CHAPTER 4

ANALYSIS of MODEL DEVELOPMENTS

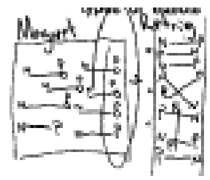
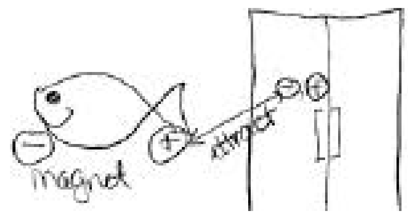
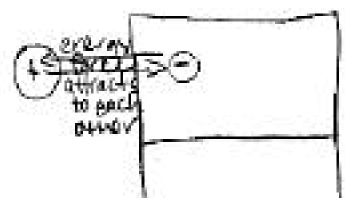
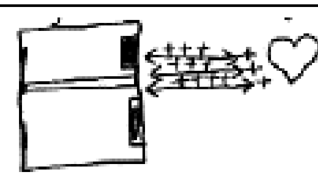
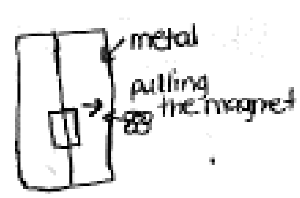
This chapter will examine in detail both groups' and individual students models as they were drawn and described by students throughout the four weeks of Cycles I and II. In the first major section, I will describe a categorization scheme with six major categories which can encompass practically all of the model diagrams produced throughout the two cycles. The six categories are (1) Alignment, (2) Separation of charges, (3) Two kinds of charge appear, (4) One type of charge on each, (5) Energize or increase, and (6) Showing effects. These model categories will be explained for each cycle, along with examples. The later part of this chapter will discuss progressions in group models.

The models described below were constructed by individuals or groups when they were asked to represent their thinking. Thus, they probably represent how students were thinking about magnets. However, when the students were asked to reason about situations involving magnets and magnetism, they didn't always use their latest model to guide their predictions, and except for the video group studied, no systematic attempts were made to determine students' depth of commitment to or consistency in use of their models. Thus, the following model diagrams are not intended to represent "mental models" that students held in their minds. They are also not full-fledged scientific models intended to satisfy requirements of logical consistency, completeness, and connection to other ideas. Instead, they are diagrams that represented students thinking when the students or groups made them.

EARLY IDEAS - BEGINNING OF CYCLE I THROUGH ACTIVITY I-D2

The Cycle I Elicitation discussion took place on Day 1 of the unit. Students were asked to draw a picture to describe how they thought a refrigerator magnet sticks to a refrigerator, and what causes clothing to stick together in a clothes dryer. Students were asked to draw their own pictures first, and then to discuss their drawings with group partners. A few students apparently drew diagrams based on what they saw or discussed on their group partners papers, rather than drawing something on their own. Individual students' diagrams can be grouped into a the set of model types that were listed above. Specific examples and names are shown in Table 4-1 which is on the next page. Models with features closest to the course targets are listed first.

Table 4-1: Individual students' models in Cycle I Elicitation

Type of model	Characteristic diagram(s)
Category 1: Alignment 2 students in 1 group	
Category 2: Separation of charges 1 student	
Category 3: Two kinds of charge appear or charges are created	No students drew this kind of model
Category 4a: One type of charge on the magnet and **opposite** type on the refrigerator 12 students in 8 groups	
Category 4b: One type of charge on the magnet and the **same** type on the refrigerator. 3 students in 2 groups	
Category 5: **Energize** the object **or increase** the number of one kind of particles	No students drew this kind of model
Category 6a: Showing attraction with charges and arrows 2 students in 2 groups	
Category 6b: Showing attraction with no charges or other mechanisms 7 students in 5 groups	

Total = 28 (no data for 3 students.)

The relevant model categories are described below, with accompanying descriptions by students.

Category 1: Alignment

Out of 31 students in the course, only Carl proposed on Day 1 a model that showed aligned, two ended "units" inside magnets, and randomly aligned "units" inside a steel refrigerator door. It is quite possible that he may have seen a diagram of aligned magnetic domains in a book somewhere, years ago, although when asked about it on Day 8 he claimed he didn't remember any. Julie, in Carl's group, drew a diagram that looked just like Carl's. It is likely that she drew her picture after talking with Carl.

Carl explained his thinking in the whole- class discussion. His explanation is below. Note that he was thinking about positive and negative ends, rather than north and south.

> Carl We think that the way how the magnet works is that like the piece of metal, and one part of the magnet has more positive charges at one end and all the negative charges are more at another end. And I think, we think that when it attracts, when it touches, you have to have more positives like at one end that like makes it more of a positive charge, and then it can you know it can attach to the metal refrigerator. The refrigerator has positive and negative charges like all just scattered all around like it doesn't matter like any piece of metal.

The target model for this magnetism unit was an alignment model; Carl proposed an alignment model. Carl's model diagram looked quite similar to the target model. It seems likely, however, that when he first proposed it he did not have such a well-developed understanding of alignment models as he later developed during the unit. His explanation used "positive and negative charges" as the things causing magnetic effects. Later, Carl's group wrote about "particles with north and south ends" as the feature that caused magnetic effects. Besides exchanging positive and negative for north and south, the group also described single objects with two opposite ends. While Carl drew two-ended objects at this very early stage, he didn't seem to be talking about them as single entities yet.

Category 2: Separation of charges

This model assumes that charges exist in magnetic materials. In non-magnetized objects, two opposite types of charges are mixed together, while magnetizing an object is a process of separating the two types of charge to the opposite ends of the object. This model explicitly requires preexisting charges inside objects.

Marge drew pictures of a magnet with + and - signs on its two ends. She was the only student in the class to do this in the Cycle I Elicitation. She told Donna she remembered seeing horseshoe magnets with + and - marks on them, and that one magnet attracted or repelled another horseshoe magnet depending on how the ends were arranged. She was aware that the two ends of magnets are different, and explicitly drew her picture based on this prior knowledge.

Note that the diagram Marge drew didn't show charges as microscopic objects. She simply drew a single "+" and a single "-" at the two ends. It is not clear whether she was thinking about how the magnet came to have these different ends. Her concern at the time was to explain how a magnet would stick to the refrigerator. After class, however, she told me in an interview that she thought the magnet had electrical charges separated to the two ends: ("Int" is the interviewer.)

Marge	. . . . when I was a child when I was in school we had magnets, they were always horseshoes. Sometimes we had bar magnets but a lot of times we had horseshoes and that's the kind we bought at the five and dime. They were this little horseshoe magnet with red painted at the ends of them so that just came in my mind, and then ... I could separate the charges.
Int	You have the minus on one end and the plus on the other end and they are attracting the other thing in the refrigerator.
Marge	And our thought was that in the metal, these charges are all mixed up and they are everywhere, but in the magnet, they are separated, so with the magnet, if you put it anywhere on the refrigerator, it doesn't make any difference, it's never gonna be repelled because it will always find a charge to attract it somewhere in that metal. No matter which side. . . . .

Because of this, her diagram fits into the "separation" category. Marge's was the only example of this kind of model on Day 1 but this model type became very popular for a time, later in the course.

This model and the "charges appear" models (Category 4) seem to be quite similar to the "magnetism as charge" model mentioned in Chapter 2 (Borges & Gilbert, 1998). It also seems consistent with the thinking used by students in other physics courses (Maloney, 1985; Kraus, 1995). That students in NS412A used the same idea suggests that this idea is quite common among students of magnetism.

Category 3: Two types of charge appear.

No students proposed this type of model in the Cycle I Elicitation. No groups explicitly described it until Day 3. It is described here for completeness.

This model is similar to the separation of charges model, because students who use it say that a magnetized nail has + and - charge at the two ends (or north and south charges.) The difference is that students think that, before an object like a nail is magnetized, there is nothing magnetic inside it, and the process of rubbing with a magnet puts charges into the nail. Somehow, positive charges are put into one end, and negative charges are put into the other end. This model assumes that charges are things, like particles of some kind.

There is another type of model in this category. Some students seemed to be thinking about charge as a *condition* of the nail, rather than as particles. These students drew single symbols (+ and -, or N and S) at the two ends. Rather than saying "the nail has positive charges at the end", they would have said that "the nail is positive" at the end. Despite the ontological differences in the two models (charge as objects vs. charge as a condition) they were categorized together, because students' diagrams were not always specific. Some students might have drawn a picture suggesting charges as condition at the two ends while saying that each end "had charges."

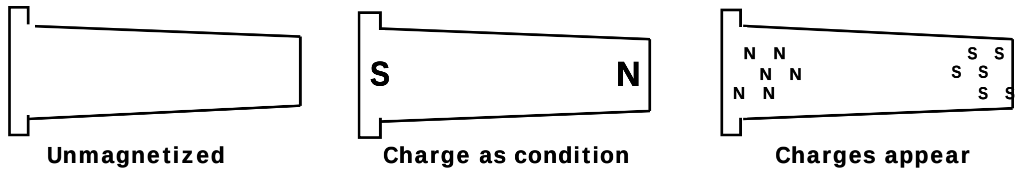


Figure 4-1: Charges added or charge condition added

Marge's diagram looked like a "charge as condition" model, but her explanation, which involved preexisting charges, clearly defined her idea as separation of charges.

Category 4: Magnet and refrigerator have one charge each.

4a: One type of charge on the magnet, and the opposite type on the refrigerator

Over 60 percent of the individual students drew diagrams showing some kind charge on the magnet, and more charge of either the same or opposite type on the refrigerator. Where did students get this idea? Recalling his initial idea in his learning commentary (written much later), Bob wrote:

> "My first model was one that entailed all of my current understanding of magnetism. I understood that opposites attract. I also thought that there were positive and negative sides. So, when I thought about a magnet sticking to a refrigerator, I assumed that one must be positive and the other must be negative. The magnet, being the active "sticker," was assigned the positive role."

It is likely that the other students who drew similar diagrams may have been thinking along the same lines. Bob's thinking makes sense if one considers an introductory student's limited background knowledge and a not - too - critical combining of ideas. Like Bob said, he knew a few things and put them together in a way that seemed sensible at the time. This model may be specific to answering the question of how a magnet attracts an unmagnetized object, so if students were asked some other question about magnets, they might not tend to construct similar models. Also, students who used this model may not have considered connections to other situations. For example, Bob's explanation, above, only makes use of the phrase "opposites attract" and he probably did not consider the other part, "likes repel." Another very important issue, initially not addressed by many students, is what "negative" means. If two refrigerators are both negative, then do they repel each other?

Some students used the word "negative" to mean "nothing". For instance, Donna used this kind of a model to explain a refrigerator magnet's attraction. I asked her about a magnetized nail and a paper clip four calendar days after the Elicitation. She said:

Donna	. . . Paper clip - I was thinking, well, the paper clip is negative, there's no charge in that..... there's no charge in that. This is my thinking.
Int	Yeah,
Donna	and the nail could be positively charged because it was rubbed against the magnet. And so I would, I'm thinking, the paper clip's negative, the nail is positive, therefore it can attract. . . . .

The essence of what Donna said is that 'negative' meant 'no charge' to her, and 'positive' meant 'charged'. She apparently combined this with the idea that opposite charges attract, so that positive would attract negative. She didn't seem to consider the idea of putting two unmagnetized, or negative, objects next to each other until her group worked on Activity I-D2. It seems that many students did not initially distinguish between "negative charge" and "no charge".

4b: One type of charge on the magnet and the same type on the refrigerator

Other students used the same one type of charge idea, but they thought about the attraction differently. One group described algebra-like thinking to explain the action of positive and negative. They said that two negative charges should attract because two negative numbers multiplied together make a positive number. When presenting her group's diagram, one member of this group said ". . . the refrigerator gives off negative charge and the magnet gives off negative charge. Two negatives make a positive, and a positive means that your magnet stays, and doesn't go anywhere. . . . a positive and a negative make negative and negatives don't stick." Their diagram is shown in the next table below.

Category 5: Energize or increase particles

Students sometimes thought that magnetizing a nail by rubbing it with a magnet "gives something" to the nail, or "energizes" it. Their drawings were not as specific as those showing charges. No students proposed this type of model in the Cycle I Elicitation. It was used by a few students for a short time, later in the unit.

Category 6 a and b: Diagrams showing attraction

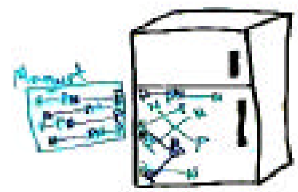
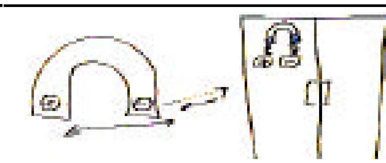
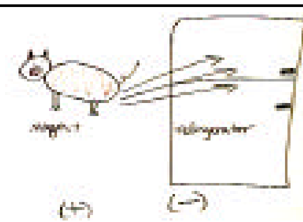
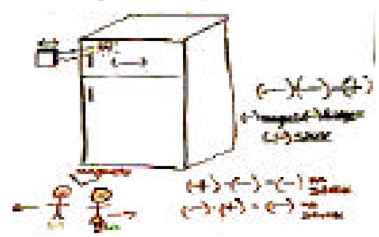
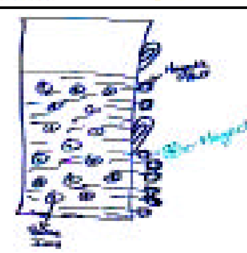
It is not easy to tell what students were thinking when they drew pictures showing no clearly described mechanisms for the attraction of a magnet to the refrigerator. Their diagrams mainly seemed to show that "magnets attract to refrigerators," but they didn't clearly suggest anything more. One student wrote on her Elicitation paper that "The refrigerator has certain properties. Example metal. If the magnet has metal properties also then they would attract and magnetize." The two students who included + symbols in their pictures may have been trying to show that they knew charges had something to do with the attraction. Some students thought charges were involved, but they didn't draw charges in their diagrams.

Diagrams in this category seem similar to Borges & Gilbert's "magnetism as a cloud" category. Students were basically showing attraction, which happens when the magnet is near to the refrigerator.

Group ideas presented to the whole class:

After writing on their own sheets of paper, the students discussed ideas within their small groups and drew diagrams on whiteboards for presentation to the whole class. In these presentations, Carl and Julie presented an alignment-like picture very similar to what Carl had drawn on his paper. Marge and Donna's diagram showed a two-ended magnet with positive charge at one end and negative charge at the other end. The remaining eight groups presented Category 3 type pictures that showed only one type of charge on the magnet or on the refrigerator. All the groups showed some kind of charge as a mechanism for the attraction.

Table 4-2: Groups' models in Cycle I Elicitation

Model category	Group diagram
Category 1: Alignment 1 group	
Category 2: Separation of charges 1 group	
Category 4a: One type of charge on the magnet and **opposite** type on the refrigerator 6 groups	
Category 4b: One type of charge on the magnet and the **same** type on the refrigerator. (Algebra explanation) 1 group	
Category 6a: Showing attraction with charges 1 group	

The types of diagrams and explanations presented to the whole class seemed similar to some individual diagrams and explanations. There were a variety of explanations for how the charges caused attraction. Five groups assigned "positive" to the magnet and "negative" to the refrigerator. When presenting her group's idea to the class, Joan said that, ". . . magnet has a positive and the refrigerator has a negative charge. And then opposites attract and causes the positive to attract to the negative and the magnet will stick." Only one group used N and S symbols to represent magnetic attraction. The magnet was N and the refrigerator was S.

The different pictures presented in the whole class discussion shared important similarities. All of the pictures showed charges as part of the explanation for a magnet sticking to a refrigerator. Only one group used N and S charges, while the rest of the groups used + and - signs, and Carl drew "n" and "p" representing negative and positive. All but two of the group presentations showed only one type of charge inhabiting the refrigerator or magnet.

The rest of Cycle I

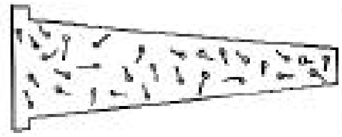
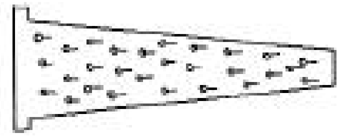
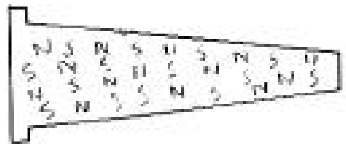
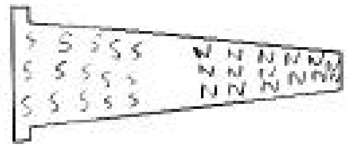
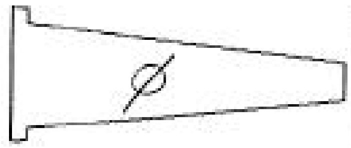
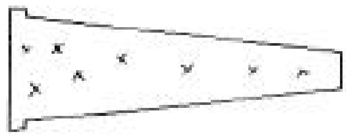
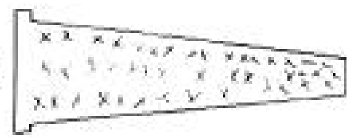
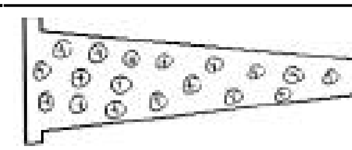
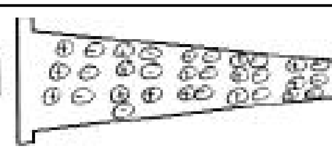
During the rest of Cycle I, groups were not explicitly asked to propose or describe models of magnetic materials. They did, however, explore important magnetic phenomena, notably the two-ended behavior of magnetized nails. Groups' changes in allegiance to models (see below) suggests that significant model development was going on. Unfortunately, because most groups did not write down their models during this time, there is no systematic data on groups' models until Day 6, in the Elicitation for the second cycle. Their models at this point are described below.

NAIL MODELS IN CYCLE II

Cycle II Elicitation

The instructor held the Elicitation discussion for cycle II on Day 6. In order to have enough class time for students to also do the first Development Activity on the same day, students were told on Day 5 to fill out the first page of the paper Elicitation document for homework. Students were to draw their own model pictures of what they thought could explain the phenomena they had seen in Cycle I. When students arrived in class on Day 6, most of them had drawn pictures already. These fit into the few categories shown in table 4-2. The term "rubbed nail" was used in class, and meant "rubbed with a magnet."

Table 4-3: Individual students' models in Cycle II Elicitation

Type of model	Unrubbed nail picture	Rubbed nail picture
1: Alignment of two-ended units 3 in 3 groups		
2: Separation of charges 15 in 8 groups		
3: Two kinds of charge appear or charges are created 6 in 3 groups		
5: Energize the nail **or increase** the number of one kind of particles. Not two ended. 3 in 3 groups		
Others 1 student		
Total: 29 diagrams	(no information for 3 students)	

Alignment type models

This category of model has the following features: Magnetic materials contain one kind of 'tiny things' that are different at their two ends. These things cause magnetic effects, and they can be rotated inside the metal. Unmagnetized objects have the 'tiny things' pointing in random directions which results in no magnetic influence on other objects. Magnetizing an object causes the things to line up so that all of the north (or positive) ends point in one direction and all of the south (or negative) ends point in the other direction.

Carl kept his alignment model. He still talked about positive and negative ends on the particles, rather than N and S. A fellow group member, Julie, who had duplicated Carl's alignment model on her own paper for the cycle I Elicitation, drew a picture in her homework showing charge separation. Apparently she had not been convinced of the alignment model. Janet, a member of one of the video groups, also came into class with a drawing of an alignment model. She had been experimenting at home with her own nails and magnets, and she talked to her husband, an electrician, about what she had seen. She said that the two of them noticed that the way she was rubbing nails (in one direction) was kind of like stroking a cat, whose fur lays in one direction. Janet said that she decided that nails may be the same way, and she used pictures of little compass needles, inspired from the magnetism simulation in Activity I-D3, to represent little magnetic objects. She used the terms "north" and "south" in talking about the magnetic objects.

Janet may have been inspired by rubbing in one direction or she may have found a picture of magnetic domains in a science book, or maybe her husband was more suggestive than she admitted. She might possibly also have remembered Carl's diagram from the Cycle I Elicitation. Or she may have come up with her idea the way she said she did. Wherever she got the idea, the rest of her group immediately accepted Janet's alignment picture, and drew pictures like it for the rest of the cycle.

The third student who drew an alignment-type diagram on her homework had been seen reading a children's book on magnetism in class, so it seems likely that she drew her diagram based on something she had seen in the book. Her group did not draw an alignment model in their group diagram.

Separation of charges

As described above, a separation model says that preexisting + and - or N and S charges are mixed together in magnetic materials, and rubbing with a magnet drags one type of charge to one end of the nail, leaving the other type of charges in the other end.

This model may have been so popular at this time because it uses existing ideas of charges to explain two-ended behavior of magnetized nails in a simple way. Eleven students drew pictures with + and - signs inside the nails. Five more students drew nail pictures using N and S symbols (one student drew both.) Some diagrams showed approximately the same number of symbols in the rubbed nail as in the unrubbed nail, while others showed less symbols in the rubbed nail! In one case, a student drew one big + sign and one - sign in the two ends of the nail, possibly as if representing a condition of the nail rather than a collection of charges.

Students drew different arrangements of the separated charges. Some drew a gap between + and - ends in the unrubbed nail, and others drew + and - regions meeting in the middle of the nail. Only one student drew a separation picture showing + and - signs mixing together in the middle part of the nail. In all of the diagrams, the 'unmagnetized' nail contained a mixture of both kinds of charges.

Altogether, about half of the students in the class drew some kind of charge separation diagram.

Two kinds of charge appear

This model is based on the assumption that an unrubbed nail has no charge. This explains why an unrubbed nail doesn't attract anything. According to the model, rubbing the nail causes the two ends of the nail to "get" opposite charge, normally + and -. Either these are collections of tiny positive and negative charges, or they are simply 'charged'. Some students may have thought that the charges come from the magnet, while others may not have specified where the charge comes from. This model does not do a good job of explaining how a magnet can attract an unmagnetized object.

The separation of charges models, and the two kinds of charge appear models, both represent magnetized nails the same way. Altogether, more than two thirds of the class drew one or the other of these models on their papers.

Other

One student drew a diagram with positive charges in the nail initially, and negative charges appeared when the nail became magnetized. It is not clear what this student was thinking, and in an interview she did not make it any clearer:

Anne Yeah, at first I put - I had all the positive charges - I'm not sure why. I might have been doing it in a hurry. It was before rubbing it was all positive charges. I thought it was all one ion.

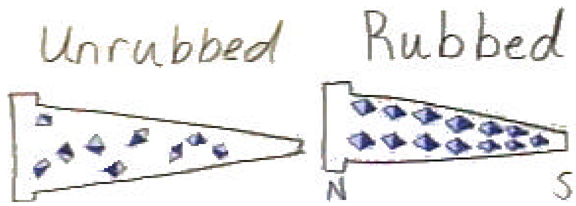
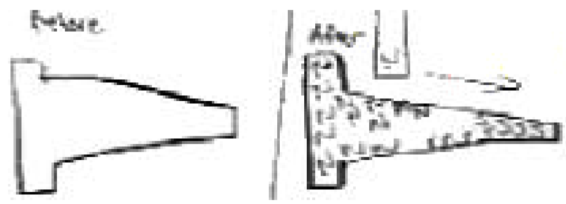
And then once you rubbed it - I don't know what I was thinking, cause once they explained it this made so much more sense to me I don't know why I would have said this. I don't know what I was doing. But when I did a second one I had them mixed up.

The first "this" that Anne referred to was her group's separation model. The second "this" was her own diagram. Anne's diagram was not categorized.

Group diagrams in the Cycle II Elicitation

Groups discussed their individual diagrams and drew their best ideas, again on whiteboards. They then presented their group models to the rest of the class. These models are represented in the table on the next page.

Table 4-4: Group model diagrams in the Elicitation discussion

Type of model	Group Diagrams
1: Alignment of two-ended units, either N and S or + and -. 2 groups	
2: Separation of charges 7 groups	
3: Two kinds of charge appear or charges are created 2 groups	

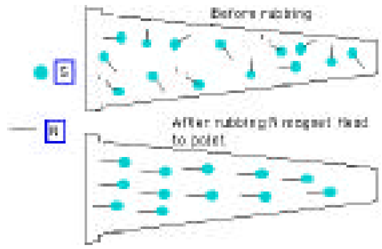
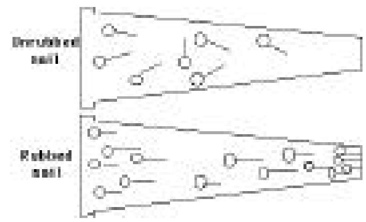
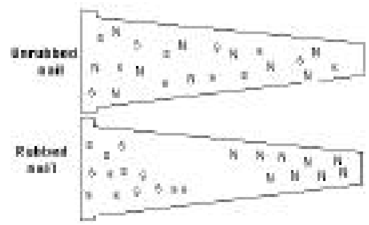
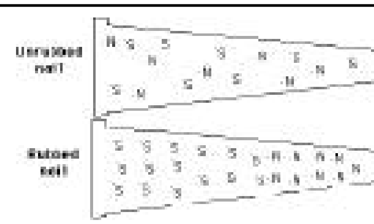
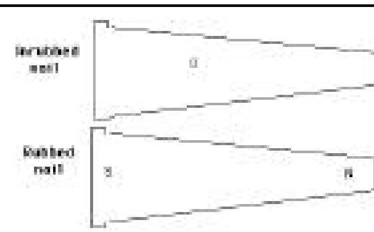
Note: one group proposed two different models

Development Activity II-D1

Groups were asked to draw diagrams of nail models a number of times during Cycle II. The first time was immediately after the Elicitation discussion, described above. There were few surprises at the beginning of the documents. All the groups simply drew diagrams on their computers that were similar to what they had drawn for the Elicitation presentations.

The first Development Activity in Cycle II was called "Breaking the Nail." It was intended to challenge the separation model by having groups magnetize a nail and break it, and then investigate its behavior. The instructor expected that each nail piece would behave like a regular magnetized nail. This didn't happen for all the groups. However, most of the groups changed their models as a result of working through this document. The table on the next page shows the models drawn by groups both before and after working through the first Development document. The columns 'Begin' and 'End' show the number of groups that drew each type of diagram at the beginning and end of the Development Activity.

Table 4-5: Model diagrams drawn for Activity II-D1

Type of model	Begin	End	Typical Diagram
1: Alignment of two-ended units, either N and S, or + and -.	1	5	
1&2: Alignment - separation hybrid using + and - charges	1	1	
2a: Normal separation of charges	7	0	
2b: Modified separation of charges	0	3	
3: Two kinds of charge appear or charges are created	1	1	

The two groups that began Activity II-D1 with alignment models did not change them. Carl's group drew a hybrid of a separation model and an alignment model, which had a concentration of two ended objects at the ends of the nail. Janet's group also did not change their alignment model.

Apparently, breaking a nail was an important influence on students' thinking. Seven groups changed their models as a result of this Activity. No groups kept their original separation models at the end of the day. Four groups changed to alignment models, but three others modified their separation models. These are described below:

Model changes before doing the experiment

Some groups anticipated problems with their separation models before they even broke the nail. Perhaps a few students had heard that a broken magnet is still two-ended. Whatever their reasons, at least two of the four groups who switched to Alignment models did so after making predictions and before breaking a magnetized nail. One group wrote: "We thought that the broken nail could not have only one pole so we went against our model. We figure that the nail contains particles and that each particle has a north and south pole in it." Another group wrote: "We changed our model (see the new page 4). We did this even before doing the experiment because our opinions changed after thinking more on our original model."

A new category: Modified separation models

Groups tried different modifications to allow their separation models to explain the behavior of the nail pieces. Two groups drew charges in the middle of the magnetized nail where before they had left it blank. The idea was that if both + and - charges were present in the middle of the nail, perhaps when the nail was broken these charges would somehow rearrange to make each nail piece two ended again.

However, four or five groups did not find that both nail pieces were two ended. Marge, Donna, and Anne, for example, found that both ends of the head piece attracted the point of a second magnetized nail. Unbeknownst to the students or the instructor, the nail piece was somehow changed magnetically when it was broken, probably by an inadvertently magnetized pair of pliers. The group didn't know that this behavior was not to be expected, so they explained it by extending the S symbols to near the point of the nail, as shown in the table above. This modification explained their results satisfactorily. The instructor had not anticipated this experimental result.

No change doesn't mean no thinking.

One group kept its "two charges appear" model. This does not necessarily imply that they felt that it was the best model, or that they didn't question it. This group may have sensed problems with its model but may not have been sure how to change it. Later on, the group did change its model.

On Day 7, groups worked on Activity II-D2. This was intended to help groups gather more evidence that could support alignment models, but groups were not asked to redraw their models on this day. The next formal group work happened on Day 8, and involved Activity II-D3.

Development Activity II-D3

In the final development document for the cycle, groups worked with a test tube half filled with iron filings. They again were asked to draw their best model diagrams at the beginning and end of the document. Nine groups drew some kind of alignment model at the beginning of the document, which indicates that three groups had made changes. One group drew a modified separation model. The following table summarizes the groups' standings.

Table 4- 6: Model types beginning and ending II-D3

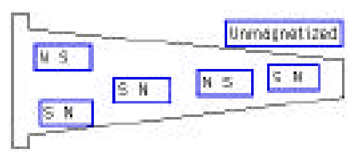
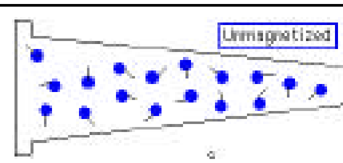
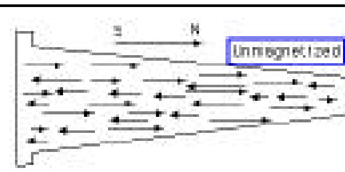
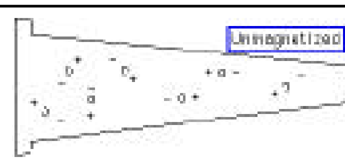
Type	Begin	End
1a: Alignment of N and S	8	9
1b: Alignment of + and -	1	1
2b: Modified separation of N and S	1	0

Notice that most groups used N and S in their alignment models, instead of + and -. As will be seen in Chapter 5, this does not mean that the groups thought that there were things other than electric charges in the magnets. Instead, their use of N and S may have indicated uncertainty about the identity of the particles, and was thus related to norms about evidence or models.

Group Candidate Ideas

For their Candidate Ideas, all the groups drew diagrams consistent with the Alignment model category. The major differences in diagrams were in three kinds of details. Most of the groups indicated that the tiny units had north and south ends, while one group explicitly described + and - charges on opposite sides of particles. Groups used a variety of representational schemes to illustrate their models. Four used text to create rectangles with N and S ends, one group used text to create + and - objects, three groups drew lollipop shapes (like Carl's original model), and two groups drew arrows. There were differences in representing the unrubbed nail. Three groups drew tiny magnets that pointed either S-N or N-S along the nail's long axis, (restricted to one dimension) while seven groups drew objects that pointed in a variety of directions in a plane. The characteristic diagrams are shown below.

Table 4- 7: Variations in Candidate Alignment Models

Model Description	Diagram of unmagnetized
NS rectangles, one dimensional	
Lollipops, two dimensional	
Arrows, one dimensional	
Charges, two dimensional	

Because of the relative uniformity of the groups' candidate models, the instructor did not have to help groups come to agreement in the Consensus Discussion on Day 9. The final class model diagram presented by the instructor was very similar to the above two-dimensional alignment diagrams.

PROGRESSION OF GROUP MODELS OVER TIME

This section contains answers to my research question "What was the time progression of groups' model types in this classroom?" A number of diagrams and explanations in this section represent answers to this question. Figure 4-2 illustrates the number of groups using each major model type during the first eight days of the course.

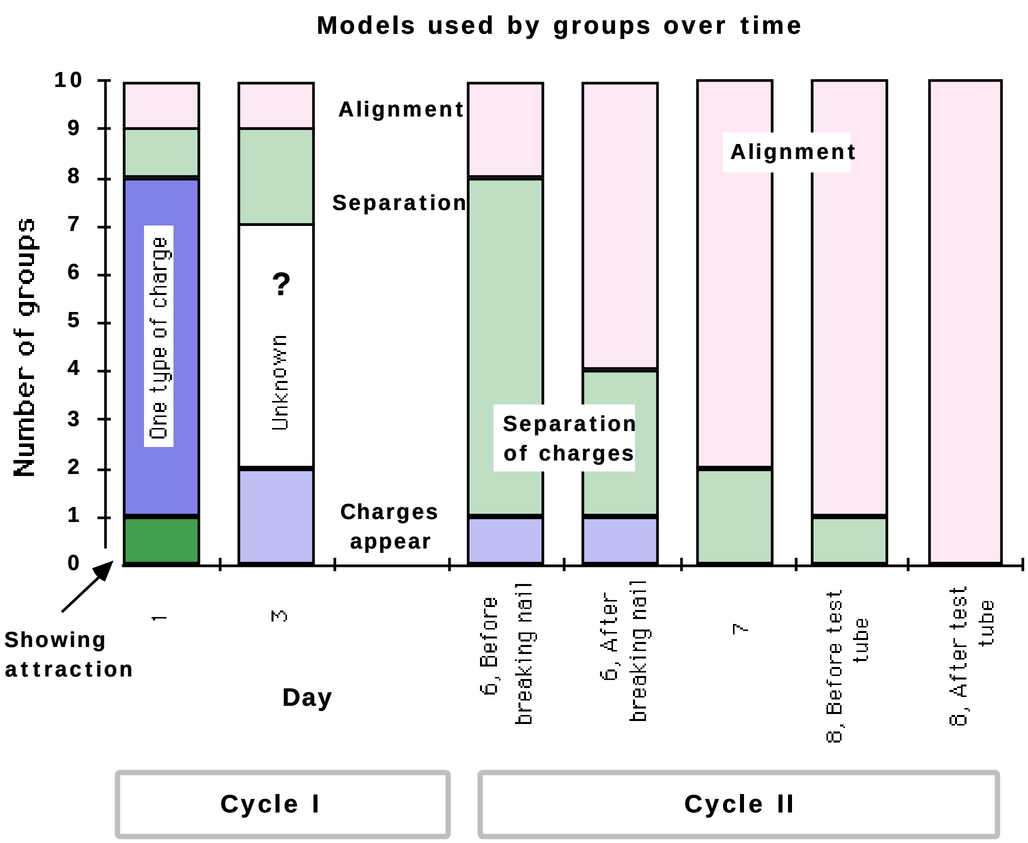


Figure 4-2: Numbers of groups using major model types over time

This graph shows data that was available from group work in the classroom. A gap is left to suggest that, while things happened on Days 4 and 5, there is not sufficient data to tabulate groups' ideas for those days. Also, on Day 3, five groups did not represent any models. This is represented by a blank column portion. Even with this limited information, it is possible to tell that ideas were changing during the first cycle. For instance, five groups used ideas involving "one type of charge" to explain refrigerator magnets on the first day, and no groups suggested this kind of model on Day 3. This may be partly because the groups encountered two-ended nail behavior on Day 3. After Day 3, no groups described one-type-of-charge models for nails. Instead they began talking and writing about two kinds of charges in a nail. Separation models were very popular in the Elicitation discussion on Day 6. Just before the discussion, over two thirds of the individuals in the class drew nail diagrams representing opposite charges at the two ends of a magnetized nail.

On Days 6 and 8 the students did "critical experiments" - they broke a nail on Day 6, and they magnetized a test tube containing iron filings on Day 8. The instructor anticipated that groups would make changes, and so the documents asked groups to describe their models before and after these experiments. Two bars are drawn for these days. After encountering the question of breaking a magnetized nail, groups began dropping separation models in favor of alignment models. At the end of Cycle II, every group suggested some kind of alignment model.

The above data and histogram suggest a general pattern for development of alignment models in this class:

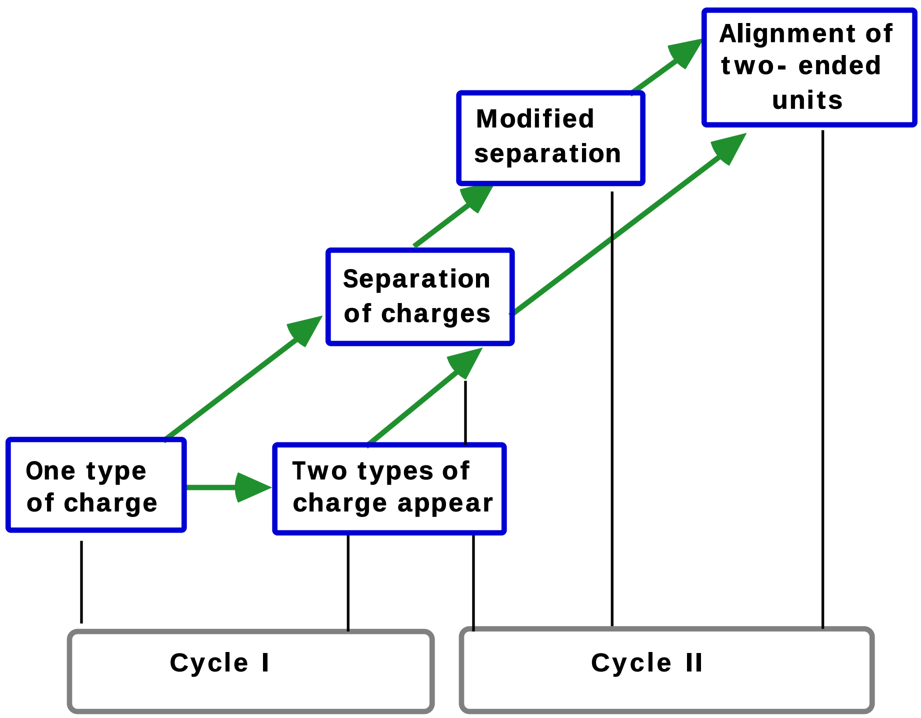


Figure 4-3: Pattern of progressions of group's models

Each model shown is more sophisticated, and has more explanatory power, than those below it. The arrows represent likely changes in models. Based on data from this class, groups did not move directly from early "one type of charge" models to alignment models, even though one group had proposed an alignment model on Day 1. Instead, groups seemed to adopt models that allowed them to explain new phenomena with relatively small changes in their thinking. Thus, the groups went through a progression of models on their way to final alignment models.

Please note that this is not a prescription for students' models in any other classroom. There are probably many ways that groups of students can construct alignment

- like models of magnetic materials. In this classroom, however, separation of charges seemed to serve as an "intermediate model", as its use did not stop groups from eventually developing or adopting alignment models.

The actual "paths" taken by groups are shown below. Each bold horizontal line represents the model used by one group. Here, the lack of conclusive model data between days 1 and 6 and shifts from one model to another are indicated by thinner straight lines. Many groups probably preferred the separation model before the second Elicitation discussion. If graphed, this would appear as a bundle of horizontal lines from around Day 4 to Day 6 at the Separation level.

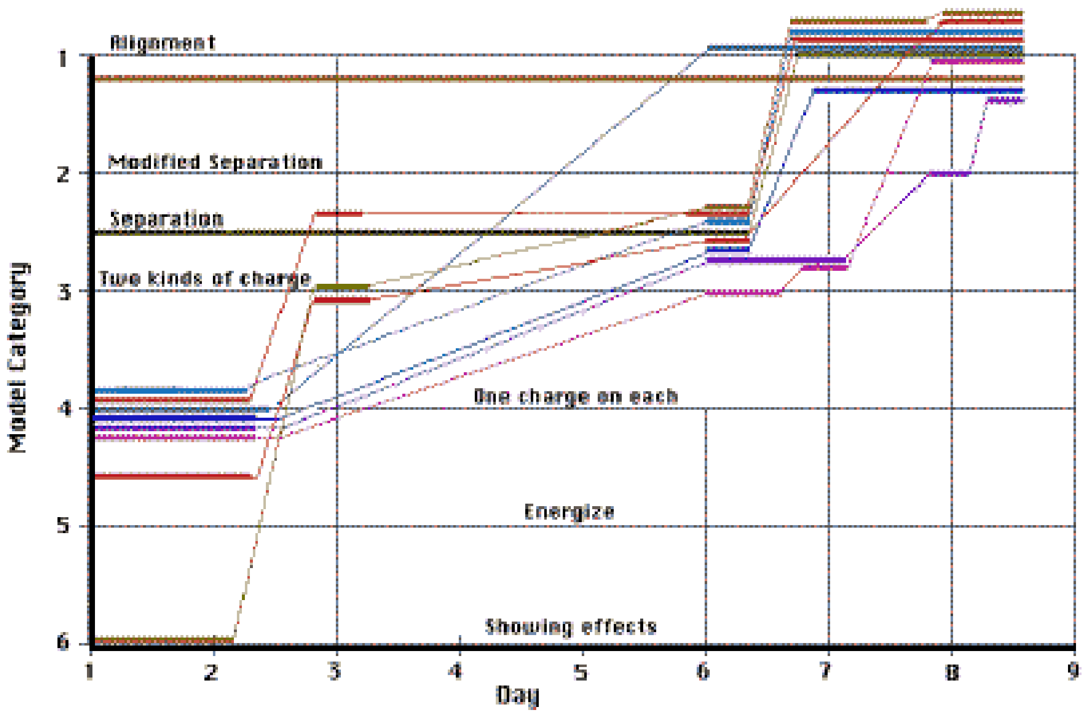


Figure 4-4: Models used by ten groups in the course

The summaries just offered above might suggest that each group had a single idea at any given time, and that once they made a change to a new model, their understanding was more or less stable at that new level. However, what groups produced as their group model may not have represented the thinking of all the members of the group. Also, when a group adopted a new model, some group members didn't immediately use it appropriately. For example, Megan drew the following diagrams for a nail on Day 7, after her group had produced an alignment model diagram. She seemed to be using the idea of alignment in a different way than most other groups did. The little "sn" units did not rotate but always pointed in the same direction. When the nail was magnetized they moved from random positions into rectangular arrays.

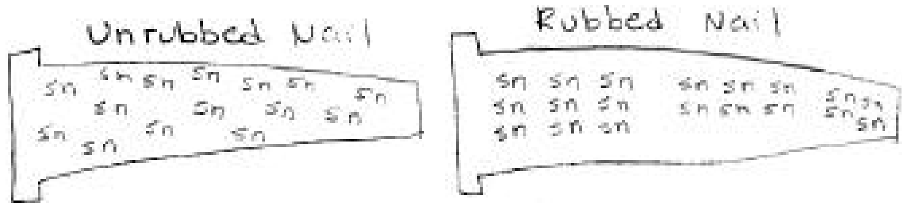


Figure 4-5: Megan's Unrubbed and Rubbed model diagrams

The value of the alignment model for most groups was that it could explain the behavior of broken nail pieces. The picture below shows how Megan drew a broken nail (on the same sheet of paper as the diagram above.) It appears that she had not yet completely made sense of *how* the alignment model could explain the broken nail pieces. Instead, she modified the separation model for this part of her diagram.

Figure 4-6: Megan's broken nail pieces

These pictures are not offered to point out problems with the groups' models, nor to spotlight an individual student's difficulties. (In fact, Megan later managed to use the class alignment model satisfactorily.) The point here is that focusing on models drawn by groups doesn't tell the whole story of conceptual development in the class. Sometimes students understood parts of what they talked about and didn't understand other parts. Their understanding may have changed more gradually than the model category lists above can capture. The model progressions described in this chapter are generalized, and don't tell the whole story.

SUMMARY OF MODEL DEVELOPMENTS

The above analysis shows that all groups in the course developed alignment models of magnetic materials. The analysis does not show the depth of the students' understanding, which appeared to be considerable in some but not all cases, and it does not show the breadth of students' understanding and experience with magnetic phenomena. Observations in the course suggest that students understood more than simply the class model for magnetism. This may be apparent in some of the data to be presented in Chapter 5.

Two interesting phenomena in the class that are related to the development of models were the gradual reduction in variation in models from the beginning of the unit to the end, and an apparent model development pathway. These are discussed below.

Model Convergence

Students' models varied most at the beginning of the unit. Their diagrams ranged from alignment models to pictures showing no causal mechanisms at all. Four major model categories were represented in students' diagrams, and only one of those categories "survived" at the end of the second cycle. It appeared that the students began with a variety of different ideas, but as the unit progressed, this variety decreased until all of the groups proposed alignment models. This phenomenon may not have a single cause. Did regularities in the physical world determine which model would make the most sense to students? Did the guidance provided by the Activity documents and the instructor influence students' thinking? Did the students come together because they talked to each other so much and perhaps desired a common way to think about and explain the phenomena they saw? The analyses in Chapter 5 suggests that all three types of influences were important.

One way to characterize the degree of variation in students' thinking is to consider the words they used to describe charges. Early in the unit, students had not sorted out a lot of issues, and their language reflected uncertainty, and a number of ways to address relationships. Donna wanted a general term to describe those things that caused attraction effects. She chose to use the word "forces" when talking about charges. This usage suggests that Donna had not yet distinguished between causal agents (charges) and their effects (forces), but it may also simply be an unfortunate choice of intentionally non-specific language.

Similarly, another group said that magnets "give off" charge. They perhaps were referring to attraction at a distance. Their description of charge as something that magnets "give off", while inconsistent with the target ideas, represented a way of talking about how magnets attract things.

These examples represent ways that students attempted to use language to express ideas that were new to them. In many cases, they were groping for words, and when groups came up with something that they felt expressed an idea, they used the terms without realizing that their ways of speaking would make some physicists cringe. Then, during the development of ideas, and as a result of whole class and small group discussions, groups began using language that was more and more uniform, and which represented ideas that more and more students took as shared. They began talking about charges, or poles, in magnets, and about how these charges attracted or repelled other things. In small groups as well as in the whole class, the students and teacher gradually established common ways of talking, and shared sense of assumptions and background knowledge. This process is the development of Garfinkel's "reciprocity of perspectives", this time for magnetism. This term is described in Chapter 2 and in Heritage (1984).

Data from this class suggests that having a reciprocity of perspectives is part of the development of a scientific community, and of the development of useful ideas within a community. In a real sense, students in this class were members of a scientific community, and their struggles to use words that expressed their thinking, that other students could accept, were important parts of model development processes in the class.

Model pathways

The analysis in this chapter shows that most groups did not develop or accept alignment models right away. Instead, most groups began with a variety of ideas before considering separation models for awhile. This suggests that a separation model, while problematic when it appears at the end of an instructional sequence in magnetism, may be pedagogically useful in some instructional sequences. The non-immediate development of alignment models also begs the question of how students change their thinking. Do changes happen gradually, or all at once? That is, are students' changes in thinking similar to quantum mechanical state changes that happen nearly instantaneously, or are students changes more gradual, stepwise developments? This issue is discussed below, and again in Chapter 6.

The idea of learning pathways was introduced by Driver and others (Scott, Asoko, & Driver, 1992; Scott, 1992; Niedderer, 1995). This idea assumes that individual students develop conceptual understandings gradually, so their thinking changes in a stepwise fashion. They start with an idea, and develop different ideas as a result of engaging with ideas in instruction. In some cases, students may develop ideas that they will not keep, but which nevertheless appear to contribute to the process of developing the appropriate conceptual understanding later. Such ideas, when expressed as models, might be called "intermediate models."

The single most prevalent intermediate model used in this class was that involving separation of charges. This model seems to have been used by many of the students in studies reported by Maloney (1985) in Nebraska, by Kraus (1995) at the University of Washington, and by Borges and Gilbert (1998) in Belo Horizonte, Brazil. This suggests two things. First, the separation model is apparently quite common, as separate research done in different kinds of courses, in different areas of the US as well as in Brazil, has all found many students thinking in terms of opposite charges at opposite ends of magnets. While some aspects of learning are thought to be unique to the particular course in which they arise, it seems clear that the separation model represents a way that very many students tend to make sense of magnetism. It is interesting to note that Wilcke and Brugmans both proposed separation models of magnetism in the late 18th century, as well. Two centuries ago, some of the brightest scientists had similar ideas. Modern physics students have some distinguished, but very old, company.

A second idea inspired by the prevalence of separation-like thinking on the part of many students in diverse post-instructional circumstances is that separation is not the most naive model, but actually represents some learning. The students in NS412A only espoused separation models after discovering a number of properties of magnetized nails, notably that two opposite nail ends have opposite effects. The other research also reported on students' thinking *after* instruction in static electricity and magnetism. Thus, it is possible that the students in the other studies also developed ideas of charge separation as a *result* of instruction (despite the earnest attempts of the instructors, in some cases.)

Thus, it seems that separation models represent an intermediate position or a "stepping stone" in a learning pathway. How readily students adopt separation models, and whether or how quickly they move beyond them probably depends on the details of instruction. If one assumes that all students traverse learning pathways, then the more traditional instruction used in the other courses which Maloney, Kraus, and Borges & Gilbert reported on apparently did not provide sufficient cause and/or opportunities for students to move beyond separation models.