according to the articulated reflective criteria or without clarifying the criteria. The first row shows the total instances of clear use by individuals of different criteria. The remaining rows show whether the use of that criterion clearly increased the level of
explanation, made the explanations more coherent, led to a revision or reworking of a model, or led to the addition of more detail to the model (concatenation) without revision of the underlying model. Here, revision is defined as when students modified the properties or activities of the elements they previously proposed inside the magnets or other objects so that their explanations would better explain their observations.

Concatenation is defined as when students did not modify the elements they previously proposed in the magnets or other objects, but added new and different elements into their explanations for different magnetic phenomena.

Table 12

How Students in FS Groups Employed Metaconceptual Criteria to Facilitate Their Model Evaluation and Revision

<table>
<thead>
<tr>
<th>Result</th>
<th>Type of reflective criteria</th>
<th>No articulation of reflective criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Visualization</td>
<td>Explanatory power</td>
</tr>
<tr>
<td>Total</td>
<td>28</td>
<td>23</td>
</tr>
<tr>
<td>Level</td>
<td>7 (25%)</td>
<td>5 (22%)</td>
</tr>
<tr>
<td>Coherence</td>
<td>8 (34%)</td>
<td></td>
</tr>
<tr>
<td>Revision</td>
<td>11 (39%)</td>
<td>12 (52%)</td>
</tr>
<tr>
<td>Concatenation</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 12 reflects that students in FS groups revised their explanations primarily on the criteria of visualization and explanatory power and less on their self-generated criteria. In this study, students in the FS groups proposed several self-generated criteria, such as more detail, understandability, consistency with other ideas or experiences, and the nature of explanation. The self-generated criteria were defined as the criteria that students articulated about how they evaluated certain ideas in the activities before they were introduced to these criteria or before they were explicitly asked to evaluate their explanations by using these criteria in the FS groups. The far right column depicts how
often students spontaneously revised or changed their explanations without articulating the reflective criteria. In 27 occurrences of spontaneous revision, there were 15 incidents of students’ revising their ideas to include the ideas that others proposed. There were 12 incidents where students initiated or suggested the revision. Table 13 shows self-generated criteria that were proposed by the FS groups.

Table 13

*How Students in FS Groups Employed Self-Generated Criteria to Evaluate and Revise Their Models*

<table>
<thead>
<tr>
<th>Type of other self-generative criteria</th>
<th>Consistency with other ideas or experiences</th>
<th>The nature of explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>More detail</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Understandability</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>1</td>
<td>6</td>
</tr>
<tr>
<td>Level</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Coherence</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Revision</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Concatenation</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 13 displays that employing the criterion of the nature of explanation enabled one student to revise his explanations once. Employing other, self-generated criteria only allowed students to assess others’ or their own explanations, but did not help them revise their explanations.

The criterion of *more detail* (the explanation which includes more details is better) and *understandability* (the explanation which is understandable is better) were proposed by only one FS student each, but those students did not revise their explanations according to these criteria. The criterion of more detail was mentioned by most students in the FS groups (Frank and Freddie were the exceptions) as part of their interpretation for the criterion of explanatory power. During the activities, students used the criterion of
more detail to evaluate their pictures only when comparing their group explanations, but
not to revise or to add more details in their explanations. For example, Finn perceived
that the final group picture of the M3: Metal Bars Activity was better than the one in the
M2: Cutting Magnet Activity, “Because we put more stuff on this picture [the final group
picture of M3] than we did on that one [the final group picture of M2].”

The criterion of the consistency with other ideas or experiences was also
mentioned by several students (Frank, Felix, Freddie, and Faye) in the FS groups. They
often expressed reasons for agreeing with ideas that fit with their own existing ideas or
experiences, and why they disagreed with certain ideas that did not fit with their own
experiences. However, they did not revise their ideas according to this criterion.

The criterion of the nature of explanation that was proposed by Frank before the
introduction of the metaconceptual modeling criteria is the only self-generated criterion
that prompted Frank to revise his own explanations and to convince other students to
accept his hypothesis (elements inside the magnet). For example, in the M1: Two
Magnets Activity, Freddie and Felix either employed verbal symbolic knowledge (about
the relationship between positive and negative electricity) or they employed analogy
/about bullies and nice kids or football players) to describe the attraction and repulsion
between two magnets. However, they did not support Frank’s hypothesis about minerals
inside the magnet until Frank commented that describing what happened between two
magnets did not explain why this might happen. At that point, he visualized unobservable,
moving material lines within magnets to explain the attraction and repulsion between two
magnets. He commented that Freddie and Felix’s ideas using verbal symbolic knowledge
or analogy “just explain what a magnet does,” but did not explain why a magnet does
what it does.

The roles of the metaconceptual modeling criteria in students’ explanations in FS groups. The criterion of visualization appeared to foster students’ progression mainly in terms of level of explanation; the criterion of explanatory power appeared to foster students’ progression in level of explanation as well as coherence. This result is shown in the Table 12.

Visualization. Reflecting on the criterion of visualization encourages students to revise their explanations to higher levels in three ways. First, when students only described their observations, without hypothesizing any unseen elements inside the magnets, using the criterion of visualization would help them to visualize unseen elements in the magnet and in other objects interacting with it. Thus, reflecting on the criterion of visualization enabled students’ explanations to progress from lower levels to higher levels of explanation.

As an example of how students’ explanations progressed to higher levels before and after introducing the criterion of visualization in the M1: Two Magnets Activity, the students in the second FS group originally only offered a Level 1 explanation (that two same ends have the same force, so they would not connect, and two different ends have different forces, so they would connect). This explanation did not involve any hypothesized macroscopic or microscopic elements in the magnet. Students’ drawings before employing the criterion of visualization to their group explanations are recorded in the left column of Figure 25. During the evaluation of their group pictures, when they were instructed to use the criterion of visualization, students agreed that there should be something inside the magnets. Fiona was the first to propose microscopic “elements and
atoms” inside the magnet. Hence, their explanations progressed from Level 1 to Level 3-2 micro or Level 2-2 micro. The right column of Figure 25 shows students’ drawings in the M1: Two Magnets Activity after employing the criterion of visualization.

<table>
<thead>
<tr>
<th>Before employing the criterion of visualization</th>
<th>After employing the criterion of visualization</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.png" alt="Image" /></td>
<td><img src="image2.png" alt="Image" /></td>
</tr>
</tbody>
</table>

*Figure 25. Students’ group explanations in the second FS group before and after employing the criterion of visualization to reflect on their explanations.*

Moreover, when students reflected on the criterion of visualization, they were more likely to inspect or revise their pre-existing macroscopic and microscopic explanations to better account for their current observations. Sometimes students claimed their macroscopic and microscopic explanations met the criterion of visualization without revision. Sometimes, they revised their hypotheses about elements inside the magnet or the activities of the element within the same microscopic or macroscopic levels to better account for their current observations.

An example of revision within the same microscopic level comes from the results of the M2: Cutting Magnet Activity. Before reflecting on the criterion of visualization, the students in the second FS group agreed that microscopic elements inside the magnet act like smart people, so there are always N and S co-existence on each element.
Students’ drawings before employing the criterion of visualization are recorded in the left column of Figure 26, in which they drew small dots representing the elements they mentioned. Nevertheless, during the discussion of the criterion of visualization, Faye was the first one to propose the “close-up” view of these elements by drawing co-existence of N and S on these small elements: “I’m going to draw this [N and S on opposite ends of two elements] and it is really this big, but that might be close-up….Because you cannot draw that and be like North and South on the dot [small dots in the magnet].” Hence, reflecting on group explanations by using the criterion of visualization enabled these students to revise their idea of microscopic unknown elements in the magnet into microscopic N-S elements inside the magnet. Students’ drawings during and after employing the criterion of visualization to reflect on their group explanations are recorded in the right column of Figure 26, in which they started to enlarge the dots as N-S elements.

<table>
<thead>
<tr>
<th>Before employing the criterion of visualization</th>
<th>After employing the criterion of visualization</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1" alt="Before" /></td>
<td><img src="image2" alt="After" /></td>
</tr>
</tbody>
</table>

Figure 26. Students’ group explanations of the second FS group in the M2: Cutting Magnet Activity before and after employing the criterion of visualization to reflect on their explanations.

In addition, reflection on the criterion of visualization encourage students to better
articulate the relationship between microscopic and macroscopic levels of element they hypothesized to explain different magnetic phenomena. As described in the above case study, in the M3: Metal Bars Activity of the first FS group, when students reflected on the visualization of their group explanations the second time, Frank articulated the relationship between microscopic structure (the particles inside the magnetite) and macroscopic structure (the magnetite inside the magnet). When they found the limited explanatory power of a macroscopic level of explanation, this differentiation between different levels of explanation helped them to select the microscopic level of explanations because it allowed them to account for all of their observations.

Explanatory power. When students reflected on the criterion of explanatory power they were more likely to revise their explanations to better coherence and higher levels in three ways. First, reflecting on the explanatory power of their explanations to account for current observations prompted students to examine the consistency between their current explanations and their observations. When students in the FS groups considered that their explanations were not consistent with their observations, they revised the unseen elements they hypothesized inside the magnet. In the M2: Cutting Magnet Activity, Fiona’s idea about monopole ideas was questioned by other group members because they considered that this idea could not explain the co-existence of N and S on the smallest pieces. In the M3: Metal Bars Activity, Faye pointed out that their current explanation could not explain why the metal bars cannot stick to the middle part of the magnet. Hence, the assessment made students revise monopoles N and S elements to become dipole N-S elements to account for observations in M2 and revise the property of hypothesized microscopic elements in different parts of the magnet in order to account for the middle
part of the magnet in M3. Although these revisions did not help students make direct progress in terms of level and coherence, the revisions at the microscopic level helped them to account coherently for all observed magnetic phenomena later.

Second, when students reflected on the explanatory power of their explanations to account for what happens between elements, they were better able to articulate the interactions between these elements, which promoted students’ explanations progress in terms of level. When students only proposed a simple image of microscopic N-S elements inside the magnet, the reflecting on the criterion of explanatory power helped them articulate the attraction and repulsion between these N-S elements, thereby inducing the consistent alignment of these elements. Being able to articulate the activities of N-S elements raises students’ explanations from Level 2-2 micro to Level 3-2 micro.

Third, when students reflected on the explanatory power of their explanations to account for their previous and current observations, they were better able to evaluate whether their explanations could account for all of their observations, thereby improving the coherence of their explanations. In the M2: Cutting Magnet Activity, all students in the FS groups applied their group explanation involving N-S elements to account for the M1: Two Magnets Activity. In the M3: Metal Bars Activity, when they found the explanatory power of their explanations was limited, students revised their explanations for increased coherence (from involving different levels of unseen element or involving unknown microscopic elements to microscopic N-S elements to explain all of their observations at the end). The second FS group, for example, increased the coherence of their explanation after evaluating the explanatory power of their group picture to account for their previous observed phenomena. Faye found that their explanations could explain
M1, but not M2. Fiona and Finn suggested refining these unknown elements inside the magnet to become N-S elements in their picture. As Finn suggested, “You have to put North and South in each one of these.” Then, they started involving N-S elements to explain all of their observations in M1, M2, and M3.

The left column of Figure 27 shows the second FS group’s explanation of the M3: Metal Bars Activity before employing the criterion of explanatory power to reflect on their explanation. This picture contains only dots to represent elements in the magnet and metal bars. The right column of Figure 27 shows the second FS group’s explanation of the M3: Metal Bars Activity after employing the criterion of explanatory power to reflect on their explanation. This picture shows the interaction between microscopic N-S elements in the one magnet and between two magnets, and it also shows the interaction between N-S elements in the magnet and unknown elements in the metal bars at the bottom of the picture.

<table>
<thead>
<tr>
<th>After employing the criterion of visualization and before employing the criterion of explanatory power</th>
<th>After employing the criterion of visualization and after employing the criterion of explanatory power</th>
</tr>
</thead>
</table>

*Figure 27. Students’ group explanation of the second FS group in the M3: Metal Bars Activity before and after employing the criterion of explanatory power to reflect on their explanation.*

Overall, if students did not develop microscopic N-S elements or particles in their
of explanatory power, they would revise their original explanations, which involve monopole or unknown elements inside the magnet or different levels of explanation for different observations, to involve microscopic N-S elements to explain all magnetic phenomena coherently.

*The roles of metaconceptual modeling criteria in students’ employment of different conceptual resources in the FS groups.* Reflecting on the criterion of explanatory power made student apply verbal symbolic knowledge about how the ends of magnets work from the interaction between two magnets to the interaction between microscopic N-S elements within magnets. When students reflected on both the criteria of visualization and explanatory power they applied the implicit model stating that *the pieces of something should be the same as the whole thing* that they had developed about how observable, cut pieces of magnets behave to how unobservable, hypothesized, microscopic elements behave. Reflecting on both criteria also encouraged the revision of causal agents from magnets to microscopic N-S elements in students’ explanations.

Figure 21 illustrates when and how students revised their causal agents with or without the facilitation of reflection on the modeling criteria. This diagram reflects that half of the time, students revised their causal agents with the aid of scaffolding procedures that encouraged them to reflect on the metaconceptual modeling criteria. The other half of the time, students revised their causal agents spontaneously, without such scaffolding.

Most of the time, students in the FS groups needed to reflect on the criterion of visualization or explanatory power to revise their causal agents into microscopic N-S elements and to extend their implicit model and verbal symbolic knowledge from the observational level to the hypothesized, microscopic level. However, this does not mean
that in all other instances students did not evaluate and revise their explanations according to the modeling criteria. Figure 21 and Table 12 show that students also spontaneously revised their explanations even without scaffolding that encouraged their reflection or articulating the metaconceptual criteria they employed. In the post-interview, half of the students in FS claimed they had spontaneously employed these modeling criteria in the activities without scaffolding or articulating them. For instance, Figure 21 illustrates that the only instance of spontaneous revision of causal agents from magnets to microscopic N-S elements happened in the M2: Cutting Magnet Activity of the first FS group. Felix was the student who first proposed N-S elements and claimed that he had spontaneously employed these criteria to reflect on their explanations during the activities, but he was unable to provide a specific example in the post-interview: “I think I have done it (used these criteria spontaneously) like once or twice because when I’m looking at page shots, I just look at the picture like—What do I think about it?”

There is some indirect and unobservable evidence that students may have been influenced by reflecting on the criteria of visualization and explanatory power. For example, most students in the FS groups employed the implicit model $\text{same outside} \rightarrow \text{same inside}$, but not the students in the PS groups. However, in the group discussions of the FS groups, students spontaneously proposed this idea to hypothesize that there are elements in the metal bars as well as in the magnet before being asked to reflect on the visualization and explanatory power of their explanations in the M3: Metal Bars Activity. Since both criteria had been introduced in the previous activities, students were able to extend the application of this implicit model by spontaneously reflecting on modeling criteria without scaffolding. However, students only articulated these modeling criteria
when they were scaffolded to use these criteria. Because this kind of spontaneous reflection was not articulated by students, how students executed this spontaneous reflective process became unobservable.

The above data analysis from the multidimensional framework has revealed the differences between how students in FS and PS groups revised and applied their different conceptual resources. Next I will describe how the criteria of visualization and explanatory power helped students to develop coherent and higher-level of explanatory models.

**Visualization.** Reflecting on the criterion of visualization helped students in the FS groups revise their attributions of causal agency and extend the implicit model that *the pieces of something should be the same as the whole thing* from their observable magnets to unobservable microscopic elements in the magnets. However, there is no direct evidence that it helps students extend their verbal symbolic knowledge from observable magnets to unobservable hypothesized elements.

In terms of the direct influence that reflecting on the criterion of visualization had on students’ core intuition, it enabled students in the FS groups to revise their causal agents across different levels, from observable magnets to microscopic unknown elements in the M1: Two Magnets Activity, or within the same microscopic level from microscopic unknown elements to N-S elements in the M2: Cutting Magnet Activity and the M3: Metal Bars Activity. It seems that reflecting on the criterion of visualization is associated with these activities. Reflecting on the criterion of visualization helped students to hypothesize microscopic unknown elements to explain attraction and repulsion in M1 and microscopic N-S elements to explain the co-existence of N and S
ends on each cut piece of the magnet in M2 and M3. This reflection also helped students to articulate the relationship between different levels of causal agent, eventually selecting microscopic N-S elements to explain all observations at the end of M3.

Regarding the direct influence that reflecting on the criterion of visualization had on students’ implicit models, it encouraged students to extend their intuitive implicit model that the pieces of something should be the same as the whole thing from their observations to make sense of the hypothesized microscopic elements inside the magnet. This study shows that when students in the FS groups did not spontaneously apply this implicit model in the M2: Cutting Magnet Activity, further reflection on the criterion of visualization would promote students to apply this implicit model, transferring it from describing their observations about what happened to the cut pieces of magnet to visualizing what happened to the hypothesized N-S microscopic elements in the M2: Cutting Magnet Activity. It appeared that reflecting on the criterion of visualization is associated with these activities, since this reflection only helped students to further visualize N-S elements in M2, but not at the stage of reflecting on the criterion of visualization in the M1: Two Magnets Activity or the M3: Metal Bars Activity. In M1 and M3, reflecting on the criterion of visualization resulted either in students’ hypothesizing unknown microscopic elements or their articulating the relationships between different levels of element they proposed.

Explanatory power. Reflecting on the criterion of explanatory power helped FS students revise the attribution of causal agency and extend the implicit model that the pieces of something should be the same as the whole thing and verbal symbolic knowledge about the attraction and repulsion between the N and S ends from their
observable magnets to unobservable microscopic elements in the magnets.

With regard to the direct influence reflecting on the criterion of explanatory power had on students’ core intuition, it encouraged students in the FS groups to revise their causal agents across different levels: from macroscopic elements to microscopic, unknown elements in M3; within the same microscopic level from microscopic unknown elements; or from monopole N and S elements to microscopic N-S elements in the M2: Cutting Magnet Activity and the M3: Metal Bars Activity. That reflection on the criterion of explanatory power was also associated with the activities. Reflecting on the criterion of explanatory power helped students progress from attributing causal agency to macroscopic or microscopic unknown elements to attributing causal agency to microscopic N-S elements, so as to explain the co-existence of N and S ends on each cut piece of the magnet in M2 and M3. This reflection also encouraged students to inspect the limited explanatory power when they attributed causal agency to macroscopic elements, so they ultimately attributed causal agency to microscopic N-S elements to explain all of their observations at the end of M3.

In addition to the direct influence reflecting on the criterion of explanatory power had on students’ implicit model, this reflection also helped students extend their intuitive implicit model that *the pieces of something should be the same as the whole thing* from their observations and use it to make sense of the hypothesized microscopic elements inside the magnet. This study reveals that if students did not apply this implicit model from their observation of cut pieces of the magnet to hypothesize elements after their reflection on the criterion of visualization in the M2: Two Magnets Activity and the M3: Metal Bars Activity, then further evaluation of the explanatory power of explanations to
account for all observations prompted students to do so in order to account for M2. It appears that reflecting on the criterion of explanatory power is also associated with the activities, since this reflection helped students to further visualize microscopic elements, such as small magnets having co-existence of two poles, while reflecting on whether their explanations can account for M2.

Considering the direct influence reflecting on the criterion of explanatory power had on students’ verbal symbolic knowledge, it encouraged students to further apply their verbal symbolic knowledge the attraction between unlike poles and the repulsion between like poles from their observations to microscopic elements. Evaluating explanatory power to account for what happens between these hypothesized elements helped students to further apply this verbal symbolic knowledge from the interaction between observable magnets to the interaction between unobservable microscopic N-S elements inside the magnet. This verbal symbolic knowledge was further applied by Frank and Felix to explain what happened between microscopic N-S elements in the magnet and metal bars in the post-interview. As mentioned in the data analysis section about verbal symbolic knowledge, this further application of verbal symbolic knowledge allowed students to develop a coherent explanatory model that explained not only what happened to the magnet, but also what happened to the objects which interacted with the magnet.

In addition, using this verbal symbolic knowledge to make sense of the interaction between particles in the magnet and metal bars also enabled students to overcome the constraint of their intuitive implicit model that force is substance to move from magnet to other objects. Frank and Felix had pointed out that using the attraction and repulsion
between the N and S ends to explain the interaction between the microscopic N-S elements in the magnet as well as metal bars allowed their final individual explanations to have a better explanatory power to describe how these elements move than drawing unknown materials flowing from magnet to metal bars. As Felix stated in the post-interview, “It does most because I show the things like moving around and then I show it went an hour kind of thing, moving around and then I will draw these (particles) bigger like North/South.”

**How students in the PS groups evaluated and revised their explanations.**

Students in the PS groups evaluated and added their explanations (concatenation) mostly following their self-generated criterion of the need for more detail in the model. Through reflecting on their explanations using the criterion of more detail, most students in the PS groups gradually added the ideas they previously proposed in other activities together without revising them. Hence, their explanations sometimes moved toward higher levels of explanation, because they added different levels of explanation to account for different magnetic phenomena. There was seldom improvement in terms of coherence of explanations.

Table 14 shows how PS groups evaluated and changed their explanations according to different, self-generated criteria. The first row shows the total instances of clear use by individuals of different criteria. The remaining rows show whether the use of that criterion clearly increased the level of explanation, made the explanations more coherent, led to a revision or reworking of a model, or led to the addition of more detail to the model without revision of the underlying model (concatenation). In the far right column, numbers reflect how many students spontaneously revised or changed their
explanations without articulating the reflective criteria. In these six instances of spontaneous revision, there were five cases wherein students revised their ideas after listening to others’ ideas. In these cases, they revised their explanations to higher levels of explanation that their fellow group members proposed. In other words, most of the time, students in the PS groups revised their proposed elements because of influence of others’ higher-level ideas.

Table 14

How Students in the PS Groups Employed Their Self-Generated Criteria to Facilitate Their Model Evaluation and Change

<table>
<thead>
<tr>
<th>Result</th>
<th>Type of Reflective Criteria</th>
<th>Total</th>
<th>Level</th>
<th>Coherence</th>
<th>Revision</th>
<th>Concatenation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Visualization</td>
<td>Explanatory power</td>
<td>More detail</td>
<td>Others</td>
<td>No articulation of reflective criteria</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>1</td>
<td>4</td>
<td>18</td>
<td>20</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Level</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>6 (33%)</td>
<td></td>
</tr>
<tr>
<td>Coherence</td>
<td></td>
<td></td>
<td></td>
<td>1 (5%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Revision</td>
<td></td>
<td></td>
<td></td>
<td>1 (5%)</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>Concatenation</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>9 (50%)</td>
<td></td>
</tr>
</tbody>
</table>

Table 14 also reflects that students changed their explanations most often according to the criterion of more detail and seldom according to other self-generated criteria. In this study, students in the PS groups proposed diverse self-generated criteria, including the criteria of visualization and explanatory power as well as the criterion of more detail. This latter criterion was also employed by students in the FS groups, but how they utilized these criteria was different. In the following section, how students in the PS groups employed the criteria of visualization and explanatory power as well as other self-employed criteria is illustrated.

The roles of the criteria of visualization and explanatory power in students’ explanations in the PS groups. Although students in the PS groups also employed the
criteria of visualization and explanatory power to evaluate their explanations on few occasions, without the introduction of the metaconceptual modeling criteria, they did not revise their explanations according to these criteria. This was because they perceived there were more important criteria to evaluate and change their pictures, such as including more details.

The self-generated criterion of visualization was employed only once, by Paige in the M1: Two Magnets Activity. During group discussion for developing the best picture, Paige supported Paul’s idea that the same or different directions that positive and negative molecules move would make two magnets attract or repel. Yet, she perceived Patty’s idea about the molecules in the two ends of the magnet and the invisible force between them to pull them together as a good idea, stating, “I like the molecule idea [Patty’s idea], because it depends on what the size is and how it is then you are able put in what Patty said about South and North.” Paige considered Patty’s molecule idea to offer the best image about the size of the molecules and how these molecules are arranged in the N and S ends of the magnet. Even though Paige assessed Patty’s moving-molecules idea as having better visualization, she did not use this criterion to evaluate the positive-and-negative-molecule idea that Paul proposed. Neither did she use it to compare these two explanations or to further revise others’ or her own ideas.

The criterion of explanatory power was also employed, but in a self-generated fashion, by most students (Pearl, Paul, Patty, and Paige). Nevertheless, they only employed this criterion to assess whether their picture could explain their current observations, instead of having the explanatory power to explain all magnetic phenomena. For example, in the first PS group, Peggy had proposed a puzzle-piece idea to explain the
attraction and repulsion between two magnets: “The opposite, for the puzzle piece, they can go together but the two of the same puzzle pieces won’t connect, because they are the same shape and they won’t go into the right places.” Pearl disagreed with this idea, “I think that if we did the puzzle piece, it doesn’t exactly explain the middle, where there is nothing, and the iron and the metal part of it. Then the puzzle doesn’t really have a North part and a South.” Pearl argued that the puzzle-pieces idea could not explain two different ends of the magnet and no attraction or repulsion between the two middle parts of the magnet.

Another similar instance can be found in the second PS group, when Paul, Patty, and Paige were devising the best picture for the M3: Metal Bars Activity. They assessed their explanations by using their self-generated criterion of whether their explanations could account for their current observation. Paul proposed an idea to explain why he thought the energy inside the magnet flows to the two ends, instead of middle part of the magnet: “Because the energy flows from South to North, it doesn’t go down….Here comes the charge. It goes through here, comes from here, so it goes here. It is like layer of a tube right here. It sticks here and it can’t go down here.” He asserted that only his explanation could explain why metal bars can stick to the two ends of the magnets. Paul’s drawing of flowing charges or energy in a tube within a magnet is in Figure 28.

Patty opposed Paul’s idea and thought that his explanation could not explain why metal bars stick to the two ends of the magnet instead of the middle part, because when energy flows through the two ends, the energy would go through the middle part, too. However, she did not provide the underlying reason of her argument; she only stated, “I knew what you [Paul] were talking but it just doesn’t make any sense. It does not.” Paige
supported Patty’s assessment and expressed that Paul could not offer reasons why magnetic charges would go to the two ends instead of the middle part of the magnet: “We don’t agree because he said it only goes here. I got what he said but even if it goes through North/South, it doesn’t mean that it can’t go to the other bottom and touch here.” In a word, using this self-generated criterion of explanatory power allowed them to evaluate others’ explanations, but did not encourage them to revise their own explanations.

Figure 28. Paul’s explanation of why metal bars would stick to the two ends of the magnet in the M3: Meal Bar Activity.

The roles of other self-generated criteria in students’ explanations in the PS groups. Besides the above-mentioned self-generated criteria of visualization and explanatory power, students in the PS groups evaluated and changed their explanations most often according to the criterion of more detail and seldom according to other self-generated criteria. Table 15 depicts other self-generated criteria proposed by the FS groups, besides the criteria of visualization and explanatory power.
Table 15

*How Students in the PS Groups Employed Self-Generated Criteria to Evaluate and Change Their Models, Beside the Criteria of Visualization and Explanatory Power*

<table>
<thead>
<tr>
<th>Types of Other Self-Generated Criteria</th>
<th>More detail</th>
<th>Including energy ideas</th>
<th>Others</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total</td>
<td>18</td>
<td>3</td>
<td>17</td>
</tr>
<tr>
<td>Level</td>
<td>6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coherence</td>
<td></td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Revision</td>
<td></td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Concatenation</td>
<td></td>
<td>9</td>
<td></td>
</tr>
</tbody>
</table>

*The criterion of more detail.* The most common self-generated criterion that students in the PS groups employed to evaluate their explanations is that the best explanation should include more details than other explanations. They usually described “more details” as meaning either the explanation providing more details or including all the ideas from different group pictures or others’ ideas. In order to have more details in the picture, they usually put all of the details they knew or mentioned in one picture, without revising the elements or ideas they previously proposed. Hence, this process of combining all unrelated details together cannot be deemed as revision cycles as the FS groups went through. Nevertheless, during the process of adding more detail into their explanations, students usually added different levels of explanation, which included higher and lower levels of element, thereby causing a progression in terms of level. However, doing so did not help them to revise the underlying models. Pearl, for example, asserted in the post-interview that her final individual drawing was the best explanation, because she included more detail:

[01:06:34]
Pearl: It [her final individual drawing] shows everything out of all of these, instead of just one specific thing.

I: What do you mean “everything” and “specific thing?”

Pearl: Like this, it [the final group picture of M1] shows pulling and pushing apart and connecting and this [the final group picture of M2] was just splitting and this [the final group picture of M3] was the energy, but this [her own final drawing] did all that.

I: One time you mentioned about “more details” and sometimes you mention “explains more.” Could you explain to me what you mean by “more details” and “explains more?”

Pearl: It has more stuff in it to explain it.

I: More stuff, like what?

Pearl: If we did not put nothing on the first time, then we put nothing on that one.

I: You put nothing here and originally you did not add the iron and metal stuff. How about “explain more”?

Pearl: Like include everything.

I: Include everything?

Pearl: Yes, it included everything that we talked about.

For Pearl and most of the students, the criterion of more detail means including every detail that had been mentioned. For example, Paul also stated, “This one [the final picture of M3 is the best], because it has four explanations [for the observation of different magnetic phenomena] together and explains more.”
Besides including all details that have been mentioned in the activities, Paul, Patty, and Paige in the second PS group also commented that the criterion of more detail should also mean including the ideas from other people. Paul stated that his own final drawing was not the best in the post-interview; he regarded the final picture of the M3: Metal Bars Activity as the best, because it included the ideas from other people. “Because I am the only one who worked on it and I need other ideas probably so I just think this one is best and it is better with other people for other ideas,” Paul claimed. Other students in the second PS group also voiced the same idea about including others’ input. Patty stated the following to clarify why the final group picture of M3 was better than her individual final drawings:

Because we all came up with it. It is more like a team effort, it is not like one single person did it, because when one single person does it…like me I have my own idea, but on this one we agreed on mostly everything…. Yes, it’s a mix between three people’s ideas.

The criterion of more details was commonly employed by students in the PS groups not only while they compared different pictures, but also while they developed the best picture. Here, the criterion of more detail is similar to one of the interpretations for the criterion of explanatory power and one of the self-generated criteria in the FS groups. Nevertheless, students in the FS groups sometimes also articulated that they used the criterion of more detail to compare different pictures when they were asked to evaluate the explanatory power of different explanations, but they did not develop or revise their picture according to the criterion of more detail. Comparing the criteria they used to evaluate, compare, and revise their explanations in the FS and PS groups, it was found
that students have intuitive, self-generated criteria that the explanations which have more
details are better.

*Other self-generated criteria.* There are some self-generated criteria proposed by
one or two students in the PS groups. Students commented that the best picture should be
judged according to certain criteria, such as whether the explanations include energy idea,
*have certainty of information, have been taught, make sense, or being understandable,*
*scientific, more advanced, or simpler.* Usually, students did not articulate the meaning of
these self-generated criteria, let alone clarify the underlying reasons why the pictures
including these criteria would become better. These criteria may have helped them to
evaluate others’ or their ideas but did not help them to revise their explanations. There is
only one criterion, *including energy idea,* which was proposed by Peggy to assess and
revise group explanations become more coherent. As Peggy argued with Pearl, “I don’t
think we can do that (in the final picture of M3). Because it wouldn’t explain how this
will work...Because it doesn’t explain the energy part.” Peggy, in the M3: Metal Bars
Activity, suggested that simply including more detail would not make their pictures better
as Pearl had stated, so they should include an energy idea to explain the cut pieces of the
magnet in M2 and the attraction between the magnets and metal bars in M3.

**Fiona’s different understanding about the criterion of visualization and**
**explanatory power.** In the FS groups, Fiona was the only student who did not develop
coherent explanatory models at the end. She was also the only student who had problems
articulating the meaning of the criteria of visualization and explanatory power. In contrast,
other students in the FS groups pointed out that certain elements, such as N-S elements,
allowed their pictures to have better visualization inside the magnet or better explanatory
power to explain all of their observations.

According to Fiona’s clarification of the meaning of these criteria and her application of these criteria to evaluate different explanations in the post-interview, she seemed to have a different interpretation for the criteria of visualization and explanatory power. Despite Fiona’s ability to hypothesize microscopic elements or atoms inside the magnet after reflecting on the criteria of visualization in the activities, she interpreted the criterion of visualization to have been met because she could claim that she “drew it by myself,” which was different from the interpretations other students offered in the post-interview. Similarly, despite Fiona’s ability to revise her ideas from hypothesizing monopole N and S elements or unknown elements to hypothesizing N-S elements and articulating the interaction between those N-S elements to better explain their observations, Fiona interpreted the criterion of explanatory power different from other students’ in the FS groups. She considered a picture to have better explanatory power if she drew it with others collaboratively or she devoted more time to show more information.

In her first application of her definition of explanatory power, she meant that drawing the picture as a group allowing her to explain the content more. She pointed out that the final group picture of the M3: Metal Bars Activity had the best explanatory power: “This one [the final group picture of M3] since we drew it together yesterday, I thought I explained it more.” Her second application of the term was to signify that the picture to which they devoted more time and in which they showed more detail had the best explanatory power. She made this application after being asked not to consider who drew the picture. Fiona perceived the final picture of the M2: Two Magnets Activity has
the most explanatory power:

[00:45:25]

Fiona: Well, this one right [the final group picture of M2] here I think is more explanatory than mine [Fiona’s individual final drawing]….Because this one [the final group picture of M2] we showed more. Like we cut into pieces, we showed the elements, we showed North and South, North/South and then we drew the air and we drew the little particles…Because this one [the final group picture of M2] we explained more like when we did the project. We actually got to cut the magnet and we got to think about it for a while.

Most of Fiona’s understandings about the criteria of visualization and explanatory power were different from other students’ in the FS groups and different from the meanings they learned in the activities, but close to the self-generated criteria in the PS groups, like whether the picture showed more information or were developed by the group. Hence, even though Fiona was able to mention N-S elements in the magnet during group discussion and in the post-interview, she could only develop a simple image of microscopic N-S elements in the post interview, instead of explanatory models illustrating the activities of these elements. This may be the possible reasons why Fiona had difficulties developing explanatory models to explain all magnetic phenomena.
Chapter 5
Discussion and Conclusion

Introduction

The purpose of this research was to investigate fifth-grade students’ self-developed explanations about magnetic phenomena and how using the metaconceptual modeling criteria as a reflection tool would help students to develop explanatory models. There were four groups of 11 students recruited from two afterschool programs. The first 6 students were assigned into the two fully scaffolded (FS) groups, and the rest of the students were assigned into the two partially scaffolded (PS) groups. Students were assigned to groups according to their scheduled availability.

In the pre-interview, these students were asked about their explanations of and learning experience with regard to magnetic phenomena. During the activities for the FS groups, the criteria of visualization and explanatory power were introduced; these criteria were not introduced to the students in the PS groups. All students in the FS groups and PS groups used journals to record their ideas and group discussion to foster their reflective thinking. In the post-interview, I asked students questions to explore whether their explanation of magnetic phenomena had developed. They were asked to clarify (a) their final best explanations to account for observed magnetic phenomena, (b) their own criteria to select the best explanations, and (c) their reasoning during the activities in the videos and in the journals.

So as to understand the pathway of students’ self-generated explanations and the process of students’ reflective thinking, students’ verbal responses and behaviors were
video-recorded in the pre- and post-interviews as well as during the activities. Students’ drawings in the group discussion and writing about their individual ideas in their own journals were also collected.

I analyzed the data in a three-step process to answer research questions. First, in order to understand the larger patterns in students’ explanations, I coded their explanations according to different levels of sophistication and coherence of explanations. Next, in order to further understand the various conceptual resources that students used to develop and modify different levels of their explanation, students’ explanations were further interpreted based on the multidimensional framework (Brown, 1993, 1995a, 1995b; Cheng & Brown, 2010). Finally, I identified students’ metaconceptual evaluations (Yuruk, 2007; Yuruk, Beeth, & Andersen, 2009) according to the criteria that students employed to evaluate their explanations.

The result of the study showed that students in the FS groups evaluated and revised their explanations mostly following the elicited scientific criteria of visualization and explanatory power. This process encouraged the development of higher-level and more coherent explanations, as well as the application of appropriate conceptual resources to develop coherent microscopic explanatory models. In contrast, students in the PS groups evaluated and added to their explanations mostly following their self-generated criteria with regard to the need for more detail in the model without revision. Accordingly, their explanations stayed fragmented and at similar levels. They were unable to apply their conceptual knowledge based on what they observed to what they hypothesized about the magnet as an explanation for the underlying mechanism of magnetic phenomena, so they had difficulties developing coherent microscopic
This chapter has three main sections. In the first section, I summarize and discuss the findings for each research question. The second section, I discuss the limitations of the study. In the third section, I provide the implication of the study and the suggestion for future research.

**Discussion of the Study**

In this section, I present the findings of each research question and discuss the conclusions by drawing from my earlier research and existing literature about students’ explanation, conceptual resources, and metacognition.

**Question 1: How do students develop and revise their explanations?** Through reflection on their explanations by using the metaconceptual modeling criteria, most students in the FS groups gradually developed, evaluated, and revised their explanations to the highest level and most coherent explanations. In contrast, students in the PS groups evaluated and added unrelated explanations that they proposed in different activities without revision, so their explanations made little or no progress in levels and were fragmented at the end.

**Pathway of developing explanations.** From the previous illustration about how individual students developed their ideas in Chapter 4, the pathway of developing explanations in the FS groups was a progression within and across activities. Within activities, students usually revised their explanations from lower levels to higher levels of explanation during group discussion or during their reflection on the criteria of visualization and explanatory power. Across different activities, students usually revised
or further applied explanations they previously proposed to become coherent
explanations for different magnetic phenomena during their reflection on the criterion of
explanatory power.

This revision cycle is similar to Clements’ research (1989, 2008c) regarding how
experts resolve problems beyond their expertise by following the cycles of generation,
evaluation, and modification (GEM cycles) which are also further employed to foster the
development of students’ models close to scientific models (Clements & Steinberg, 2002,
2008). The general pattern of the revision cycle of students’ explanations in the FS groups
is illustrated in Figure 29. In this revision cycle, students activated related conceptual
resources to generate their explanations through the context of the activities, and then
they evaluated their ideas mostly according to the metaconceptual modeling criteria of
visualization and explanatory power. If they regarded their explanations as having met the
modeling criteria, they maintained the same explanations or further applied their
explanations for other observations. If they believed that their explanations did not meet
the modeling criteria, this reflection prompted them to activate and apply the conceptual
resources that enhanced the visualization and explanatory power of their explanations to
revise their explanations in order to meet the modeling criteria.
Figure 29. The revision cycle of explanations in the fully scaffolded groups.

By contrast, the pathway to developing explanations in the PS groups was typically a process of adding unrelated ideas together during group discussion, rather than a revision process as in the FS groups. Without the facilitation of reflection on their explanations by using the modeling criteria, students in the PS groups evaluated their ideas largely according to the self-generated criterion that a better explanation has more detail, and so they would add different ideas from different activities without revision of the ideas previously proposed. Consequently, their explanations were not revised to achieve higher levels or greater coherence. They only employed different levels and fragmented explanations together for different magnetic phenomena.

Figure 30 shows the general pattern of the accumulation of students’ explanations.
in different activities in order to develop their final best explanations in PS groups. In this linear accumulation, students began with activating their related conceptual resources to generate their initial explanations through the context of the activities, and then they evaluated their ideas mostly according to the criterion of more detail. If they regarded their explanations as having enough detail, they maintained the same explanations. If they considered that their explanation did not have enough details, they added ideas from other activities to increase the number of ideas in their explanations. Without inspecting the problems of ideas they previously proposed further or feeling the need to revise them, students did not further activate or apply the appropriate conceptual resources among their related conceptual resources to revise their explanations to the highest level and most coherent explanations.
Figure 30. The process of adding ideas in their explanations in the partially scaffolded groups.

**Level of explanation.** In science, microscopic levels of explanations are usually regarded as providing underlying mechanisms to makes sense of observed phenomena. However, it is usually difficult for students to understand and explain hidden and nonobservable mechanisms at the microscopic level (Al-Balushi 2009; Calyk, Ayas, Ebenezer, 2005; Chiou & Anderson, 2010; Garcia-Franco & Taber, 2009; Gilbert, 2005, 2008; Hesse & Anderson, 1992). It has also been found that after learning microscopic levels of knowledge, high school and middle school students still have difficulties progressing from an observational level to a microscopic level of explanations (Margel, Eylon, & Scherz, 2008; Nakhleh, Samarapungavan, & Saglam, 2005; Taber, 2008 ). The
findings of this study demonstrate that with the facilitation of reflection on the metaconceptual modeling criteria, fifth-grade students’ explanations can spontaneously progress from macroscopic observations to microscopic explanations in several sessions of activity.

Students in the FS groups gradually revised their explanations to higher levels than students in the PS groups. Figures 16, 17, 18, and 19 in Chapter 4 reveal the progression of individual student’s explanations in terms of the three main levels. Most students in the FS groups made significant progress to move from Level 1 or Level 2-1 macro explanations to finally reach Level 3–2 micro explanations. Despite the condition that these students did not propose any microscopic explanations in the beginning of the study, by the end of the activities they could develop microscopic explanatory models to explain magnetic phenomena.

Not so the PS groups. Most of the time, students in the PS groups made either little or no progress in the same activities. They usually maintained the same explanation previously proposed to account for previous observation without revision and used a different and unrelated explanation to account for their current observation. The progress they made was either because they added higher levels of explanation to lower levels of explanation for different observed magnetic phenomena or because the students who had lower levels of explanation agreed with higher levels of explanation that others proposed. When students in the PS groups had macroscopic levels of explanation at the beginning of the study, they were unable to develop microscopic explanations by the end. Only the students who had microscopic levels of explanation at the beginning of the study, or the student who was in the same group with the students proposing microscopic levels of
Coherence of explanation. Students’ naïve conceptions are usually perceived as either more coherent and theory-like (e.g., Carey, 1988; Ioannides & Vosniadou, 2002; McCloskey, 1983; Vosniadou, Vamvakoussi, & Skopeliti, 2008; Wellman & Gelman, 1992; Wise, 1987) or more fragmented (diSessa, 1988, 1993, 2006, 2008; diSessa, Gillespie, & Esterly, 2004). In this study, most students in both the FS and PS groups started with simple explanations in the pre-interview or in the beginning of the activities without having any existing explanatory models.

Students in the FS groups revised their explanation to become more coherent than did students in the PS groups. Table 8, 9, 10, and 11 in Chapter 4 reveal the coherent versus fragmented explanations that the students developed. Most students in the FS groups progressively revised the attribution of causal agency and finally developed Level 3–2 micro explanations, which involve microscopic North–South (N–S) elements to coherently account for different magnetic phenomena.

Again, students in the PS groups not only used different levels of explanation but also developed fragmented and disconnected ideas to account for different magnetic phenomena without considering the relationships between these different ideas they proposed. For instance, one PS group of students had three fragmented and disconnected explanations for different magnetic phenomena: (a) using moving or static molecules to explain two ends of the magnets in M1, (b) using flowing magnetic charges to explain the attraction between metal bars and the magnet in M3, and (c) using teleological explanations or the external factor, such as air influencing the cut pieces, to account for the dipoles of the smallest cut pieces of magnet in M2.
By the end of the activities, only students in the FS groups had activated and reorganized existing ideas to develop coherent and theory-like explanatory models. Most students in the FS groups employed a microscopic model with N–S elements, like small magnets inside the magnet to explain how magnets work. Two of the students even developed explanatory models employing N–S elements inside the magnet and other metal bars to coherently account for all magnetic phenomena. These students’ self-developed explanatory model is the same as the “tiny-magnets model of magnetism” which was suggested by Harlow (2010) in the professional development courses to help teachers develop a simplified version of the scientific domain model of magnetism. In this tiny-magnets model of magnetism, ferromagnetic materials are composed of small entities acting like small magnets, and whether these small magnets representing magnetic domains align with each other or not would determine whether the objects are magnetic or not. See Appendix G for explanations of magnetism.

By contrast, at the end of the activities, the students in the PS groups still maintained fragmented explanations without making connections between their different explanations for different magnetic phenomena. They usually developed one independent explanatory model to account for only one magnetic phenomenon, but failed to apply it for other magnetic phenomena or failed to revise their explanatory models to coherently account for all magnetic phenomena. Hence, most of their explanations were not theory-like, more fragmented.

A similar problem of fragmented explanations was investigated in Nakhleh et al.’s study (2005). They found that even though middle school students were able to develop microscopic levels of explanation, their ideas were fragmented because of the difficulties
in assimilating microscopic levels of scientific knowledge into their original macroscopic knowledge frameworks. The findings of my study indicated that scaffolding the reflection on the modeling criteria encouraged students in the FS groups to self-develop coherent microscopic explanations for their observable magnetic phenomena. Students in the FS groups did not have the difficulties progressing from their original macroscopic knowledge to microscopic knowledge.

Compared with the current study, previous clinical interviews with several third and sixth graders showed that only one sixth grader developed coherent microscopic explanations for most of her observations (Cheng & Brown, 2010). This current study reveals that through the teaching experiments, five of six fifth graders in the FS groups were able to develop coherent microscopic explanations for all observed magnetic phenomena. Additionally, in the previous study, most students developed lower levels of explanation or different levels and fragmented explanations for different magnetic phenomena, which is similar to the fifth graders in the PS groups of this teaching experiment. Therefore, this study verified that assisting students to reflect on their explanations by using metaconceptual modeling criteria helped students progressively evaluate and revise their explanations toward not only coherent but also higher levels.

**Question 2: What are the conceptual resources involved in students’ explanations about for magnetism?** How students developed and revised their explanations is discussed according to the multidimensional framework (Brown, 1993, 1995a, 1995b; Cheng & Brown, 2010), which offers interpretations for the conceptual resources involved in students’ explanations. Based on the multidimensional framework, students in the FS groups revised the causal agency from observable magnets to
hypothesized microscopic elements, as well as further applied appropriate implicit models and verbal symbolic knowledge from their observation to make sense of the hypothesized microscopic elements.

At the end, they were able to construct coherent explanatory models for different magnetic phenomena through applying their conceptual resources from the observational level to the microscopic level. On the other side, without revision of causal agency and application of appropriate implicit models from observational levels to other hypothesized levels, students in the PS groups did not develop coherent explanatory models in the end.

**Explanatory models.** This study demonstrates that through the facilitation of reflective thinking by the use of metaconceptual modeling criteria, students in the FS groups, who originally did not offer any explanatory models in the pre-interview or at the beginning of any activity, were able to finally develop explanatory models involving microscopic N–S elements inside the magnet to coherently explain most of their observations. The reflection on their explanations by considering metaconceptual modeling criteria encouraged students to visualize simple images or causal agents inside the magnet, further examine these hypothesized elements, articulate the causal relationships between them, and finally develop and revise their explanations to generate coherent microscopic explanatory models similar to the simplified version of the domain model proposed by Harlow (2010).

Initially, students in the PS groups seemed to develop better explanatory models in the beginning than students in the FS groups, but by the end, they could not develop coherent and sophisticated explanatory models as students in the FS groups. Even though
students in the PS groups were able to develop macroscopic and microscopic explanatory models to account for few activities, these explanatory models were independent and fragmented without connection between the different models. Without constant reflection on the metaconceptual modeling criteria, students had problems visualizing the elements and the causal relationships between them in the magnet during the activities, let alone inspecting whether these hypothesized elements could help them to explain all magnetic phenomena.

The previous study (Cheng & Brown, 2010) with several third and sixth grade students revealed that only one sixth grader could develop coherent explanatory models to explain most magnetic phenomena, which is similar to most of the students in the FS groups in this study. Most students in the previous study could only generate one or two disconnected and tentative explanatory models to explain one or two activities, which is similar to most of the students in the PS groups in this study.

Next, how students in the FS and PS groups activated, applied, and revised the conceptual resources differently is discussed.

**Core intuitions.** The revision of attributing causal agency in core intuition from observable magnets to microscopic N–S elements enabled students in the FS groups to develop coherent explanatory models at the end. A lack of revision of causal agents induced students in the PS groups to develop tentative and fragmented explanations or explanatory models.

In the FS groups, the causal agents in the explanations were usually gradually revised from observable magnets or unobservable macroscopic elements to microscopic N–S elements or particles, because the students indicated that hypothesizing the activities
of microscopic N–S elements enabled their explanation to have better visualization and explanatory power. Attributing causal agency to microscopic N–S elements offered better visualization than attributing causal agency to observable magnets and microscopic unknown elements. This attribution also provided better explanatory power than attributing causal agency to macroscopic components and unknown microscopic elements.

Nevertheless, the causal agency in the explanations of the PS groups usually remained the same without revision. They tended to propose different and unrelated causal agencies, such as observable magnet or unobservable macroscopic or microscopic elements inside magnets, to account for different magnetic phenomena, because they believed that using various hypothesized elements enabled their explanation to better meet the criterion of more detail. Without consistently revising the causal agency they previously proposed in order to explain all observation, they ended up using different causal agents for different magnetic phenomena. Therefore, they had difficulties developing the highest level and most coherent explanatory models.

These findings unveiled the fact that refining the causal agency in core intuition seems to be difficult if students are not scaffolded to reflect on their explanations by using metaconceptual modeling criteria. The previous study (Cheng & Brown, 2010) confirmed that most third and sixth graders, similar to the fifth graders in the PS groups in this study, attributed causal agency to different causal agents in order to account for different magnetic phenomena without revision of the causal agents to better explain their observations. In that study, only one sixth grader who proposed a simple image of positive and negative elements in the beginning was able to constantly revise and apply
the activities of these elements to develop more coherent explanatory models.

Nevertheless, the revisions that this sixth grader made in the previous study were only within microscopic levels of explanation, which is minor compared to the revision from the observational level or macroscopic level to microscopic level made by most students in the FS groups.

The difficulties of refining the causal agents from the observational level to microscopic level and further coherently applying microscopic level of causal agents to account for different magnetic phenomena have been disclosed in Sederberg and Bryan’s (2010) study about students’ learning progression. In their study, most high school students who had revised their initial model to become the domain model were only able to apply this idea to explain magnetized nails, but were not able to apply the domain model to explain the magnet itself. The magnet was still perceived as the direct causal agent acting on the other objects at an observational level without referring to the magnetic field or the domain inside the magnet.

**Implicit models.** Previous researchers found that it is intuitive for students to attribute macroscopic properties to microscopic entities or particles (e.g., Albanese, & Vicentini, 1997; Eilam, 2004; Harrison & Treagust, 2002; Rappoport & Ashkenazi, 2008; Taber & García-Franco, 2009, 2010; Talanquer, 2009; Wiser & Smith, 2008; Yair & Yair, 2004). In these studies, this intuitive assumption is regarded as an obstacle to constrain students from explaining macroscopic observation appropriately. Yet, in this current study, hypothesizing microscopic magnet-like elements helped students in the FS groups develop coherent explanatory models similar to the simplified version of the domain model. In the progression of students’ explanations, most students in the FS and PS
groups shared similar implicit models regardless of whether they developed explanatory models or revised the attribution of causal agency from magnets to microscopic N–S elements in core intuition.

The first common implicit model was that the pieces of something should be the same as the whole thing. This implicit model appeared to be activated and adopted by most students in the M2: Cutting Magnet Activity. Nevertheless, how students in the FS and PS groups applied this implicit model was different. Students in the PS groups seemed to only apply this implicit model to explain the coexistence of N and S on the small cut pieces of magnet. Meanwhile, students in the FS groups seemed to extend this implicit model from thinking about the dipole on the small cut pieces to imagining the dipole on the smallest hypothesized elements inside the magnet. This was also the start for the student in the FS groups to employ microscopic N–S elements in the magnet to explain their observation.

The second common adopted implicit model was that force is substance. In the pre-interview, magnetic force appeared to be considered an inherent property of the objects by some students in the FS groups, so they would mention that the magnet has a force to pull other objects. In the M3: Metal Bars activity, students in both groups seemed to consider the magnetic force between the magnet and the metal bars as moving elements, or a substance-like energy or a force. In other studies, this intuitive implicit model was also commonly activated and employed by students in their reasoning about abstract physics concepts, such as light, electricity and heat (Chiou & Anderson, 2010; Reiner, Slotta, Chi, & Resnick, 2000; Slotta & Chi, 2006; Slotta, Chi, & Joram, 1995), and even by scientists in their historical development of microscopic levels of
explanation for observable phenomena (Scheffel, Brockmeier, & Parchmann, 2009).

Nevertheless, later in the study this implicit model seemed to be overcome when Frank and Felix, in the FS groups, started to apply verbal symbolic knowledge about the attraction and repulsion between N and S ends to explain the interaction between N–S elements. Thus they were able to apply the interaction between N–S elements not only to explain what happen in the magnet and between two magnets, but also to explain what happen between the magnet and metal bars. This spontaneous shift from regarding magnetic force as the property of the magnet or as a kind of concrete object to hypothesizing about the interactions between the microscopic elements in the magnet and other objects corresponds to an ontological shift from a matter category to a process category (Chi, 1992, 2005, 2008; Chi & Hausmann, 2003; Chi & Roscoe, 2002; Chi, Slotta & de Leeuw, 1994; Slotta & Chi, 2006). However, according to Chi’s categorical shift theory (Chi, 1992, 2005, 2008; Chi et al., 1994; Slotta & Chi, 2006), it is impossible for students’ conceptions to spontaneously progress from matter ontology to process ontology without directly teaching these categories.

When comparing the implicit models that students involved in this study and in the previous study (Cheng & Brown, 2010), one can find the M1: Two Magnets Activity and the M3: Metal Bars Activity in the current study had also been employed in the previous study. Hence, most of the implicit models, such as that like things would go together and that force is substance, involved in students’ explanations to account for M1 and M3 in this study are similar to the ones employed by students in the previous study. Nevertheless, the M2: Cutting Magnet Activity was an additional activity involved in this current teaching experiment, but not in the previous study, so this activity seemed to
activate a different implicit model that the pieces of something should be the same as the whole thing. The attribution of the properties of magnets to the hypothesized microscopic elements or particles seemed essential for students in the FS groups to develop their explanatory model.

**Verbal symbolic knowledge.** Interpreting students’ explanations by using the multidimensional framework also unveils that when students employed appropriate verbal symbolic knowledge in their model construction, they developed more coherent explanatory models consistent with their observations. The common appropriate verbal symbolic knowledge employed by students covers the attraction and repulsion between the N and S ends of the magnet. When it was applied by students in the PS groups to account for only what happened between two magnets at the observational level instead of model development, they were unable to develop coherent explanatory models. But, when it was applied by most students in the FS groups to explain not only what happens between two magnets, but also what happens between microscopic N–S elements, it facilitated their development of coherent explanatory models.

If this verbal symbolic knowledge was further applied by students in the FS groups to not only the interaction between N–S elements in the magnet, but also to the interaction between N–S elements in the magnet and objects interacting with the magnet, students developed more coherent explanatory models for magnetic phenomena. This application of verbal symbolic knowledge in the model development also helped them escape from the intuitive implicit model that force is substance, where there should be something moving from the magnet to the metal bars, by referring to abstract ideas such as “waking up” or “reacting to” to describe what happens between the N–S elements in
the magnet and the metal bars. Comparing how students utilized the verbal symbolic knowledge about the attraction and repulsion between the N and S ends of the magnet in this study and in a previous study (Cheng & Brown, 2010), it was found that students in the previous study did not apply this verbal symbolic knowledge at a microscopic level as students in the FS groups. Instead, they only applied it at an observational level, identical to the students in the PS groups.

However, when students applied inappropriate verbal symbolic knowledge (e.g., using the interaction between positive and negative charges) into their model construction, they had problems developing their explanatory models in a way that was consistent with their observations. In this study, some students tried to apply the verbal symbolic knowledge from a familiar domain, such as the idea of positive and negative charges in static electricity, to make sense of a less familiar domain, such as the attraction and repulsion between the N and S ends of the magnet. They usually had problems distinguishing the differences in the knowledge between two different domains or were unaware of the limitations of these applications.

More than half of the students in the FS and PS groups referred to the notion about attraction and repulsion between positives and negatives, which may have been derived from their previous learning about batteries or static electricity. In the FS groups, only two students could either distinguish the differences between static electricity and magnetism or were aware of the limitation of the application of the idea of electricity to magnetism. Other students applied this verbal symbolic knowledge from static electricity to explain what happens between two magnets in the pre-interview or in the activities, but it was unclear why they did not apply it in the post interview to account for attraction and
repulsion between two magnets or other phenomena.

Only Freddie in one of the FS groups continued applying this inappropriate verbal symbolic knowledge about static electricity to explain all observed magnetic phenomena in the post interview. Continuing to apply the verbal symbolic knowledge about static electricity to explain magnetism may make Freddie develop explanatory models inconsistent with his observation and different from other students in the post interview. Inasmuch as Freddie believed the elements inside the magnet work like static electricity, N and S should not coexist in the same elements permanently, or these elements would become neutralized.

The application of knowledge from static electricity to magnetism also happened with several students in the previous study (Cheng & Brown, 2010), in which only one student could develop coherent explanatory models that involved microscopic monopole elements to explain magnetic phenomena. Students’ spontaneous application of static electricity to explain magnetism was documented while researchers investigated students’ conceptions of magnets (Barrow, 1987; Guisasola, Almudi, & Zubimendi, 2004; Guth & Pegg, 1994; Haupt, 1952; Hickey & Schibeci, 1999; Maloney, 1985; Saglam & Millar, 2006; Sederberg & Bryan, 2009, 2010). The application of knowledge from more familiar domain, electricity, to unfamiliar domain, magnetism, is usually considered students’ confusion. Therefore, the way to encourage students to adopt appropriate existing verbal symbolic knowledge into their model construction will need to be further explored in future research.

The obstacles to developing higher-level and coherent explanatory models. The findings of this study show that all students in the PS groups had difficulties developing
coherent microscopic explanatory models which would allow them to explain all of their observations. Even when they were able to develop explanatory models to explain certain activities, they were both tentative and fragmented. Their models were tentative in that students did not apply them to explain other phenomena. Additionally, their models were fragmented in that students did not connect them with other explanations. In contrast, there was only one student, Fiona, in the FS groups who had difficulties employing the metaconceptual modeling criteria to develop explanatory models, whereas most students in FS groups were able to develop coherent microscopic explanatory models.

There are two common difficulties in the process of students’ model development. First, when students did not hypothesize the activities of microscopic elements inside the magnet in the process of model development and revision, they had difficulties developing coherent explanatory models. In other words, when students either used the activities of macroscopic elements or a simple static image of microscopic elements in their explanations, they were unable to develop coherent explanatory models.

Second, when students added different microscopic or macroscopic elements to their existing model (i.e., concatenation rather than revision), they also had difficulty developing higher-level and more coherent explanatory models. Even though students were able to use one kind of microscopic element to explain certain phenomena, they used other different kinds of microscopic elements to explain other phenomena without articulating the relationships between these elements.

Based on the multidimensional framework (Brown, 1993, 1995a, 1995b; Cheng & Brown, 2010) students’ difficulties developing higher-level and more coherent explanatory models in the PS groups was because they used their self-generated criterion
of more detail to evaluate their explanations and added more detailed information from different activities into their explanations. They did not feel the need to revise their notion of causal agency and contemplate the relationships and interactions between these causal agents so as to develop explanations with better visualization and explanatory power. Nor did they feel the need to further apply their existing implicit model or verbal symbolic knowledge from their observation level to the other hypothesized levels of unseen elements. Consequently, without activating and applying appropriate conceptual resources through their evaluation of their explanations, students in the PS groups used different tentative and fragmented explanations for different magnetic phenomena.

In a previous study (Cheng & Brown, 2010), overly relying on their implicit model (e.g., same things getting together or verbal symbolic knowledge or a magnetic field from the magnet acting on other matter) made several students unable to develop explanatory models. However, in this study, no students relied on only one implicit model or verbal symbolic knowledge throughout the activities, so they could develop at least one explanatory model for one certain phenomenon. Yet, students in the PS groups still had difficulties employing appropriate conceptual resources to develop coherent explanatory models for all magnetic phenomena without reflecting on the metaconceptual modeling criteria.

It appeared that students’ ability to employ appropriate conceptual resources was fostered by their observation of the magnetic phenomena in these activities and their use of the metaconceptual modeling criteria to reflect on their explanations. Students in the PS groups and the FS groups seemed to activate similar related conceptual resources due to the same contexts of the activities. Nevertheless, additional reflection using the
modeling criteria further promoted the FS students to further apply the appropriate conceptual resources into their model construction and revision. Thus, the FS students developed higher-level and more coherent explanations, whereas the PS students developed lower-level and fragmented explanations.

Figure 31 provides a cognitive model, inferred from this study and based on the theory about knowledge activation (Brown, 1993, 1995a, 1995b; diSessa 1993, 2002; Hammer, 2000; Hammer, Elby, Scherr, & Redish, 2005; Sabella & Redish, 2007; Taber & Garcia-Franco, 2010; Wittmann, 2006; Taber, 2008), which illustrates how the contexts of activities and reflection on the modeling criteria facilitate students’ cognitive process. First, students’ related conceptual resources were activated by the particular contexts of activities. Both FS students’ and PS students’ conceptual resources related to magnets were activated in order to explain different observed magnetic phenomena. Their verbal symbolic knowledge about electricity and the attraction and repulsion between N and S ends, the implicit model that like things would go together, and the core intuition about the causal relationship between causal entities were engaged in order to explain the attraction and repulsion between two magnets in M1. Their implicit model that the pieces of something should be the same as the whole thing was further activated to explain the coexistence of N and S on the small pieces of the magnet in M2. Their verbal symbolic knowledge about electricity, the implicit model that force is substance, and the core intuition that more agency begets greater effects were further activated in order to explain how metal bars stick to the two ends of the magnet in M3.

Second, their reflection using the metaconceptual modeling criteria activates their appropriate conceptual resources among these related conceptual resources. Students
apply and reorganize the appropriate conceptual resources into their process of model construction and revision in order to enable their explanations to meet the modeling criteria. In this study, the FS students reflected on their explanations mostly according to the criteria of visualization and explanatory power, whereas the PS students reflected on their explanation mostly according to the criteria of more detail. For the FS students, reflection on the modeling criteria enabled them to find the lack of visualization and explanatory power of their explanation, which then enabled them to activate the conceptual resources necessary to improve the visualization and explanatory power of their explanations.

Reflection on the criterion of visualization encouraged students to hypothesize unseen elements to explain observed magnetic phenomena, which activated their core intuition about the attribution of causal agency in all activities and the implicit model that the pieces of something should be the same as the whole thing in M2 from the observable level of magnets to apply to the microscopic level of elements. Moreover, reflection on the criterion of explanatory power encouraged students to articulate the interaction between hypothesized causal agencies and to revise the property of hypothesized elements in order to account for all magnetic phenomena. This reflection activated their core intuition about the attribution of causal agency, the implicit model that the pieces of something should be the same as the whole thing, and their verbal symbolic knowledge that the attraction and repulsion between N and S ends in M2 and M3, from the observable level of magnets to apply them to the microscopic level of elements.

Eventually, through continual reflection using the modeling criteria, the appropriate conceptual resources were gradually applied and reorganized into coherent
microscopic explanatory models at the end. In order to meet the criteria of visualization and explanatory power, students’ conceptual resources were not fragmented and unrelated pieces independently activated to explain different magnetic phenomena. Developing explanatory models allowed them to reorganize these appropriate conceptual resources, which connected the causal relationships of their hypothesized elements with their implicit model and verbal symbolic knowledge at the microscopic levels. Without reflecting on the modeling criteria, students may be able to activate related conceptual resources, but they may have problems activating, applying, and restructuring the appropriate conceptual resources to develop coherent explanatory models.

**Figure 31.** The process of the PS and the FS students’ knowledge activation.
In short, the PS and FS students’ related conceptual resources were activated by the contexts of the activities. With further metaconceptual scaffolding, the FS students’ appropriate conceptual resources were activated, applied, and reorganized to develop coherent explanatory models. Without further metaconceptual scaffolding to activate, apply, and reorganize the appropriate conceptual resources, the PS students’ related conceptual resources stayed piecemeal and disconnected.

The difficulties of developing higher-level and coherent explanatory models to account for magnetic phenomena were also revealed in some previous studies (Barrow, 1987; Cheng & Brown, 2010; Erickson, 1994; Harlow, 2010; Haupt, 1952). According to these studies, to explain magnetic phenomena students at the primary level usually rely on their intuition that attraction is the inherent nature of magnets or that magnets would send out force or energy to pull other objects toward them. Although many students in the secondary and university levels were able to utilize abstract terminology, such as magnetic field or magnetism to explain magnetic phenomena, the way they used these terms was similar to younger students’ intuitive knowledge (Borges & Gilbert, 1998; Cheng & Brown, 2010; Erickson, 1994; Guisasola et al., 2004; Guth & Peggy, 1994; Haupt, 1952; Sederberg & Bryan, 2009). Thus, these intuitive ideas were painted over by abstract terminology, but the underlying meanings or explanations remained the same. Based on the categorization of level of explanation, both intuitive and abstract explanations are regarded as at an observational level without developing a working model for the underlying mechanism of magnetism.

**Question 3: How does promoting metaconceptual evaluation facilitate the process of students’ model construction, evaluation, and revision?** The findings of this
study indicate that students in the FS groups evaluated and revised their explanations mostly following the elicited scientific criteria of visualization and explanatory power, whereas students in the PS groups evaluated and added to their explanations (concatenation) mostly following their self-generated criterion of more detail (the need for more detail in the model). Table 16 shows a summary of the differences between how the FS and PS groups evaluated and revised their explanations according to different criteria mentioned above.

Table 16

*How Students Employed the Reflective Criteria to Facilitate Their Model Evaluation and Revision*

<table>
<thead>
<tr>
<th>Employed Criteria</th>
<th>Fully Scaffolded Groups</th>
<th>Partially Scaffolded Groups</th>
</tr>
</thead>
<tbody>
<tr>
<td>Criterion of visualization</td>
<td>Evaluate &amp; revise</td>
<td>Evaluate</td>
</tr>
<tr>
<td>Criterion of explanatory power</td>
<td>Evaluate &amp; revise</td>
<td>Evaluate</td>
</tr>
<tr>
<td>Criterion of more detail</td>
<td>Evaluate</td>
<td>Evaluate &amp; concatenate</td>
</tr>
</tbody>
</table>

The FS groups gradually developed, evaluated, and revised their explanations to the highest level explanations through reflecting on their explanations using the metaconceptual modeling criteria. They also activated and applied appropriate conceptual resources so as to construct coherent explanatory models to account for all magnetic phenomena. The criterion of visualization appeared to foster students’ progression mainly in terms of their levels of explanation; the criterion of explanatory power appeared to promote students’ progression in terms of their levels of explanation as well as coherence.

The PS groups added different ideas from different activities without revising the ideas that they previously proposed through reflecting on their explanations using their
self-generated criterion of more detail. Hence, they used different levels of explanation and disconnected ideas for different magnetic phenomena, so that their explanations were tentative and fragmented.

Despite the fact that students in the PS groups spontaneously employed the criteria of visualization and explanatory power to evaluate their ideas in a few occasions, they did not revise their explanations according to these criteria. The results demonstrate that the metaconceptual modeling criteria may be intuitive because students in the PS groups spontaneously employed the scientific criteria to evaluate their ideas without scaffolding. However, only students in the FS groups who were scaffolded to reflect on the scientific criteria were able to revise their ideas, suggesting that scaffolding encourages students to revise their ideas according to scientific criteria, instead of the self-generated criterion of more detail.

**The criterion of more detail.** The criterion of more detail seems to be an intuitive criterion, which was spontaneously employed by students in both the FS and PS groups. However, this intuitive criterion was employed differently by students in the two types of groups in this study. Most students in the PS groups concatenated their ideas according to the criterion of more detail because they perceived the criterion of more detail as the most important issue. But, the criterion of more detail was also used by some students in the FS groups as part of the criterion of explanatory power or a self-generated criterion. However, they only employed the criterion of more detail when they compared and evaluated different pictures without revising their explanations because they perceived the criteria of visualization and explanatory power as the more important criteria for them to use in revising their explanations.
The common intuitive criteria in this study, such as more detail and understandability, were also employed by students in other studies (Baek, Schwarz, Chen, Hokayem, & Zhan, 2011, Buckingham & Reiser, 2010; Kenyon, Schwarz, Hug, & Baek, 2008; Schwarz et al., 2009). These studies engaged students in scientific inquiry by emphasizing the relationship between evidence they collected and the explanations they developed so as to promote students’ testing and revision of their ideas. Nevertheless, how students revised their explanations according to these intuitive criteria was not explored.

This study tackled the issue of students’ intuitive self-generated criteria and found that the criterion of more detail is an intuitive criterion employed by most students regardless of whether they were scaffolded to reflect on scientific criteria. Without scaffolding students’ reflection on the scientific criteria, students regarded more detail as the most important criteria to evaluate their explanations and added different explanations from different activities without revision of these ideas. As a result, they had problems developing higher-level and coherent explanatory models for different magnetic phenomena.

**The criterion of visualization.** The results of this study showed that if students were scaffolded to reflect on the criterion of visualization, the level of their explanations was enhanced. Reflection on the criterion of visualization prompted students to hypothesize and examine the unobservable elements to explain observable magnetic phenomena. Consequently, this reflection facilitated students’ articulation of different levels of causal agency. It also assisted with their revision of the attribution of causal agency across different levels, from observable magnet to unseen microscopic elements,
or within the same level, from microscopic unknown elements to N–S elements in the magnet. In addition, this reflection aroused students to further apply implicit model that the pieces of something should be the same as the whole thing from their observational level to hypothesized microscopic level so as to visualize microscopic N–S elements inside the magnet.

The essential role of visualization of unseen causal entities and their causal relationships has been stressed in the development of explanatory models (Clement, 1989, 2008a, 2008b; Gilbert 2005, 2008; Harlow, 2010). Nevertheless, novices are usually regarded as lacking in the microscopic levels of explanation or having problems understanding and explaining hidden and nonobservable mechanisms at the microscopic level (Al-Balushi 2009; Calyk et al., 2005; Chiou & Anderson, 2010; García-Franco & Taber, 2009; Gilbert, 2005, 2008; Hesse & Anderson, 1992). The previous research about students’ explanations of or learning about magnetic phenomena has revealed that without existing models, students had problems spontaneously constructing microscopic explanatory models or revising their models to coherently explain magnetic phenomena (Barrow, 1987; Borges & Gilbert, 1998; Erickson, 1994; Harlow, 2010; Haupt, 1952).

Harlow (2010) pointed out the difficulties of transferring a teacher training program about magnetism to student classroom learning. She found that this teaching training program only worked for teachers who already had existing microscopic models, but when these teachers tried implementing a similar program for their students who did not have any existing macroscopic or microscopic models, these students had problems spontaneously generating microscopic models. The current study discovered that scaffolding students’ reflection on the criterion of visualization helped students overcome
the obstacle to hypothesizing unseen microscopic elements. It also helped them apply appropriate conceptual resources to make sense of these hypothesized elements.

_The criterion of explanatory power._ This study showed that, if students were scaffolded to reflect on the criterion of explanatory power, the level and coherence of their explanations were enhanced. Reflecting on the criterion of explanatory power encouraged students to articulate the interaction between hypothesized microscopic causal agency and to inspect the limited explanatory power of their previous hypothesized causal agency. Consequently, this reflection facilitated students’ revision of attribution of causal agency across different levels—from macroscopic elements to microscopic unknown elements or within the same level from microscopic monopole or unknown elements to microscopic N–S elements—in order to coherently explain all observed phenomena. This reflection also aroused students to activate and further apply the implicit model that the pieces of something should be the same as the whole thing from their observational level to hypothesized microscopic level so as to visualize microscopic N–S elements inside the magnet.

In addition, it helped students activate and apply verbal symbolic knowledge that the attraction and repulsion between N and S ends from their observational level to hypothesized microscopic elements in order to account for the interaction between unseen N–S elements inside the magnet and other objects which interacted with the magnet. Further applying this verbal symbolic knowledge to make sense of the invisible interaction between microscopic N–S elements in the magnet and other objects interacting with the magnet also helped students lower the status of their intuitive implicit model that force is substance moving from the magnet to other objects.
The difficulties of articulating the causal interactions in microscopic model have been identified in studies of students’ explanations about the structure of matter (Talanquer, 2009, 2010). Talanquer (2010) indicated that novices usually possessed a static microscopic model that was less advanced than a dynamic model. The current study revealed that when students in the FS groups could involve appropriate verbal symbolic knowledge about the attraction and repulsion between N and S ends from observable magnets to microscopic N–S elements, they were able to revise their static models to become more advanced dynamic models.

The criterion of explanatory power as applied to explanations has been implicitly emphasized in many studies by promoting students’ model revision based on the data they collected or observed (Baek et al., 2011; Buckingham & Reiser, 2010; Harlow, 2010; Kenyon et al., 2008; Schwarz et al., 2009; Sederberg & Bryan, 2010; Windschitl, Thompson, & Braaten, 2008a, 2008b). Or, the criterion of explanatory power has been explicitly emphasized in several studies by asking students to evaluate their explanation according to this criterion (Cartier, 2000a, 2000b; Cartier, Passmore, Stewart, & Willauer, 2005; Schwarz & White, 2005; Stewart, Cartier, & Passmore, 2005). Without explicitly scaffolding students’ reflection on the criterion of explanatory power, Baek et al.’s study (2011) found that students had problems spontaneously generating a coherent explanatory model. Some students developed different models to explain different phenomena.

A similar problem was also identified in the PS groups in this study, which may offer explanations about why students in this and other studies developed unstable and fragmented explanations without scaffolding students’ reflection on the criterion of explanatory power. Although the criterion of explanatory power is also an intuitive
criterion developed by students when asked to examine the consistency between their data and model, without explicit scaffolding, students may perceive other intuitive self-generated criteria, such as the criterion of more detail, as a more important criterion to utilize in revising their explanations. This study discovered that scaffolding students’ reflection on the criterion of explanatory power encouraged students to inspect the limited explanatory power of their models, which prompted students to activate and apply more appropriate conceptual resources into their model revision in order to develop coherent explanatory models.

*The essential role of scaffolding reflection on the modeling criteria.* An earlier study (Cheng & Brown, 2010) and the current teaching experiments verified that only relying on students’ intuitive metaconceptual evaluation is not enough to regulate students’ reflective thinking to develop higher-level and more coherent explanatory models. The result of this study demonstrated that scaffolding students to employ the scientific criteria can promote their reflective thinking to activate or apply appropriate conceptual resources, thereby encouraging them to evaluate and to revise their explanations to the higher level and coherence. Without scaffolding, even though students may be able to spontaneously use scientific criteria to assess their ideas, they did not further revise their explanations according to these criteria.

The result of current study revealed that both the criteria of visualization and explanatory power were required for students to activate and apply appropriate conceptual resources in order to develop coherent microscopic explanatory model. Without reflection on both the criteria of visualization and explanatory power, students had difficulties developing coherent microscopic explanations for all observed magnet
phenomena.

Comparing students in the FS and PS groups as well as before and after students in the FS groups were asked to employ the scientific criteria, one would find that without reflecting on the criterion of visualization, students had difficulties in progressing from their observable level of explanations to the microscopic level of explanations. Meaning that, if students did not have microscopic models without scaffolding, students would have difficulties spontaneously developing coherent microscopic models. However, an evaluation of the explanation according to the criterion of visualization alone is not sufficient. Reiner and Gilbert (2008) pointed out two common problems in visualization: the tendency for students to ignore theories when their intuition is more accessible or apply different fragmented ideas to (inconsistently) account for different situations.

This study also found that even though students could develop microscopic elements, without further reflecting on the criterion of explanatory power students may have difficulties with hypothesized elements: articulating the activities, selecting and applying appropriate ones, or revising ones to develop coherent explanations for different magnetic phenomena. Hence, as this study found, students need the reflection on the criterion of explanatory power in order to develop coherent explanatory models.

In this study, reflection on the metaconceptual modeling criteria helps students not only to visualize the microscopic model of magnetism, but also to inspect, activate, apply, or reorganize their conceptual resources in order to construct explanatory models with better visualization and explanatory power. This process is similar to the reasoning of experts who are usually considered have more organized and sophisticated conceptual networking or mental representations (Al-Balushi, 2009; Rapp & Kurby 2008).
Limitations of the Study

Several limitations need to be considered regarding the present study in these three areas: (a) the assessment of students’ metacognition, (b) the design of research, and (c) generalization of the findings.

The assessment of students’ metacognition. One limitation of the study comes from how students’ metacognition was evaluated. In this study, students’ metacognition in general learning was evaluated by both them and their teachers, whereas their science performance was self-evaluated before teaching experiments. Although these assessments offered information that students in the FS and PS groups had similar performance levels in school, measuring students’ metacognition in learning and their science performance is different from measuring students’ metacognition about modeling or their metaconceptual evaluation of model. Without assessing the difference between students’ metaconceptual evaluation of model in the pre- and post-interview, this study relies on students’ discourse, behavior, drawing, and writing to investigate their metacognitive process in the activities and post-interviews as well as the comparison of students’ metaconceptual evaluation in the FS and PS groups.

Consequently, this design could not answer whether students change their metacognition about evaluating and revising their models. This means that, despite the fact that most students in the FS groups were able to employ scientific criteria to evaluate their models in the activities and post interview, it could not be verified whether they had already used similar criteria to evaluate their models before the teaching experiment. Thus, if an instrument or scale could be designed to diagnose students’ metacognition
about modeling or evaluation of models in the pre- and post-interview, it would provide better explanations for whether there was any progression in students’ metaconceptual evaluation.

**The design of research.** The main goal of this study was to explore the interaction between students’ model development and metaconceptual evaluation, but there was no direct access to students’ internal cognitive and metacognitive process. Thus, these reasoning processes are inferred from students’ observable action and speaking (Justi & Gilbert, 2000; White, 1998). In order to keep track of individual thinking, students were encouraged to articulate and record their individual ideas before, during, and after activities and to compare and justify their evaluation of their own and others’ ideas. However, students might sometimes support others’ ideas without articulating their own or evaluating others’ ideas.

In other words, students’ implicit reasoning process cannot be directly studied. Notwithstanding that the group was small enough for students to articulate their individual thoughts, social interaction may constrain students from articulating their ideas. Students may not always propose their different ideas or evaluations in their groups. In this study, employing stimulated recall helped to attenuate this limitation. For instance, in the post-interview, Freddie recalled that he had idea about hypothesized elements inside the magnet in the activities. He thought of monopole elements inside the magnet, whereas other group members expressed the idea of dipole elements inside the magnet, but he did not propose his different idea at that time. This idea about a monopole element remained the same, because it stayed implicit and was not challenged by other group members. Nevertheless, even in the stimulated recall, students might not articulate the reasons for
the modification of their ideas.

**Generalizability of the findings.** Another essential limitation of this study is the generalizability of the findings due to sample selection and the nature of the study. First, the participants in this study were a convenient small sample who were not randomized in any way. Because they voluntarily joined in the studies, they may have a greater interest in science than other students. Moreover, students were assigned to groups according to their availability instead of by random assignment. As this is a comparative analysis between a small number of students in the FS and PS groups, this study does not intend to make generalizations beyond the observed cases. The advantage of studying small numbers of students is that it allows the instructor to keep track of individual students’ cognitive and metacognitive processes as well as offer more individual support (Blatchford, Moriarty, Edmonds, & Martin, 2002), which cannot be accomplished in a large-scale study.

Second, the goal of teaching experiments is to develop models to account for students’ conceptual schemes (Steffe, Thompson, & von Glasersfeld, 2000), so this study was designed to make an in-depth investigation. This small scale study helps to monitor cognitive and metacognitive processes simultaneously. Here, the most important value of the study is to propose explanatory model which can explain students’ cognitive and metacognitive process, which will provide new insight into existing theoretical framework, rather than evaluate statistical generalizability.

**Instructional Implications**

Through exploring how students developed their explanations with and without
scaffolding by using metaconceptual modeling criteria, this study brings several instructional implications from a content perspective, a constructivist perspective, and a modeling perspective. These suggestions, which have been advocated by other researchers (Duschl, Schweingruber, & Shouse, 2007; Metz, 2008; Nersessian, 1995), are intended to diminish the gap between how scientists practice science and how science is taught.

**From a content perspective.** The discussion shows that most students in the FS groups were able to develop explanations similar to the “tiny-magnets model of magnetism,” which was suggested by Harlow (2010) to help teachers develop a simplified version of the domain model of magnetism. This implies that the scientific domain model can be an intuitive model for upper elementary students. Even though the facilitator did not present this model, students were capable of self-generating this model with appropriate metaconceptual scaffolding.

The domain model of magnetism has been involved in the curriculum for preservice teachers (Harlow 2010) and high school students (Sederberg & Bryan, 2010) who could revise their initial microscopic models to become similar to scientific domain model at the microscopic level. For middle school students, scientific domain models have been introduced to students directly (Botzer & Reiner, 2005). Studies shows the developing microscopic elements or domain models does not spontaneously happen to younger students (Botzer & Reiner, 2005; Harlow, 2010).

The difficulty of developing and revising microscopic models was found in this study, because the younger students involved did not have existing microscopic models like the previously mentioned older students, who can revise their models within the
same microscopic level. There is a big gap between younger students’ original lower levels of explanation (Level 1 or Level 2-1 macro) and the final highest level of explanations (Level 3-2 micro). Not only were students’ explanations required to progress from the observational or macroscopic level to the microscopic level, but also their hypothesized elements in the magnet needed to progress from static elements to dynamic causal agency.

Nevertheless, the results of this study show that when scaffolded by using modeling criteria, students were able to move beyond the intuitive observational level and static explanations to develop the tiny-magnet model from their existing knowledge. This suggests that reflection on both criteria of visualization and explanatory power helps students to develop coherent microscopic models. First, reflection on the criterion of visualization helps students who do not have any existing model to develop initial macroscopic or microscopic models. Next, reflection on the criterion of explanatory power helps students to examine and revise the unseen causal elements they hypothesize to develop the coherent tiny-magnet explanatory model.

Without scaffolding students’ reflection on the explanatory power of their models, several studies made clear that even though students were offered the scientific domain model or prompted to self-generate the domain model, they still had problems applying the visualized domain models to coherently account for all observed magnetic phenomena (Botzer & Reiner, 2005; Harlow, 2007, 2010; Sederberg & Bryan, 2010). Without scaffolding students’ reflection on the visualization of their models, their visualization was usually limited to the objects interacting with the magnet. Magnets are still perceived as a direct initiating agent to act on other objects without applying domain
model they learned or self-generated to make sense of how magnets work.

From a constructivist perspective. Instruction should build on students’ prior knowledge instead of perceiving their prior ideas as misconceptions and replacing their ideas with scientific models (Özdemir & Clark, 2007; Redish, 2004; Smith, diSessa, & Roschelle, 1993; Taber & Garcia-Franco, 2010). Students’ ideas are not incorrect; they are different from scientists’ because of different organization or activation of conceptual resources (diSessa 1988, 1993, 2006; Smith et al, 1993). Therefore, instruction should pick the most essential ideas students have and encourage students to revise them or apply them to develop scientific concepts. The results of this study unveil how students can be supported to activate and apply appropriate conceptual resources to develop and revise their models to be close to the domain model of magnetism. It suggests implication for the identification of appropriate conceptual resources and how they can be activated, applied, and reorganized.

Based on this study, in order to develop the domain model, students’ conceptual resources about the attribution of causal agency, the implicit model that the pieces of something should be the same as the whole thing and the verbal symbolic knowledge that the attraction and repulsion between N and S ends should be activated first through the context of the activities at the observational level. Then, students’ reflection on the modeling criteria fosters the activation and application of these conceptual resources from the observational to the microscopic level.

For instance, the M2: Cutting Magnet Activity prompts students to employ the implicit model, and the M1: Two Magnets Activity prompts students to employ the verbal symbolic knowledge at the observational level. Reflection on the criteria of visualization
and explanatory power encourages students to revise the attribution of causal agency and to apply the above implicit model and verbal symbolic knowledge from the observational level to the microscopic level. The process of activating and applying conceptual resources to develop coherent explanatory models through reflection on modeling criteria allows students to rearrange their unstable and fragmented conceptual resources into more organized and sophisticated networking as experts.

Researchers recognize that students tend to rely on their intuitive understanding of observed phenomena without looking for a formal explanation (Taber & Garcia-Franco, 2009; Reiner & Gilbert, 2008). Reiner and Gilbert (2008) pointed out that students usually tend to ignore theories when their intuition is more accessible or to apply fragmented and inconsistent ideas for different observed phenomena. That is why this study suggests that using the context of activities triggers the appropriate conceptual resources at the observational level. Scaffolding reflection on the modeling criteria regulates students’ application of conceptual resources at the microscopic level to develop coherent domain model, instead of relying on just their intuitive ideas at the observational level. Employing conceptual resources from the observational level to make sense of the microscopic level enables microscopic levels of explanation to become intuitive to students.

**From a modeling perspective.** This teaching experiment shows that scaffolding reflection on the modeling criteria helped students in the FS groups to develop and revise their explanations to reach the highest level and coherence. Relying only on self-generated criteria, students in the PS groups did not revise their original fragmented ideas toward higher-level and more coherent explanations. Even in these highly
interactive and hands-on activities, simply asking the students to generate and then compare explanations using their own criteria in order to come up with their best explanation seemed to be insufficient. It implies that in order to encourage students to generate, evaluate, and revise their models to be close to scientific models, students should be explicitly scaffolded to evaluate their models by metaconceptual modeling criteria.

Consistent with the results of this study, it is common for students to employ self-generated criteria to evaluate their models without explicitly scaffolding with modeling criteria (Baek et al., 2011; Buckingham & Reiser, 2010; Kenyon et al., 2008; Schwarz et al., 2009). Although students in the PS groups also spontaneously proposed to evaluate their explanations according to the criteria of visualization and explanatory power in few occasions, they did not revise their explanations according to these two criteria. Instead, they added different ideas from different activities according to their most important self-generated criteria of more detail. Thus, explicitly asking students to evaluate their explanations in light of the modeling criteria would make students to perceive that the criteria of explanatory power and visualization are the most important criteria, encouraging them to revise their ideas accordingly. Without the designed activities and guided reasoning or discussion, students have problems monitoring their reasoning and developing appropriate models (Harrison & Treagust, 2006).

Offering students metaconceptual modeling criteria to evaluate their ideas assists students in controlling the direction of the revision of their models in line with scientific processes. Without reflection on the criterion of visualization, students who do not have any existing microscopic models will stay at the more intuitive observational level of
explanation without hypothesizing unseen elements. Without reflection on the criterion of explanatory power, students will have problems inspecting the limited explanatory power of their hypothesized elements and revising them to coherently account for all observed phenomena.

**Contributions and Future Research**

The present study makes contributions in the areas of modeling, conceptual resources, and metacognition, and provides recommendations for theory, methodology, and pedagogy.

Theoretically, literature in learning theory addresses the essential role of metacognition in students’ modeling and their knowledge activation and reorganization. Yet, the mechanism and the relationship between them lacks clarification and empirical support. This study contributes to the effort of building an explanatory model to account for how students’ metacognition can activate different levels of conceptual resource to generate, evaluate, and revise their models. In this study, I discovered that when students were scaffolded to think about their thinking scientifically, students could activate and apply appropriate conceptual resources to generate and revise their original naive ideas closer to scientific models. However, this explanatory framework was created within the context of developing models of magnetism, with which students are less familiar. Thus, future research is recommended to investigate whether this theoretical framework can also be applied to account for students’ metacognitive and cognitive process in other domains in order to establish more general claims across different domains.

Methodologically, conducting teaching experiments allowed this study to
investigate students’ cognitive and metacognitive processes and the interaction between these two, instead of only presenting the final product of the students’ model. Fine-grained data analysis, which is advocated to study learning processes and knowledge development (Parnafes et al., 2008), enables this study to inspect momentarily dynamic processes and to consider diverse features of model development. This contributes new insights into existing theory about the mechanism of modeling and knowledge development. The method of analyzing the progression of the students’ model development, conceptual resources underlying the modeling process, and the influence of their metacognitive process on their cognitive process offers both empirical examples and an analytical framework for further research. Due to the limitations of the nature of this study, further quasi-experimental studies are recommended to assess the impact of scaffolding students’ metacognition on their progression in terms of their model development, as well as generalizing to most upper elementary students.

Pedagogically, this study contributes to work bridging the gap between how science is learned by students and how it is practiced by scientists. Studying how students’ explanations progressed from intuitive ideas to scientific models by activating, applying, and reorganizing their conceptual resources suggests how to diminish the gap between novices’ intuitive ideas and experts’ scientific ideas. Studying how scaffolding students’ metacognitive process enhanced their cognitive process suggests how to diminish the gap between novice reasoning and scientific reasoning. These suggestions serve as a base for further curriculum design about magnetism and other abstract scientific concepts. Ideas about how to adopt the strategies of scaffolding students’ metacognition to better support them to activate, apply, and reorganize their appropriate
conceptual resources to develop scientific models in classroom should be explored in the future research.
References


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Appendix A

Junior Metacognitive Awareness Inventory
Please read the following sentences and circle the answer that relates to you and the way you are when you are doing school work or home work. Please answer as honestly as possible.

1 =Never  2 =Sometimes  3=Always

1. I know when I understand something. Never Sometimes Always
2. I can make myself learn when I need to. Never Sometimes Always
3. I try to use ways of studying that have worked for me before. Never Sometimes Always
4. I know what the teacher expects me to learn. Never Sometimes Always
5. I learn best when I already know something about the topic. Never Sometimes Always
6. I draw pictures or diagrams to help me understand while learning. Never Sometimes Always
7. When I am done with my schoolwork, I ask myself if I learned what I wanted to learn. Never Sometimes Always
8. I think of several ways to solve a problem and then choose the best one. Never Sometimes Always
9. I think about what I need to learn before I start working. Never Sometimes Always
10. I ask myself how well I am doing while I am learning something new. Never Sometimes Always
11. I really pay attention to important information. Never Sometimes Always
12. I learn more when I am interested in the topic. Never Sometimes Always
Appendix B

Teacher Rating of Student Metacognition
Metacognition refers to one’s thinking about thinking or one’s knowing about knowing. Students who are HIGHLY metacognitive tend to exhibit cognitive behaviors that are different from LOW metacognitive students. Listed below are several behavioral descriptors that would distinguish students who are HIGH and LOW in metacognition.

<table>
<thead>
<tr>
<th>HIGH Metacognition</th>
<th>LOW Metacognition</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Focuses attention</td>
<td>1. Attends randomly</td>
</tr>
<tr>
<td>2. Studies purposefully</td>
<td>2. Studies haphazardly</td>
</tr>
<tr>
<td>3. Makes study plans</td>
<td>3. Doesn’t plan much</td>
</tr>
<tr>
<td>5. Asks questions to insure understanding</td>
<td>5. Continues work without understanding</td>
</tr>
</tbody>
</table>

Using the following scale, rate each student in your class regarding your best judgment of his or her level of metacognition.

6 = Very High Metacognition
5 = High Metacognition
4 = Above Average Metacognition
3 = Below Average Metacognition
2 = Low Metacognition
1 = Very Low Metacognition

Class: __________ Students Name: ______________________ Rating: ________
(1-6)
Appendix C

Metacognitive Journal
Magnet Activities Journal

This journal is to help you keep track of your thinking as you do some activities with magnets. When you are asked, please record your own explanations. You will also be asked to discuss how your ideas have changed, if they have. Diagrams or pictures are often very helpful in describing your ideas, so it will often help to draw something.
M1: Two Magnets Activity

**Prediction**
1.1. Please write and draw pictures that will explain why this may happen between the two magnets.
Explanation
1.2. Please write and draw pictures that can explain what happens between the two magnets.
Thinking about Your Thinking
1.3. After discussing the group explanation, is your explanation right now the same as your explanation for your observation (in 1.2)

(a) Same. Please explain why it is the same.

(b) Different. If it is different, please draw your current pictures, and explain what is different and why you changed it.
Thinking about Your Thinking after Black Box Activity

1.4. After the black box activity, is your own explanation right now the same as your earlier explanation before the black box activity (in 1.3)?

(a) Same. If it is the same, please explain why it is the same.

(b) Different. If it is different, please draw your current pictures, and explain what is different and why you changed it.
M2: Breaking Magnet Activity

Prediction
2.1. Please write and draw pictures that will explain why this may happen after cutting the magnet in half and to the smaller pieces that you cannot see.
**Explanation**

2.2. Please write and draw pictures that can explain why there are always two different poles of the magnet no matter how the magnet is broken down.
Thinking about Your Thinking

2.3. After discussing the group explanation, is your own explanation right now the same as your earlier explanation for your observation (in 2.2)?

(a) Same. If it is the same, please explain why it is the same.

(b) Different. If it is different, please draw your current pictures, and explain what is different and why you changed it.
M3: Metal Bars Activity

Prediction
3.1. Please write and draw pictures that will explain which part of the magnet can attract more metal bars and illustrate why this may happen to the magnet and metal bars.
**Explanation**

3.2. Please write and draw pictures that can explain what happens to the metal bars and how the magnet influences the metal bars.
Thinking about Your Thinking

3.3. After discussing the group explanation, is your own explanation right now the same as your earlier explanation for your observation (in 3.2)?

(a) Same. If it is the same, please explain why it is the same.

(b) Different. If it is different, please draw your current pictures, and explain what is different and why you changed it.
Appendix D

Pre-Instructional Interview Protocol
Individual student is 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 were then asked to pick up the ones which were magnets and to explain how and why magnets work.

**Prediction**
1. Which ones are magnets? Why?

**Observation**
2. What do you observe?

**Explanation**
3. Which ones are magnets? How do you know that?
   
4. What is your idea about how magnets work to act on other materials?

5. Have you ever learned anything about magnets before? What do you learn and where do you learn that?
Appendix E

Post-Instructional Interview Protocol
1. What is your current best model to explain how and why a magnet works in these activities? Why do you think it is the best explanation compared to others?

2. Could you summarize and illustrate you’re the progression of your models in all activities? Please explain when, why, and how you modified or changed your ideas during these activities.

Students will be showed some video clips and some of their writing in journal in order to clarify their reasoning process. The selection of video clips and journal is based on the purpose to understand students’ reasoning, so the selected segments are the parts that the interviewer has less clear about students’ reasoning process.

3. Could you explain what you were doing and thinking in this video clip or in this part of writing in the journal?

4. Did using the criteria—visualization, explanatory power, and predictive power, and consistency—help your reasoning? If so, how? If not, why not?

5. Did writing in the journal (recording your ideas) help your reasoning? If so, how? If not, why not?

6. Did doing the activities (prediction-observation-explanation) help your reasoning? If so, how? If not, why not?

7. Did the group discussion (discussion about best models and using these criteria) help your reasoning? If so, how? If not, why not?

8. When you were asked to consider your individual model, did you consider it in terms of visualization, explanatory power, predictive power, and consistency all the time, did you only consider these criteria for certain cases, or did you never consider it? Could you offer an example?

9. Do you think using these four criteria in your reasoning would help you to construct models to explain unfamiliar phenomena or abstract ideas in your future learning?
Appendix F

Summary of the Pathways of Individual Students’ Explanations
**The First Fully Scaffolded Group**

**Pre-Interview**

<table>
<thead>
<tr>
<th>Freddie</th>
<th>Felix</th>
<th>Frank</th>
</tr>
</thead>
<tbody>
<tr>
<td>The magnet has a force to pull it.</td>
<td>A magnet has a certain metal in it. The magnet sends out like “magnetic wave”, “something invisible,” so metal stuffs will get sucked to that at a certain distance.</td>
<td>There’s like little stuff container and then when you get the magnet to it then it goes straight and sticks.</td>
</tr>
</tbody>
</table>

---

**The First Fully Scaffolded Group**

**M1: Two Magnets Activity**

<table>
<thead>
<tr>
<th>Freddie</th>
<th>Felix</th>
<th>Frank</th>
</tr>
</thead>
<tbody>
<tr>
<td>The magnets push each other away is because positive side face positive side, the magnets attract because positive side face negative side.</td>
<td>The relationships between N-N S-S are like the ones between a bully and a nice kid. Because they do not like each other, so they will not get together. The relationship between S and N is like two bullies or two nice kids. Because they are alike, so they will go together.</td>
<td>Magnets work because of some of the minerals in the magnets.</td>
</tr>
</tbody>
</table>

---

**Frank:** Understandability (Evaluation of Felix’s idea)

- Group Explanation
  - Frank: The consistency with other ideas

- Prediction and Explanation after Observation

---

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Positives and negatives are like the football player running to each other or turning away from each other.

“Material Line” explanation: The moving positive and negative mineral elements or material lines in the magnet as an explanation for the attraction and repulsion between two magnets.

Propose a different ideas that there should be something like positive and negative stuffs which can be interchanged and chained inside the magnet so two magnets can stick together.

Frank & Freddie: The consistency with other ideas or experiences
Frank: The nature of explanation

Visualization

Frank: The consistency with other ideas or experiences
Felix: Explanatory power for current observation
The First Fully Scaffolded Group
M2: Cutting Magnet Activity

<table>
<thead>
<tr>
<th>Freddie</th>
<th>Felix</th>
<th>Frank</th>
<th>Stage</th>
</tr>
</thead>
<tbody>
<tr>
<td>The cut smallest pieces should either be N or S which will find ways to reorganize and reconnect.</td>
<td>The cut smallest cut pieces should have the co-existence of N and S, because the cut smallest pieces should be like the shreds of the whole magnet.</td>
<td></td>
<td>Prediction</td>
</tr>
<tr>
<td>The small cut pieces of magnet follow the earth axis.</td>
<td>Magnet is made out of a bunch of magnetic particles which have N and S on them.</td>
<td></td>
<td>Explanation after observation</td>
</tr>
<tr>
<td>Magnets are obtained from the mineral particles with N and S in the earth.</td>
<td>Magnet stuff in the ore to make a magnet.</td>
<td></td>
<td>Group Explanation</td>
</tr>
<tr>
<td>Magnetic atoms or particles make up of minerals and rocks which would be carve to make magnets.</td>
<td></td>
<td></td>
<td>Visualization</td>
</tr>
<tr>
<td>The interactions between N-S elements are like civil war.</td>
<td>A bunch of particles inside got melted together with heat and pressure.</td>
<td>Illustrate the interaction and arrangement or N-S elements.</td>
<td>Explanatory Power: for explaining current observation</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Explanatory Power: for explaining what happen between elements</td>
</tr>
</tbody>
</table>

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Their final group picture at the molecular level could also explain the attraction or repulsion between two magnets.

**Explanatory Power:** for explaining previous observed phenomena

Comparing Group Pictures by Using the Criteria
The First Fully Scaffolding Group
M3: Metal Bars Activity

<table>
<thead>
<tr>
<th>Stage</th>
<th>Prediction</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Freddie</th>
<th>Frank</th>
<th>Stage</th>
</tr>
</thead>
<tbody>
<tr>
<td>There was no N and S on the metal bar, the metal bar would stick to any place of the magnet instead of repelling from the magnet.</td>
<td>1) Two ends are stronger than middle part of the magnet 2) Magnetic force goes through these metal bars, so they would stick to the magnet, but gravity pulls them down.</td>
<td>Prediction</td>
</tr>
<tr>
<td>1) There are magnetic material inside the magnet, and there is a casing (container) in the middle part of the magnet, so there is no magnetic force in the middle part. 2) Because the magnetecy goes through the metal, the metal bars will stick to the magnet.</td>
<td>Explanation after Observation</td>
<td></td>
</tr>
<tr>
<td>They shared the same idea that there is no or less force in the middle part of the magnet so metal bars would be pulled toward the two ends, and that there must have been something going from the magnet to the metal bars to make them stick to the magnet.</td>
<td>Group Explanation</td>
<td></td>
</tr>
<tr>
<td>1) One part is how metal bars stick to the two ends of the magnet because of magnetite inside the magnet, and the casing or less magnetite makes the middle part of the magnet not work. 2) The other part is how metal bars can stick to the magnet because the “stuff” in the magnet reacts to the metal bars, or “stuff” in the magnet goes into the metal bar so the metal bars would turn in to a half magnet to stick to the magnet.</td>
<td>Visualization</td>
<td></td>
</tr>
</tbody>
</table>
Can explain M2 and M3, but cannot explain M1:
Explaining M2: there was no power in the middle part of the magnet, because of a container cover on it. When the magnet was cut, the magnetite would show, and there was no cover on it to block the power out, so the middle part would become magnetic.

Explaining M1: Magnetized particles would go toward or away from each other.

Using microscopic particles to explain M1 and use macroscopic magnetite to explain M2 and M3.

Q: microscopic particles and macroscopic magnetite.

Clarify the relationship between macroscopic magnetite and microscopic particles: Particles are inside the magnetite, which is rock shape and inside the magnet.

Use microscopic elements to explain all.
M1: These microscopic elements inside would stay away from each other when two N ends of the magnet faced each other; these elements inside would go together when the N end of the magnet faced the S end of the magnet.
M2: When the magnet is cut, the exposed part would become the other magnetic end of the elements.
M3: Frank expressed that the elements inside the two ends of the magnet react to the microscopic elements inside the metal bar, thereby making the metal bar become a magnet, and then react and attract the following metal.
<table>
<thead>
<tr>
<th>Freddie</th>
<th>Felix</th>
<th>Frank</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.png" alt="Diagram" /> The structure of the magnet: N particles in the N end of the magnet. S particles in the S end of the magnet. There is a container to hold these magnetic particles inside the magnet. There is no or less particle in the middle part of the magnet.</td>
<td><img src="image2.png" alt="Diagram" /> The structure of the magnet: There are N-S particles melted together and scattered around the magnet. The N of the particles will point toward N end of the magnet; the S of the particles will point towards the S ends of the magnet, so they will connect each other.</td>
<td><img src="image3.png" alt="Diagram" /> The structure of the magnet: There are N-S particles inside the magnetite making magnets magnetic. The N parts of the particles face the N end of the magnet. The S parts of the particles face the S end of the magnet. There is a “container” in the middle part of the magnet, so this container would block the power from the middle part of the particles.</td>
</tr>
<tr>
<td><strong>M1:</strong> N and S are like positive and negative on a battery. N to N is positive to positive so if you put positive with positive, it will go away because N particles will only attract to something that is S particles. Positive means the N particles of the magnet.</td>
<td><strong>M1:</strong> There are N-S particles in the two ends of the magnet. N face N of the magnet, both N part of the particles know each other so they will go away. N and S of the particles do not know each other, so they will get together.</td>
<td><strong>M1:</strong> The S parts of the particles inside face the S end of the magnet, and versa. The N and S end of the magnet would attract because these particles would move and sticks to the end of the magnet. When the N and S end are moved away, the particles would go back to where they were. On the other hand, the N and N end would push each other away because the particles in the N end of the magnet float away and the momentum of this moving would push the magnets.</td>
</tr>
<tr>
<td><strong>M2:</strong> When you cut the magnet, the pieces would become N-S particles temporary, and then they will eventually separate to the two ends and become N</td>
<td><strong>M2:</strong> Because there are N-S particles in the same order inside the magnet so when you cut the magnet, the pieces will be still connected.</td>
<td><strong>M2:</strong> when you cut any place of the magnet. There are still North end is here, and South end is here, because all N of the particles is still facing N</td>
</tr>
</tbody>
</table>
particles and S particles. Because when we did the experiment of cutting the magnet, it grew its own N and S. Also, the N-S particles cannot stay like that forever. If they stay like that it will be neutral and not magnetic. end of the magnet, and S of the particles is still facing S end of the magnet. S end of the particles will stick to N end of the particles.

| M3: The magnetized particles are what make the magnet. The magnetic force or power comes from the magnetic particles inside the magnet will make the metal bar stick to the magnet and make the power goes from magnet to the metal bar, like electricity. This metal bar will start to become a magnet and the magnetic power would go thought it to the last other metal bars. It is like an ongoing chain of magnetic power or force | M3: The magnetic force from the N-S particles in the magnet is strong enough to wakes up the random N-S particles in metal bars. Then these randomly scattered and floating N-S magnetic particles would line up because of the magnetic force from the magnet and attraction and repulsion between them. The force would become like a weaker signal when the metal bars are farther away from the magnet. The magnetic particles in the metal bar is floating and moving, which are different from the restricted and fixed magnetic particles in the magnet. | M3: The N-S particles in the magnet go to the end of the magnet where metal bars stick to and then these N-S particles will react to the N-S particles in the metal bar to make particles move to align with each other so they will stick. Then, this metal bar becomes a magnet to react to the next following metal bars. The farther the metal bar chain gets, the weaker the reaction is. There is a container in the middle part of the magnet which would block the power from the middle part of the particles, so the metal bars would not stick to it. |
The Second Fully Scaffolded Group
Pre-Interview

<table>
<thead>
<tr>
<th>Fiona</th>
<th>Faye</th>
<th>Finn</th>
</tr>
</thead>
<tbody>
<tr>
<td>There is force in the magnet so it can pull things closer.</td>
<td>Maybe there is something inside or outside the magnet that work to make it pull other stuff.</td>
<td>The magnet has a force in it that would attract or pull other certain kind of metals.</td>
</tr>
</tbody>
</table>

The Second Fully Scaffolded Group
M1: Two Magnets Activity

<table>
<thead>
<tr>
<th>Fiona</th>
<th>Faye</th>
<th>Finn</th>
<th>Stage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Two N have the same force, so they will not go together. N and S have different forces, so N and S go together.</td>
<td></td>
<td></td>
<td>Prediction and Explanation after Observation</td>
</tr>
<tr>
<td>There is no difference between N and S end. The lines separating N and S end is only the appearance of the magnet.</td>
<td></td>
<td>Regard the lines separate different structure of the magnet: Nothing in the middle part of the magnet, so they do not attract each other.</td>
<td></td>
</tr>
<tr>
<td>There is no difference between N and S end. The lines separating N and S end is only the appearance of the magnet.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>There should be elements or atoms inside the magnet</td>
<td></td>
<td></td>
<td>Group Explanation</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Visualization</td>
</tr>
</tbody>
</table>
The dots inside the magnet are the stuff that makes the magnets pull together. They want to get connected so magnets will go together.

There are elements, iron, and stuff inside the magnets. When they have different forces, these two will connect. When they have the same amount of force, they don't want to go together.

Elements, like iron, inside the magnet. Air in between N and S is forced out or expelled when N and S connect. When that is the wrong side, air and the force push them away.

Agree with air ideas that Fiona proposed.

Agree with Finn’s idea and add ideas about same or different forces: When elements in the two magnets match (N and S), the different forces will pull them together. When the elements in the two magnets don't match (N and N or S and S), the same forces will make them push against each other.

Agree with air ideas that Fiona proposed.

South and North will connect, because the elements inside the magnet will fight through the air or wind in between, so they will connect. For N and N, the elements will go with the air or wind in between, so they can't go together.

Faye: The consistency with other ideas.
Finn: More detail.
The Second Fully Scaffolded Group
M2: Cutting Magnet Activity

<table>
<thead>
<tr>
<th>Fiona</th>
<th>Faye</th>
<th>Finn</th>
<th>Stage</th>
</tr>
</thead>
<tbody>
<tr>
<td>The same as Finn</td>
<td>The two ends of small pieces of the North end will become N, and the two ends of small pieces of South end will become S, because the small pieces should be the same as the big one, just small version. (NN NN SS SS).</td>
<td>The whole small pieces of the North end will become N, and the whole small pieces of South end will become S. (N N S S).</td>
<td>Prediction</td>
</tr>
<tr>
<td>The pieces in the S end are S. The pieces in the N end are N. Two ends of pieces in the middle part are N and S. (S NS N).</td>
<td>The two ends of small pieces still have N and S. It is like the pencil should always have sharpened part and eraser part of the magnet. (NS NS NS NS).</td>
<td>The each small elements still have N and S, because these elements are smart, so they know which way is still N and S. (NS NS NS NS).</td>
<td>Explanation after observation</td>
</tr>
<tr>
<td>Particles or elements inside the magnet are smart.</td>
<td>Propose the close-up view of these elements (N and S on the two ends of the elements).</td>
<td></td>
<td>Group Explanation</td>
</tr>
<tr>
<td>Agree that there is N and S on the close-up view of the elements inside the magnet.</td>
<td></td>
<td></td>
<td>Visualization</td>
</tr>
</tbody>
</table>
N elements and S elements inside the magnet.

N-S elements inside the magnet.

These elements separated from each other will come together. The arrangement of the magnet should be NS NS so these pieces will come together.

N-S elements inside the magnet.

The small pieces still have NS because when the magnet is cut, the small elements should still be a magnet.

They will explode.

The interaction between these elements is like what happen between two bar magnets. If the elements inside the magnet repel each other, the elements will float around inside the magnet.

Explanatory Power: for explaining current observation

Explanatory Power: for explaining what happen between elements

Explanatory Power: for explaining previous observed phenomena

Comparing Group Pictures by Using the Criteria
<table>
<thead>
<tr>
<th>Stage</th>
<th>Prediction</th>
<th>Explanation after Observation</th>
<th>Group Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stage</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Prediction</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Observation</td>
<td></td>
<td>There are elements in the magnet going from the magnet to the metal bar, so the metal bars become magnets for a short time.</td>
<td></td>
</tr>
<tr>
<td>Explanation</td>
<td>There is a limited distance for a magnet to attract certain number of metal bars. There are some elements on the two ends of the magnet, so the metal will be attracted to two ends.</td>
<td>There are elements in the magnet going from the magnet to the metal bar, so the metal bars become magnets for a short time.</td>
<td></td>
</tr>
<tr>
<td>Stage</td>
<td></td>
<td>There is no magnet or material in the middle part of the magnet.</td>
<td></td>
</tr>
<tr>
<td>Stage</td>
<td></td>
<td>The magnet will pass the magnetism, wave, or elements to the metal bars, so the metal bars will stick to the magnet. The elements inside the magnet go from the magnet to the metal bars like the fluid go through your body. The elements will go all the way down to the ends of the last metal bar. After the metal bars are removed from the magnet, the magnet cannot pass more elements to the metal bars.</td>
<td></td>
</tr>
<tr>
<td>Stage</td>
<td>Fiona</td>
<td>There are more elements inside two ends to attract more stuff.</td>
<td></td>
</tr>
<tr>
<td>Stage</td>
<td>Faye</td>
<td>There is no magnet or material in the middle part of the magnet.</td>
<td></td>
</tr>
<tr>
<td>Stage</td>
<td>Finn</td>
<td>There is no magnet or material in the middle part of the magnet.</td>
<td></td>
</tr>
</tbody>
</table>

The Second Fully Scaffolded Group
M3: Metal Bars Activity
The elements in the magnet are extremely strong so the elements in the metal bar will be attracted to the ends of the magnet and makes metal bars stick together. The elements in the metal bar are not as strong as the elements inside the magnet. When the magnet is removed, the elements inside the metal bars are not strong, so the metal bar will not stay together. The elements of the magnet are only strong enough to hold four metal bars, so there is a limitation of the distance that the magnet can go.

Group picture can explain why two ends can attract more metal bars than the middle part of the magnet, because the middle part of the magnet is empty.

Agree Faye’s idea that the middle part is weaker than two ends of the magnet and as strong as metal bars.
What happen between two magnets is because of different forces.

There are elements inside the magnet. Because the elements (in N and S end of the magnet) want different force, so they can go together. N and N have the same force, so they don't want to go together. They don't like the same forces because they already have these forces and just try to get rid of it.

N and N have the same force so they will repel. This may related to the elements inside the magnet, but do not know how to explain it.

Group picture cannot explain no matter how we cut there are still N and S in two ends of the pieces.

Suggest N-S elements in the magnet.

Draw N-S elements inside the magnet. N and S of the elements are consistent with the N and S of the magnet.

M1: Attraction: The elements of S end and the elements of N end of the magnet go opposite direction, they will connect.

Explanatory Power: explaining previous observation in M1

Explanatory Power: explaining previous observation in M2

Explanatory Power: explaining all observation
M1: Repulsion: Two same ends face each other away, because the elements in these two are the same.

M2: The co-existence of the N and S in the magnet pieces is because of N-S elements in the magnet.

M3: Magnetism or wave would go through the metal bars to make the metal bars connect with the magnet.

M1: Repulsion: S end of element of the S end of the magnet would go away from the S end of elements in the other S end of the magnet, because the same amount of force would push against each other, which makes them push apart.

M3: The elements in the magnet would attract the elements in the metal bars, but there is no N and S in metal bars, because they are not magnets. Also agree with Fiona.

M3: Agree with Faye and Fiona.

Comparing Group Pictures by Using the Criteria.
### The Second Fully Scaffolded Group

#### Post-Interview

<table>
<thead>
<tr>
<th>Fiona</th>
<th>Faye</th>
<th>Finn</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.png" alt="Diagram" /></td>
<td><img src="image2.png" alt="Diagram" /></td>
<td><img src="image3.png" alt="Diagram" /></td>
</tr>
</tbody>
</table>

**The structure of the magnet:**
N-S elements inside the magnet. The arrangement of N-S is not consistent with the N and S of the magnet. The two ends of the magnet are stronger and the middle part is weak.

**M1:** Attraction: Because magnets have different force.
Repulsion: Because magnets have the same force.
That is probably to do with the elements inside, but she cannot explain why.

**M2:** N-S particles or elements inside.

**M3:** There are less N-S elements inside the metal bar which are the same as the elements inside the

| M1: Attraction: The N-S elements kind of ‘sense’ that there is a magnet nearby that can attract and they are getting ready for the magnets to move forward to attract.
Repulsion: The N-S elements sense the same elements, because they don't want the same. They want different, so they back away. | M1: Attraction: N and S attract each other, because these two have same elements inside and have different forces.
Repulsion: N and N or S and S repel each other, because these two have different elements inside and have same forces. | M2: N-S elements inside the magnet |

| M2: There are N-S elements inside the magnet. Two ends are stronger and the middle part is weaker, but when you cut the magnet in half, the middle part will become stronger, because the cut pieces become the independent magnets. |  |  |

| M3: The N-S elements inside the magnet decide to attract the elements in the metal bar, so the magnetic |  | M3: The elements in the magnet are tougher than the elements in the metal bar, so the force would go from the |

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magnet, because that is how magnets are made. The magnet gives some force to the metal bars, so the metal bar would stick to each other and stick to the magnet. The two ends are stronger and the middle part is weak, so the metal bars would stick to the two ends, instead of middle part of the magnet.

force pulls the elements in the metal bar up to make metal bars stick together and stay on the magnet. These metal bars does not become magnets by putting them on the bar magnet. magnet to the metal bars, and the elements inside the metal bars are attracted to the magnet. Thus, these metal bars would stick to each other and are attracted to the magnet. The elements in the metal bars do not have magnet-like elements (N-S elements) in them.
**The First Partially Scaffolded Group**

**Pre-Interview**

<table>
<thead>
<tr>
<th>Pearl</th>
<th>Peggy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnets have a material, metal, in them that will attract one another or stick to the metal.</td>
<td>There are mineral things in magnets that allow others to come to them or attract others to them.</td>
</tr>
</tbody>
</table>

---

**The First Partially Scaffolded Group**

**M1: Two Magnets Activity**

<table>
<thead>
<tr>
<th>Pearl</th>
<th>Peggy</th>
<th>Stage</th>
</tr>
</thead>
<tbody>
<tr>
<td>There are the same type of materials in the two N ends of the magnet, so they don't have anything to pull them together. There are different types of materials in the North and South ends of the magnet, so they have something that they can attract to.</td>
<td>N and S are opposite so they will attract. N and N or S and S are the same, so they won't connect.</td>
<td>Prediction and Explanation after Observation</td>
</tr>
<tr>
<td>Metal maybe inside the magnet.</td>
<td>Iron maybe inside the magnet.</td>
<td>Group Explanation</td>
</tr>
<tr>
<td>There are metal and iron at the two ends to make them connect.</td>
<td>Two different types of materials, iron in the South end and the metal in the North end. Different ends would connect and if the same thing in the two ends, they won't connect.</td>
<td></td>
</tr>
</tbody>
</table>

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Two irons won't together, because they are not the right puzzle pieces. Going together is like puzzle pieces fitting together. Not going together is like not fitting each other.

N and N are the same metal end, so there is nothing in them to make them connect. Iron end and metal end (S and N) can connect because they are different things inside of them to allow them connect.

Puzzle pieces ideas did not offer detailed explanationS for different ends or parts of the magnet. Puzzle pieces idea is better because it is more understandable than the final picture of M1, but did not choose puzzle pieces idea, because they use the idea that both come up with.

Pearl: Explanatory power for explaining current observation. Peggy: Understandibility
The First Partially Scaffolded Group
M2: Cutting Magnet Activity

<table>
<thead>
<tr>
<th>Pearl</th>
<th>Peggy</th>
<th>Stage</th>
</tr>
</thead>
<tbody>
<tr>
<td>The smallest pieces are still NS NS NS because these pieces are small version of the big one.</td>
<td>The small pieces are NN, NN, SS, SS because these pieces are small version of the big one, so the pieces cut from the N end should be N.</td>
<td>Prediction</td>
</tr>
<tr>
<td>These unobservable pieces become weak magnet so they should have N and S ends.</td>
<td></td>
<td>Explanation after observation</td>
</tr>
<tr>
<td>When magnets are cut smaller, they will become weaker, but they are still magnets so they will always have N and S side. The small pieces are the same as big pieces. The only different is the strength and size of the magnet. The N and S of the magnet is fixed like geographic direction.</td>
<td></td>
<td>Group Explanation</td>
</tr>
<tr>
<td>Agree on Pearl’s idea about the best group picture: Two magnets have North (metal) and South (iron) ends and nothing in the middle of the magnet. When they are breaking down, they become smaller, but they still have the same things as original magnets having North and South ends. When these small pieces get too small, they may not be strong enough to push each other away.</td>
<td></td>
<td>Comparing Group Pictures</td>
</tr>
<tr>
<td></td>
<td>Pearl: More detail Peggy: Simpler</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Group Explanation</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Comparing Group Pictures</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Pearl &amp;Peggy: More detail</td>
<td></td>
</tr>
</tbody>
</table>
The First Partially Scaffolded Group
M3: Metal Bars Activity

<table>
<thead>
<tr>
<th>Pearl</th>
<th>Peggy</th>
<th>Stage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nothing is in the middle part of the magnet, so two ends can attract more metal bars.</td>
<td></td>
<td>Prediction</td>
</tr>
<tr>
<td>Original these metal bars are not magnetic. These metal bars become like magnets after they stick to the magnet for enough time.</td>
<td>Some energy stuff is coming from the magnet to the metal bars.</td>
<td>Explanation after Observation</td>
</tr>
<tr>
<td>Agree on Peggy ideas about the big magnet giving energy to other small metal bars</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nothing or not enough energy in the middle part of the magnet + passing energy through metal bars.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>The best picture should include the ideas in different pictures which explain different stuff: M1: the attraction between metal and iron end and no attraction between two meal and two iron ends M2: weak magnet M3: passing energy to metal bars</td>
<td>Opposing include all ideas in one picture. Including all ideas in one picture does not explain how magnets work. Only ideas involving energy can explain how magnets work. There is no energy ideas involved in the cutting magnet part.</td>
<td>Group Explanation</td>
</tr>
<tr>
<td>Pearl &amp; Peggy: Make sense</td>
<td>Pearl &amp; Peggy: having energy idea</td>
<td>Group Explanation</td>
</tr>
<tr>
<td>Pearl: More detail Peggy: having energy idea</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pearl: More detail Peggy: having energy idea</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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The First Partially Scaffolded Group
Post-Interview

<table>
<thead>
<tr>
<th>Pearl</th>
<th>Peggy</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1" alt="Peggy's drawing" /></td>
<td><img src="image2" alt="Peggy's drawing" /></td>
</tr>
<tr>
<td><strong>M1</strong>: There is nothing in the middle part of the magnet. There is probably iron in S end and metal in N end. Two different sides would get together because there is a different material, iron versus metal, inside.</td>
<td><strong>M1</strong>: There is nothing in the middle part of the magnet. There is iron in S end and metal in N end. There is no line to separate different parts of the magnet. Attraction: Two different ends will stick each other, because they do not have the same types of things in them. Different materials would get together, because they are not in the same family. Repulsion: Two same ends cannot attract or go together each other, because they have the same material. The materials in the same family type are not allowed to stick.</td>
</tr>
<tr>
<td><strong>M2</strong>: Because once you cut the magnet into half, the cut pieces should have some sort of North and South sides, so the pieces can</td>
<td><strong>M2</strong>: No matter which part of the magnet is cut, the pieces still have N and S ends, because these pieces are always magnet.</td>
</tr>
</tbody>
</table>

Modification of M2 in their group explanation: Applying the energy idea instead of strength (weaker) to explain cutting the magnet part. The big magnet has more energy than the cut small pieces to attract other stuff. When cutting the big magnet, the magnet will lose some of that energy so the small pieces would get weaker.
push each other away. The two ends of the pieces are still N and S and these pieces still connect, but maybe not as strong as the big magnet.

<table>
<thead>
<tr>
<th>They just become weaker.</th>
</tr>
</thead>
<tbody>
<tr>
<td>M3: The energy is at the two ends. It goes from the magnet and coming down to the metal bar. The energy gets weaker as it goes farther. There may be some energy, but not much in the middle part of the magnet.</td>
</tr>
<tr>
<td>M3: The energy in the two ends of the magnet makes the metal bars stick to them and when the energy keeps going down the metal bars, the energy becomes lesser until the energy is too weak to stick any metal bar.</td>
</tr>
</tbody>
</table>
**The Second Partially scaffolded group**

**Pre-Interview**

<table>
<thead>
<tr>
<th>Paige</th>
<th>Patty</th>
<th>Paul</th>
</tr>
</thead>
<tbody>
<tr>
<td>There's a force field around the magnet. The negative and positive areas on the two magnets would attract each other. Positive and negative are just symbols here.</td>
<td>Something different or small molecules in the magnet to make it (the magnet) pull other stuff.</td>
<td>There are molecules or special stuff inside the magnets to make them attract the other magnets or stuff. The two magnets can sense each other, so they can attract each other.</td>
</tr>
</tbody>
</table>

![Magnet Diagram]

<table>
<thead>
<tr>
<th>Paige</th>
<th>Patty</th>
<th>Paul</th>
</tr>
</thead>
<tbody>
<tr>
<td>N and N will repel from each other because they are the same. N and S attract because negative and positive are the opposite form each other. Agree with Paul’s idea that N is negative.</td>
<td>Negative plus negative equals they will push each other away, because negative only pulls positive. There are molecules in the magnet and if you put in a certain way, they will attract or dis-attract each other.</td>
<td>Prediction and Explanation after Observation</td>
</tr>
<tr>
<td>There is actually N and S, but no negative and positive.</td>
<td>N is negative; S is positive.</td>
<td></td>
</tr>
</tbody>
</table>

![Magnet Diagram]
Agrees with positive and negative ideas, but she does not know whether N is negative or positive. Magnets attract or repel because of about atoms inside.

Disagree with the positive and negative idea and think that positive and negative is only on batteries, not on the magnet.

Attraction: N and S come together because they are opposite. There is no force or energy line in between. Repulsion: The half circle line between these two magnets represent energy or forces between two magnets to make them repel each other, because these two N do not like each other so they will go away.

There are molecules inside the magnet. These molecules get the force and get positive and negatives, which depends on how small or how big they are.

Positive and negative molecules inside the magnet when put in a certain way, they will repel or attract. This may depend on what kind of molecules they are or which direction they are heading.

Group Explanation

Patty: has been taught
Support Paul’s idea about negative and positive molecules going opposite direction, but Paige seems to think Patty’s molecule idea is good because of good visualization of the size and the location of these molecules.

The atoms or molecules in one ends of the magnet will attract the atoms from the other magnet. There is an invisible force between them, so these two

Paige: The criterion of visualization.
The Second Partially scaffolded group
M2: Cutting Magnet Activity

<table>
<thead>
<tr>
<th>Paige</th>
<th>Patty</th>
<th>Paul</th>
<th>Stage</th>
</tr>
</thead>
<tbody>
<tr>
<td>The pieces in the S end are all S. The pieces in N end are all N. The pieces in the middle part are N-S. These pieces will attract each other. (S NS NS N)</td>
<td>The cut piece of the magnet would become a magnet itself. These N-S pieces are randomly arranged.</td>
<td>These pieces will attract each other. The pieces all have N-S. (NS NS NS NS)</td>
<td>Prediction</td>
</tr>
<tr>
<td>The small pieces should be the same as the big magnet, so each piece should still have two poles.</td>
<td>The cut pieces will become their own magnet, so they have their own two poles. It is impossible that two N on the same magnet, because two same poles on the same pieces of magnet would not make magnets attract.</td>
<td>Air come in the broken part and make that part become N or S. The un-cut part is safe from air.</td>
<td>Explanation after observation</td>
</tr>
<tr>
<td>Support the small magnet idea. Air idea is impossible. Paige considers Paul's idea about God creating air to influence the cut pieces of magnet is not scientifically.</td>
<td>Support the small magnet idea. Air idea is impossible, because she never learned that. Patty considers Paul's idea about God creating air to influence the cut pieces of magnet is not scientifically.</td>
<td>Support the air idea. Never learned about poles in the school. Air idea makes more sense than small magnet idea that supported by Patty and Paige. Paul claims that God create air to influence the cut pieces of magnets.</td>
<td>Group Explanation</td>
</tr>
</tbody>
</table>

Patty: possible

Paige & Patty: scientific & have been taught & making sense or possible.
Paul: have been taught & making sense or possible
Comparing Group Pictures

Paige: more advanced.
Patty: Certainty of information. More advanced.
Paul: Explain more clear.

Group Explanation

Paige, Patty & Paul: More detail—combing all topics

M1: Use the moving negative and positive idea to only explain attraction and repulsion between two magnets.

M1: There should be molecules ideas in the M1 in order to explain attraction and repulsion between two magnets.

M1: Because of the molecules inside the magnet. If they are put in a certain way, they would either attract or repel.

M2: The cut pieces of the magnet always have two poles, because these pieces would become individual magnets. (not including molecule idea)

M2: Using the air idea. (not including molecule idea)
The Second Partially scaffolded group
M3: Metal Bars Activity

Paige | Patty | Paul | Stage
--- | --- | --- | ---
Two ends can attract more metal bars, because there is more power going to two ends of the magnet. | The middle part can attract more metal bars because there is more room in the middle part of the magnet, so it can attract more metal bar. | The middle part can attract more metal bars because there are more metal in the middle part so it has more magnets. | Prediction
There is more power in the two ends of the magnet so the metal bars would stick to the ends. Agree with Paul’s idea that the magnet charges these bars so they get power to stick to the magnet. The reason why the metal bars stick to the two ends of the magnet is because there are more molecules in the two ends. | Two ends have more magnetic charges than the middle. The magnetic charge would go from the magnet to the metal bars to make the magnet hold these bars. These metal bars would become their own magnets. | Two ends have more molecules inside because metal bars stick to the two ends. The magnetic charges or energy flow from the magnet to the metal bars to charge them to become magnets. | Explanation after Observation

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Paige agrees with Patty's evaluation: Paul cannot offer the reason why magnetic charges would go to two ends instead of the middle part of the magnet.

Opposes Paul's idea and think this explanation:
1) cannot explain why these metal bars stick to the two ends of the magnet instead of middle part, because when energy flows through the two ends, the energy would go through the middle part, too. 2) Paul's new idea does not make sense.

Metal bars stick to the two ends, not stick to the middle part of the magnet is because the middle part has less molecules than two ends of the magnet.

Another idea to explain why the energy inside the magnet flow to the two ends, instead of middle part of the magnet: The charges flow in a certain layer between N and S ends, so the charges cannot flow to the edges of the middle part of the magnet.

Paige agrees with Patty's evaluation: Paul cannot offer the reason why magnetic charges would go to two ends instead of the middle part of the magnet.

Paige & Paul: Explanatory Power for explaining current observation. Patty: Explanatory power for explaining current observation & Making sense

Comparing Group Pictures

Paige: More detail—combing different levels of explanations Patty & Paul: More detail—combing all topics
Draw separated pictures to represent four different ideas.
1) N and S would attract each other because they are opposite. They have different molecules inside them. N and N or S and S would repel because they are not opposite and they have same molecules inside them.
2) There are more molecules in the two ends than the middle part of the magnet.
3) The cut small pieces will still become their own magnets, so they always have their own two poles.
4) Putting the metal bars on the magnet is like putting battery to the metal bars so they will become magnets.

The Second Partially scaffolded group
Post-Interview

<table>
<thead>
<tr>
<th>Paige</th>
<th>Patty</th>
<th>Paul</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="Paige.png" alt="Picture" /></td>
<td><img src="Patty.png" alt="Picture" /></td>
<td><img src="Paul.png" alt="Picture" /></td>
</tr>
</tbody>
</table>

Dots in the picture represent molecules. Lines represent electric or power wave.
Dots in the picture represent molecules. Lines represent electric or magnetic charges.
Dots in the picture represent molecules. Lines represent electric or magnetic charges.
M1: If there are same molecules in the two ends (two N ends and two S)  
M1: Attraction: When they’ve got different molecules, they will attract.  
M1: If molecules are put in a certain way, the molecules can sense them inside and if
ends), these two ends will not go together because of the same direction they are going to. If there are different molecules in the two ends (N and S end), these two ends will go together in the opposite direction which will make them attract.

<table>
<thead>
<tr>
<th>Repulsion: when you’ve got the same molecules, they will repel each other.</th>
<th>they don’t like each other, they will push away. If they like each other, they will pull to come together.</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>M2: The cut small pieces will always have N and S because there are always two sides. If one is N, the other would be S.</th>
<th>M2: The pieces will become their own magnets because one magnet can only have two poles.</th>
<th>M2: The magnet is protected by a layer of material from air. When it is cut, this layer is rip off, and air can come into, which will make the cut end strong to become a small magnet.</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>M3: There is like a power source in the magnet, and there is electric or power wave going through the magnet and metal bars, so the magnet can connect all of the following metal bars.</th>
<th>M3: Two ends have the strongest magnetic or electric charges, so little bars would stick to the two ends, not so well to the middle part. The magnetic charges would go through the whole magnet. Because in the middle part the charge is widely spread, and in the two ends, which is the smallest part of the magnet, the charges is more compact, so two ends got more power. The metal bar would stick to the magnet is because the charges would goes through them. &quot;The longer the chain gets, the weaker it gets. Like this metal bar that is now like a magnet is weaker than the last one because as it keeps going, the more it has to travel and the longer it has to travel, the weaker it gets.&quot;</th>
<th>M3: Two ends and the inner middle part of the magnet have more magnetic charges inside. The metal bars do not stick to the middle part of the magnet, because there is no magnetic charge in the outer middle part of the magnet. The metal bars would stick to the magnet is because the magnetic charges go though these metal bars, so these metal bars become magnets.</th>
</tr>
</thead>
</table>
Appendix G

Explanations of Magnetism
Two explanations are typically employed to explain magnetism: magnetic domains and electron spins. In this study, the students’ “tiny-magnets model” is similar to the domain model of magnetism. More advanced explanations about how electrons’ spin can be derived from quantum mechanics or relativity are beyond the range of scientific explanations appropriate for the elementary students in this study.

**The Structure of Matter**

The magnetic properties of a material depend on the structure of its atoms. The electrons in an atom have magnetic moments because of their spin (a quantum mechanical idea that is left unexplored here because it is beyond the appropriate level for the students in this study). When these moments are in opposite directions, the overall magnetic field of the atom cancels. When electrons exist unpaired, the magnetic moments of the electrons combine, making the atom act like a tiny magnet.

**Different Strengths of Magnetism**

In most materials, the magnetic fields of the atoms point in random directions, so the magnetic fields cancel out. Hence, the magnetism of most materials is very weak and cannot be detected.

However, in certain materials (ferromagnetic substances such as iron, nickel, and other metals), the magnetic fields of the atoms tend to remain lined up in the same direction, producing strong magnetic characteristics. A cluster of billions of atoms with aligned magnetic fields groups together a region called a “**magnetic domain**.” The entire domain acts like a small magnet (on the order of microns) with a north and a south pole.

When a ferromagnetic material is not magnetized, the domains are randomly oriented so that their magnetic fields cancel each other out, and the strength of the overall magnetic field of the material is close to zero. When a ferromagnetic material is magnetized by the application of an external magnetic field, the domains are lined up and point in the same direction as the applied field.
Application of Magnetic Domain Model to Explain M1, M2, and M3

The M1: Two Magnets Activity demonstrates that opposite poles of the magnet attract, while like poles repel one another. The magnetic domains in a bar magnet align with each other and point in a single direction. When two bar magnets approach each other, the magnetic fields of domains in one bar magnet react to the aligned magnetic fields in the other magnet. When unlike magnetic poles of two bar magnets face one another, the two magnets have the same alignment of the net magnetic field, and the two magnets attract each other. When like magnetic poles of two bar magnets face each other, the two magnets have the opposite alignment of net magnetic field and two magnets repel each other.

Aligned magnetic fields attract

Opposing magnetic fields repel
In the M2: Cutting Magnet Activity, when the magnet is broken into small pieces, these cut pieces still have two ends. Within the original bar magnet, there are many domains like small magnets with N and S poles. When the magnet is cut into smaller pieces, the domains still line up in the same direction. Hence, each of the small pieces of the magnet has the co-existence of N and S poles.

In the M3: Metal Bars Activity, the metal bars are pulled toward the two ends of the magnets and become like small magnets. When unmagnetized metal bars are placed within the bar magnet’s field of influence, the randomly arranged magnetic domains in the metal bars rotate toward the magnetic field of the bar magnet. When the majority of domains line up in the same direction, the metal bars become temporary magnets and then attract the other metal bars for the same reason.