Science Learning as the Objectification of Discourse

Abstract: The study presented here seeks to contribute to the dialog of how students come to learn disciplinary knowledge. Students in a highly-interactive physics course were studied as they constructed a model of magnetism. Two focus students were video taped throughout the 7-hour unit. They transitioned through 7 different representations of their models and their discourse and model-building practices evolved. The findings of this study are framed in terms of Sfard and Laive's (2005) ideas about the objectification of discourse as a definition of learning. The findings from this study are used to demonstrate the power of this perspective and to illustrate that the learning of disciplinary knowledge resulted from the students objectifying their discourse away from the self and its communication with other people and toward the self in relation to the human-independent world of magnetic phenomena.

Background and Theory

Language is often treated as a communication medium rather than as a legitimate part of cognition in research on the learning of disciplinary knowledge. Many researchers have studied the role of language in the development of scientific knowledge (Lemke, 1990; Moje, Collazo, Carrillo, & Marx, 2001; Kelly, Crawford, & Green, 2001; Lee & Fradd, 1998) and in other types of disciplinary knowledge (Gutiérrez, Lopéz, Alverez, & Chiu, 1999; Gutiérrez, Lopéz & Turner, 1997; Gee, Allen, & Clinton, 2001; Gee, 1990). It is ever clear in this body of research that both language and concepts are involved in the learning process but they are very difficult (if not impossible) to analytically distinguish from one another. Roth and Duit (2003) refer to this phenomenon as the "structural coupling" of language and concepts, a phenomenon that remains a largely unexamined field of inquiry and is the subject of the research reported in this paper.

Gee uses the term "Discourse" not to refer to the exchange of words in general, but to refer to the language and practices of a particular community. In science, Discourse includes the formal terms and how terms are put together in sentences (e.g. an object does not *have* a force, an object *exerts* a force), symbols and their uses (e.g. an arrow on top of an the letter *a* means something different from arrows extending from a dot), what is deemed salient in a given situation (e.g. differentiating "noise" and signal on a graphical representation), the practice of making evidence-based claims, mechanistic reasoning, and the practice of creating and using models of phenomena. The preceding list of scientific practices constitutes much of what is meant by *scientific literacy,* or being literate in science. Like any literacy, it consists of a set of obligations, expectations, practices, values, meanings, and ways of using language that make up participation within the community thus defined. Within the scientific community this includes the learning of scientific terms and how to use them, the symbols and their contextual applications, how to read out the appropriate features of a given situation, and how to argue mechanistically in support or rejection of a model of an observable phenomenon.

Although models of phenomena are central to all scientific discourse, research on students' understanding of models in science has only begun to blossom in the recent decade. Work on meta-modeling competence (Schwarz & White, 2005), students' understanding of the nature of models and modeling (Harrison & Treagust, 2000; Harrison & Treagust, 1998; Gilbert & Butler, 1998; Windschitl, 2004; Windschitl & Thompson, 2006; Snir, Smith, & Raz, 2003; Bhushan & Rosenfeld,1995; Harrison & Treagust,1998; and Coll, France & Taylor, 2005), and students' development of mechanistic reasoning strategies (Russ, Scherr, Hammer & Mikesha, 2008) are increasingly becoming part of the mainstream of science education research. Overall, these studies continue to show that by in large, science classes fail to explicitly teach, and students fail to learn skills for developing, revising, and utilizing scientific models to explain observable phenomena. This finding is critical because models and modeling are the crux of the Discourse of science.

The practice of reasoning with models and mechanism involves testing for a hypothesized process involving underlying *mechanisms* that could drive observable phenomena (Machamer, 2004). In a study, Windschitl (2004) demonstrated that science majors revealed a common "folk theory" of scientific inquiry that did not involve model-based or mechanistic reasoning. The secondary science teacher certification students in his study, "did not make the methodological connection that investigations should be based on some explanatory premise nor was there evidence that they understood that the goal of inquiry is to support, revise, or refute various aspects of scientific models" (p. 491). Instead, they engaged in "relation-based reasoning" where empirically testing relationships between variables was viewed as an epistemological end in itself. Windschitl argued that these students viewed models and theories as optional tools that could be used to help explain results after a scientific study is complete. In contrast, much of science *is* the practice of building models and experiments serve the purpose of demonstrating that a model is adequate for explaining phenomena. High school and college students have difficulty developing skills associated with model-based reasoning (Windschitl, 2001; Abd-El-Khalick, 2001) and often fail to learn the Discourse of science.

In a provocative publication, Sfard and Lavie (2005) argue that learning within a discipline (in their case mathematics) involves the *objectification of discourse*—the use of words as if these words signify *discourse-independent entities* out there in the mind-independent world (Sfard & Lavie, 2005). Sfard and Lavie paraphrase Vygotsky and go on to indirectly define learning as a process that "begins as an interpersonal affair (and) turns in the growing mind, into a matter of one's relation with human-independent world." They also claim that, "…this kind of development is a 1-way process, and the change from the interpersonal to between-person-and-the-world outlook, once accomplished, can hardly be reversed," (p. 238-239). This is Vygotsky's theory of concept formation (Vygotsky, 1986), and in line with Vygotsky's theory, Sfard and Lavie (2005) define learning as an irreversible change in outlook that requires the "ability to see as 'the same' things that, so far, could only be seen as different," (p. 238). I will elaborate on this idea throughout this paper, but first a note on the notion of *disciplinary knowledge*.

Human beings tend to talk about disciplinary knowledge as if it is a thing that a person can possess rather than as a narrowly defined set of obligations and expectations that form the basis for communication (synchronous and asynchronous) with individuals who are familiar with, identify with, participate in, and continue to define these obligations and expectations. In the 1930's Ludwik Fleck developed the idea of *Denkkollektiv* (or *thought collectives*) and in 1935 he carefully elaborated this idea in his book, Genesis and Development of a Scientific Fact (Fleck, 1975). Fleck used the term thought collective to describe a system of (ever evolving) knowing that participants draw from and contribute to, a system that exerts a compulsive force on the thinking of an individual and thus constrains the set of possible thoughts of individuals within a community, but not on the community itself. Similarly, Sfard and Lavie (2005) describe disciplinary knowledge in terms of "endorsed narratives," which are defined as "sets of propositions that are accepted and labeled as *true* by the given community," (p. 246). The work of Sfard and Lavie (2005) synthesizes nicely with Fleck's work in attempts of answering the shockingly complex question: *what is disciplinary learning*. Sfard and Lavie argue that because human language is ontologically and epistemologically laden, it has up to now been difficult to understand the learning process due to the fact that disciplinary terminology is often (if not always) a result of the irreversible *objectification* that they claim defines learning. In other words, since language lives in the space of "the learned" it is very difficult to apply to the space of the "unlearned" or the space of the "learning," because each space is replete with its own (somewhat distinct) set of obligations, expectations, and practices that do not necessarily lie along a continuum. In fact, an entire literature on misconceptions in science has been established that merges these two spaces (for a discussion see Otero & Nathan, 2008). Indeed, Vygotsky's theory of concept formation mostly applies to the space of "learning," and throughout his influential work he struggles with language in efforts of bridging the space of the "unlearned" and the space of the "learned." The work of Sfard and Lavie brings the field of the learning sciences closer to bridging this gap.

Sfard and Lavie differentiate between disciplinary words and routines. Disciplinary words such as *force* in physics or *smaller* in mathematics have specialized meanings within the respective Discourse. Routines are ways of approaching tasks and come in the form of *deeds*, *exploration*, and *rituals*. *Deeds* are actions actually taken by the individual that produce a change in the environment. For example, if a teacher asks a child to pick the box that is biggest, the child reaches out and moves the larger box closer. *Explorations* have the aim understanding the world. Explorations often consist of extradiscursive entities that are the subject of discourse (as is the case in reasoning with mechanism about an invisible entity such as a charge). Exploration is what science education researchers would refer to as model-based, mechanistic reasoning. Rituals on the other hand, are socially oriented, with the aim of fostering solidarity with whom they are performed. Rituals have the sole aim of communication with the other. These distinctions become important as we attempt to understand science learning through the lens of the objectification of discourse. In observing students as they learn the practice of model-building and reasoning with mechanism, we are looking for transitions from discourse that is solely ritual to discourse that involves exploration and discussion about extradisursive entities.

In the remainder of this paper, I use empirical data from a physics course for adult learners to illustrate how the perspective articulated by Vygotsky (1986) and extended by Sfard and Lavie (2005) can begin to answer the question, "what is science learning?" My perspective differs from that of Sfard and Lavie only in that when they speak of the objectification of discourse, they apply it only to learning that differentiates children from grown-ups. I use this notion more broadly, to apply to all humans engaged in the process of learning disciplinary knowledge. In the research that follows, the modest question, "what does learning look like?" is mapped out through the exploration of three specific questions: (1) How do students' representations of models of magnetism evolve over the unit? (2) How do students' model-building practices evolve over the unit? (3) How do students' language practices evolve over the unit on magnetism?

Study Context and Participants

Physics and Everyday Thinking (PET) is an introductory college level inquiry-based physics course designed to meet the needs of adult learners, non-physics majors, especially elementary and middle school teachers. This study focuses on the Models of Magnetism unit, throughout which students have several

opportunities to develop and revise explanatory models of magnetism with the expectation that through guided experimentation, negotiation, and model revision, they will arrive at an expert-like model of magnetism.

Each activity in the curriculum consists of three parts: initial ideas, collecting and interpreting evidence, and summarizing questions. In the initial ideas section, students are asked to express their prior ideas and thoughts about the phenomenon that will be explored in a particular activity. Throughout the *collecting and interpreting evidence* parts of activities, students do experiments such as rubbing iron nails with magnets and investigating phenomena with laboratory apparatus and computer simulations. Questions in the curriculum frequently ask students to explain how their conceptual models account for their observations or how they might need to revise their models on the basis of observations. In some parts of the unit, *summarizing questions* explicitly guide students through the process of mechanistic reasoning, for example, one summarizing question asks, "Based on the results of the experiment, how would you describe each of the individual entities inside the magnet-rubbed nail?" Intentionally or not, this question asks students to begin to objectify the discourse by introducing the notion that there must be something (entities) inside the nail that is worth discussing. The curriculum is built on research on how students learn, so it is not surprising that by this time in the curriculum, most students have already introduced some type of entity within their drawings. However, the former question and several that follow it explicitly direct students to consider the term "entities" as a pointer to *discourse-independent entities* out there in the mind-independent world. Questions that follow within the curriculum begin to help students to use these entities as the agents that ultimately are responsible for the outcome or observation. Whether the curriculum developers intended it or not, the questioning sequence helps students to objectify their discourse.

A classroom that uses the PET curriculum is an appropriate context for a study of this type because it relies on students' making sense of scientific phenomena by constructing models that can be supported by evidence. There is no textbook used for the course, students are expected to construct their own understandings through small group work and discussion and larger whole-class discussions. The role of the teacher is mostly to lead discussions, making sure that students support claims with evidence, consider all of the evidence when making a claim, and ultimately come to consensus as a class on the ideas that will be used to explain the data.

Study Design and Method of Data Analysis

This study focuses on a group of two students who were representative of the class, Brie (an experienced elementary teacher) and Mona (a pre-service elementary teacher), who were video taped throughout the course. Both Brie and Mona are white, middle class adults, both with families of their own and neither identified herself as a "science person" at the beginning of the course. The Models of Magnetism unit was approximately 7 hours, all of which was videotaped, transcribed and analyzed. A constant comparative method was used to generate and revise initial codes to characterize the nature of all of the discourse. On the basis of analysis and lengthy discussion by three different researchers, the following codes emerged: metacognitive discourse, explicit discussions about the nature of science and the nature of models, analogical reasoning, evidence-based reasoning, experience-based reasoning, model-based reasoning, conducting experiments, logistics, and off task discussions. All of the data were coded independently by the three researchers who met weekly over the course of one year to compare the coding of each transcript. Only those codes for which a full consensus could be established were kept and analyzed further. Of the consensus codes, all but the last three, "conducting experiments, logistics, and off task" were considered "sense-making" behaviors and were further investigated in order to understand how students' learned the disciplinary knowledge associated with a model of magnetism. Sense-making data constituted 165 minutes, approximately 40% of class time. Many episodes of what we referred to as "finding terms" were identified by all researchers, where the students struggled with terminology and seemed to be looking for the appropriate scientific terms to express their ideas. We therefore re-examined all of the sense-making data for the frequency of use of scientific terms such as force, charge, positive, and energy. The frequency measurements, the characteristics of the discourse, and the models of magnetism were then compared for the purpose of understanding how the students revised their models and how the nature of their scientific discourse changed in the process. Finally, these data were analyzed in terms of the routines used by the students, whether they were deeds, explorations, or rituals. Inferences about objectification of discourse were then made, and supported by changes in the nature of the students' talk as they moved closer and closer to the type of model associated with the endorsed narrative of magnetism in science.

Findings and Analysis

A summary of the findings of this study is organized in four sections. The first section presents the students' representations as they changed over the unit. The next three sections are organized according to three theory-laden claims that outline how discourse was objectified throughout the student's learning process and illustrate that disciplinary learning begins "as an interpersonal affair (and) turns in the growing mind, into a matter of one's relation with human-independent world."

Evolution of Students' Model Representations

The six models of magnetism that Brie and Mona wrote, discussed, and shared are described in Table 1 in the order that they occurred. Model is defined here as a representation constructed by the students along with the actual statements that they made when drawing or discussing the representation. The drawings in figure 1 were photocopied from the written work of the students. The text used to describe the group's models including the model names, were developed by the researchers but checked with the students after the course was completed. The models described below are not intended to serve as a one-to-one mapping of what was going on inside the students' heads. Instead, they illustrate the models that a group of students co-constructed and presented to each other and to the class.

In the three units that preceded the magnetism unit, the students investigated forces, different forms of energy, and energy transfers. The Energy model was Brie and Mona's initial model of magnetism (model 1), containing much of the same language that was used in the previous units of the curriculum. By the end of the magnetism unit, Brie and Mona developed a tiny-magnet (domain-like) model (model 7), which was the target model of the curriculum and aligned with the scientifically accepted (domain) model of magnetism.

Table 1: Brie and Mona's Models of Magnetism in the order that they occurred throughout the unit

Model Description	Actual Group Drawing
Model 1: Energy Model. An unmagnetized nail has no energy but it has the potential to have energy, and a magnetized nail has stored energy (usable energy), which becomes magnetic energy during interactions.	
Model 2: Energy/Charge Separation Hybrid. An adaptation to the Energy Model, where collections of positive and negative charges now appear at either end of the rubbed nail.	
Model 3a: Worm Regeneration Model. A magnet is like a worm insomuch as its properties are replicated on both pieces when it is cut in half. The properties that are replicated are that one end is positive and the other is negative.	
Model 3b: Charge Separation Model. Positive and negative charges exist randomly within unmagnetized nails. During rubbing, the charges become separated at the two ends of the nail.	
Model 4: Fractal Model: Entities exist in the nail and they are tiny versions of the nail, like an iron filing is to a large piece of iron (nail). The nail takes on the properties of the tiny iron filings.	*The students provided no illustration of this idea.*
Model 5: Activation Model. Entities exist in the unrubbed nail and are activated when the nail is rubbed with a magnet. The activated entities are represented the same way a magnetized nail is represented, by a plus or minus symbol on either end.	
Model 6: Plus/Minus Entity Alignment Model. The positive and negative charges within a magnet are coupled and inseparable. They are randomly arranged in an unmagnetized nail and by rubbing the nail with a magnet, the entities are aligned.	
Model 7: North/South Entity Alignment Model. This is similar to the plus/minus alignment model except the entities in the nail are tiny magnets. This is the target model of the unit and consistent with the domain model.	

The nuanced discussion of each of the seven models shown in Table 1 is too lengthy to include here. Instead, I present a discussion of the claims that can be made from these models and the associated discourse.

Claim 1: Models 1, 2, and 3a are illustrative of ritual routines

Brie and Mona's early models *describe* their observations. The energy model (model 1), the energy-charge hybrid model (model 2), and the worm regeneration model (model 3a) all ascribe *conditions* that can *account* for the observed phenomena (attraction, repulsion, and the dipole behavior of both ends of a cut nail). None of these three models provide a mechanism for how these macroscopic observations could come to be nor do they

provide discussion about the properties of the entities (the little plus and minus symbols that appear in model 2 and 3a) beyond that they represent opposite things.

I argue that, for Brie and Mona, the purpose of the first three models was to mediate a discursive procedure (ritual routine) rather than to understand the world (exploration routine). This is not to say that Brie and Mona's discourse does not represent their thinking about the phenomenon. On the contrary, they clearly have ideas about energy and are trying to describe the behavior of the magnetized and unmagnetized nail. The transcript and the group's representations suggest that the visual mediator of the discourse around models 1, 2, and 3a is the nail itself. The pronoun "it" is used by the students to refer to the nail (later "it" will be used to refer to the entities within the nail.) Also, a majority of the discourse was an attempt to determine the appropriate words to use. This was partially constrained by the situation; the students were expected to express their ideas first in their workbooks and then on a 3'X4' dry erase board and present it to the class. But in both cases it seems that they were preparing their ideas for others (the teacher or the other rest of the class) to describe *that* a nail becomes magnetized rather than seeking to understand *how* a nail becomes magnetized. The excerpt below demonstrates that Brie and Mona searched for the correct terminology. Some transcript has been removed for brevity, represented by ellipses.

500	M	What do we:: agree on? Yeah negative and positive. So we agree that
501	B	Something's flowing in it
502	M	And that it's become magnetized. Or, has magnetic energy, right?
…		
506	M	Um:: I like the idea that it has two opposing ends, or forces, or whatever you want to call it
507	B	So south and north?
…		
508	M	Yeah, or just somehow maybe indicating that this one is neutral, it doesn't have, you know what I mean? Does that seem right?
509	B	Yeah, what is neutral? What's the sign for neutral? S?
510	M	Mmm, or a positive N?
…		
518	B	Well, yeah. Neutral means nothing. And that's like, don't do anything,
519	M	No magnetic energy
520	B	Does not do anything. You know?
521	M	Doesn't have any energy?
522	B	((makes a circle with her hands)) No smoking
523	M	Has energy potential but it doesn't have any energy.
524	B	Let me write that on my thing, I kinda like that
…		
536	B	You're right. You said a word, now what is it, what was it?
537	M	I just said that energy was present, but energy is *infused*, I don't know.
538	B	Potent... oh no, not potential.
539	M	Stored!
540	B	((waves her arms and legs around excitedly))

In lines 500-507 the students are looking for a way to represent that the nail that has been rubbed with a magnet is magnetized and the unrubbed nail is not. They use terms such as negative and positive, magnetic energy, south and north, and neutral. In lines 518-522 they search for the term that would be necessary to describe the concept of *nothing* and conclude using the terms *neutral, no magnetic energy, potential energy,* and a circle with a line through it. In lines 536-540 the purpose of the discourse appears to be to negotiate which words would most appropriately describe an agreed upon condition of magnetized versus unmagnetized. These terms are also present on their representation of Model 1 in Table 1. Brie and Mona revised their model to include some of the symbols used by the other students (pluses and minuses) for model 2 and developed a worm regeneration analogy for model 3a when they were asked what would happen when they cut the magnetized nail in half. In all three models, Brie and Mona discussed only the nail in a broad sense and not what was happening within the nail. I argue that this represents a ritual routine because the discussion centers on how to *describe* the macroscopic properties of the observation—while privileging scientific words, rather than on *explaining* the observations themselves. The rest of the models were, however, mechanistic.

Claim 2: Models 3b, 4, 5, 6, &7 illustrate the exploration routine

I argue that models 3b-7 represent exploration routines (model-based, mechanistic reasoning), although the students were still learning how to engage in exploration as they were doing it. Brie and Mona's discussion about each of these 5 models had the visual mediator of the entities inside the nail, rather than the nail itself. The words "it" and "they" no longer referred to the nail; they now referred to the entities inside the nail. These entities were "extradiscursive" in the sense that they were treated as if they existed independent of the discussion or the classroom activity, in the human-independent world. These entities were not intended for the purpose of communication. In these cases, the purpose of the discourse was to negotiate an understanding of

why the nail behaved the way it did. The discourse was used to discuss the properties, activities, and organization of the entities and ultimately how these things impacted the behavior of the observable nail. As is evident in Table 1, all of the energy terms have vanished by model 3b, and instead plus and minus symbols are used throughout the remainder of the discussion until model 7, where Brie and Mona explicitly switched to "Ns" and "Ss" due to an activity that drew a distinction between electrostatic and magnetic phenomena. Brie and Mona were aware that they did not know what plus and minus really meant except that they were opposites and therefore could be used to signify attractive and repulsive behavior. When the students decided to switch from singular plus and minus entities (models 3b) to dipole entities (models 5-7), Brie and Mona decide to try out the term "electron" to stand in for the objectified entity that was the subject of their discourse. The point is that in later discourse (presented below), Brie and Mona were no longer negotiating which term to use, they were negotiating the behavior of the thing that they used the term to describe.

2268	B	Let's call them electrons just for kicks and see if we're right.
2269	M	Ok.
2270	B	So each electron in the nail behaves the same
2271	M	I don't know my electron. I wish I had a defin... I should have looked up electron, you know to define it. I wonder what that word means.
…		
2279	M	Ok, so
2280	B	It takes on the same...
2281	M	Right, same properties. Right.
2282	B	The nail
2283	M	The nail
2284	B	((writes)) takes on the same properties
2285	B	and...there's something else, and behaves
2286	M	and the same, um
2287	B	and behaves in the same way, 'cause don't they behave in the same exact way?
2288	M	mmhmm yeah. Each one of those behaves in the same way as the nails does, and the same way as a piece of the nail did.
…		
2293	B	because it takes on the properties and it behaves the same way, you have to say both.

The discourse above took place as the students were developing model 4, the Fractal Model. As soon as they began to discuss the actual behavior and properties of the entities they moved back to plus and minus symbols and terminology. The difference between the discourse in lines 500-540 and that in 2268-2293 is that the purpose of the former was to put words onto already agreed upon experiences—to communicate with one another, the teacher, and the other students—that the rubbed nail was magnetized and the unrubbed nail was not. In the latter (2268-2293), the purpose was to negotiate the properties and behaviors of invisible entities that might exist within the nail and help to explain the nail's behavior. Later transcript reveals how Brie and Mona chain back and forth between the microscopic entities and the macroscopic behavior of the nail.

Claim 3: The curriculum shaped the students' discourse and hence, their reasoning

The data suggest that transitions between Brie and Mona's models were facilitated by specific constraints provided by the curricular materials both in the language that was used in the workbook and in the experiments that were prescribed. An experiment that led to the generation of Model 4, provided an analogy to the nail. A closed test-tube was about ¾ filled with iron filings and students rubbed it with the magnet just as they did the nail. They observed similar macroscopic effects. They could also see the effect of rubbing the test tube (analogical nail) on the little iron filings inside the nail. This helped to shift students' attention from the nail as a macroscopic object to the entities within the nail. Further, a summarizing question asked, "Based on the results from the experiment magnetizing the test tube filled with iron filings, how would you describe each of the individual entities inside the nail." Although Brie and Mona had already been talking about entities in the form if plus and minus charges for a while, they now began to focus on the properties and behaviors of these entities. In doing so, the language that they used to describe their model shifted from discussing the magnetized nail as an "it" that behaved differently as a result of being rubbed by the magnet, to discussing the magnetized nail in terms of "they," the little things inside the nail and what they were doing as a result of the nail being rubbed by the magnet. This shift in attention refocused the discourse from the aim of communication to the aim of understanding the behavior of the entities. This
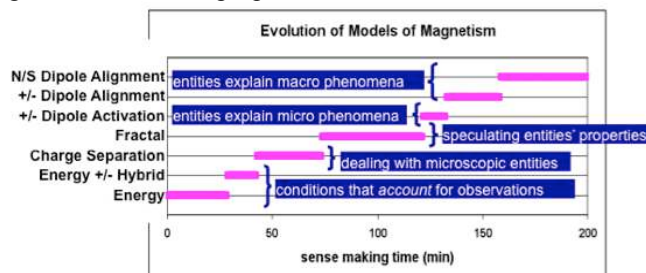

Figure 1: Students models (along y-axis) over time (x-axis) and their mechanistic reasoning.

led to discussions about the how the behavior of the entities could account for their macroscopic observations, which often led them back to change the behavior and properties of the entities until the Brie and Mona arrived at a fully mechanistic model that could account for the observed phenomenon. This backward and forward chaining between mechanistic model and observable phenomenon has been observed by other researchers who study mechanistic reasoning (Russ et al., 2008). Figure 1 summarizes how the students' models evolved along with their attention to different aspects of the entities.

 Figure 2 provides another representation of the changes in Brie and Mona's discourse patterns throughout the unit. In figure 2, two 13-minute episodes are presented according to two different coding schemes. The first coding scheme (top two graphs) was used to count the frequency of scientific term use and the second coding scheme identified reasoning strategies employed by Brie and Mona (bottom two graphs). The two graphs shown in set (a) are from early in the unit where I claim that Brie and Mona were engaged in communication-oriented ritual routines. Set (b) illustrates discourse that took place approximately 160 minutes later (not the same day).
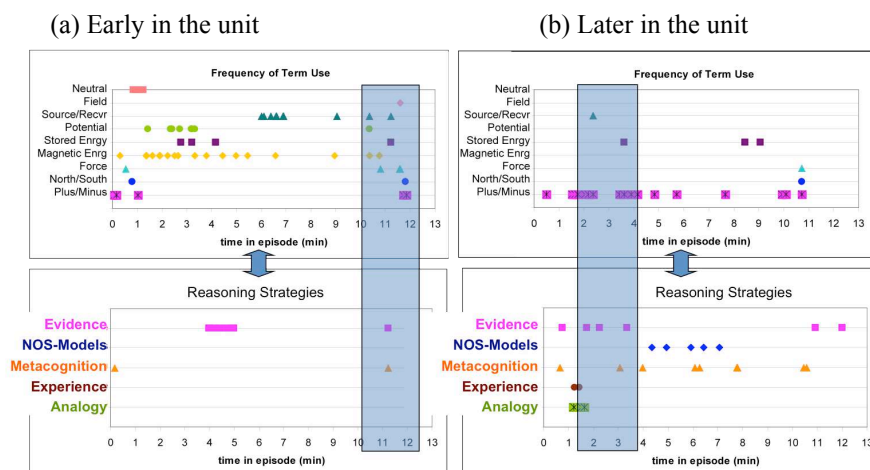

Figure 2. Comparison of students' use of scientific terms (top) and reasoning strategies (bottom). Set (a) is early in the unit and (b) is later in the unit.

As is evident from the graphs, the discourse that took place early in the unit—set (a) was dense with scientific terms such as charge, negative, positive, neutral, force, source, receiver, stored energy, potential energy and the same transcript is sparsely coded with reasoning strategies. Set (b) on the other hand, has fewer terms identified on the top graph and is rich with reasoning strategies as shown on the bottom graph. This suggests that the nature of the discourse was different in these two clips and supports the claim that focus on verbal, term-based communication was more the focus of early discourse and reasoning was more the focus of later discourse.

Discussion

Like the early math learners in Sfard and Lavie's (2005) study, Brie and Mona practiced model-building in science initially in a largely communicative style, looking for appropriate terminology with which to communicate what everyone already knew. As the unit went on, Brie and Mona increasingly focused on the mechanism that could drive observable phenomena and less on communication for its own sake.

This seeks to demonstrate how discourse becomes objectified as a result of being practiced, and this is what defines the development of disciplinary knowledge. A reasonable question to ask is, "Why do students even have to go through the interpersonal discourse? Couldn't the teacher have just started with the iron filing experiment, telling students to focus on the entities inside the nail from the get go?" The point is not that the curriculum was explicitly set up to allow the students time to engage in interpersonal discourse. Instead, this was direction taken by the students' interaction with it. The unit on magnetism was particularly suited for this type of study because it consisted of a practice that Brie and Mona had little experience with—model building. Therefore, we were able to catch a glimpse at what it looked like as they embarked on early participation in this practice. The data demonstrate that the students' models of magnetism evolved toward the scientific model, their reasoning became increasingly mechanistic, and their discourse about the magnetic phenomena moved from the interpersonal domain into the domain of invisible entities that serve as a mechanism for observable behavior. As hypothesized by Vygotsky and further elaborated by Sfard and Lavie (2005) and countless others, learning involves participation. Participation involves the self and in order for the self to engage with the endorsed narrative of a discipline, she must access any available routine that is handy. In most of our cases, this is the routine of communicative ritual. We play this routine over and over as a means by which to catch on to the rules of play within that community. This is exactly what Brie and Mona did. They played communication

as they investigated the problem space. In doing so, they caught on to subtle but critical practices that define success in mechanistic reasoning.

In this study, the task of creating a model of magnetism can be thought of as existing in two stages: (1) the task of creating product that was perceived as acceptable for the purpose of communicating with other individuals (term-dense sentences that could only account for the final conditions of the phenomenon) and (3) the task of objectifying the discourse so that the students' relationship with the objectified world of magnetic phenomena, and therefore the community of scientists, was able to flourish. The students began their model-building experience in discourse that centered on constructing term-dense sentences that could be presented to the others. Brie and Mona said things such as, "You used a word, what was it, Poten- Potential! Yea, I like that," indicating that they were looking for "good words" to use. They ended their model-building experience with a solid model of magnetic phenomena that could account for all of their observations. The entire class ended the unit with a discussion about the nature of models and their role within the scientists' activities. There is ample evidence from this study that the learning of disciplinary knowledge resulted from the students objectifying their discourse away from the self and its communication with other people and toward the self in relation to the human-independent world of magnetic phenomena.

Acknowledgements

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