CHAPTER 2

THEORETICAL PERSPECTIVE, AND REVIEW OF LITERATURE

OVERVIEW

This dissertation is an attempt to understand students' development and refinement of thinking about (ferro-)magnetic materials such as nails. To provide a perspective on ways of thinking about ferromagnetism, I will first discuss some historical models of magnetism up to the invention of the magnetic domain model about 100 years ago. There is some overlap in the concepts that historical scientists constructed and those that modern day students tend to construct about magnetic materials. However, while models proposed by modern physics students do have some similarities to historically proposed models, there are significant differences. The recapitulation of historical ideas by students is not a reenactment compressed in time, but has significant differences which may be due to students' different backgrounds and social roles. Thus while the history of science can provide insights into student thinking, it probably is not sufficient for predicting student thinking. However, there are some connections that can be made between the historical development of ideas of magnetism and students' understandings of magnetism ideas. These will be explored in this chapter and again in Chapter 4.

The section on the history of magnetic ideas will be followed by a second section on what is already known about students' ideas of magnetic materials. This section will provide a background for my first research question(s): "What types of models for magnetic materials did groups and individuals present in the class, and what was the time progression of groups' model types in this classroom? These questions are listed at the end of Chapter 1.

The third major section of this chapter considers social aspects of science learning. Sociocultural cognitive perspectives see the process of learning as developing ways to participate effectively in activity. My research questions are: "What norms relevant to learning activity of the two groups can be found?" "What types of activities did groups engage in when they shared the task of constructing group representations?" and "How do these things relate to students' learning?" To provide a foundation for these research questions, research and theories on inscriptions in science learning and on classroom norms will be explored in this section.

HISTORICAL MODELS OF MAGNETIC MATERIALS

Ideas about magnetism developed over a long period of time, with a concept similar to the currently accepted magnetic domains model emerging about a hundred years ago. The purpose of this section is to identify points of comparison between scientific ideas that were developed historically and scientific ideas that students tend to develop in a classroom. This section tells a story about ideas and the culture of scientific inquiry which also changed when models of magnetism changed. The two parts of the story are best told together.

The first portions of this section describe in chronological order the progression of ideas that took place primarily among European magnetic researchers. A later portion discusses similarities and differences of the historical story with the ways that students appeared to think about magnetism in the course that is the topic of this work.

Early Chinese discoveries

Early discoveries of magnetic effects were all based on the discovery and investigation of pieces of the mineral magnetite that attracted iron. Europeans called these "lodestones" or "loadstones." Joseph Needham (1954) has shown that the Chinese civilization probably developed a basic magnetic technology earlier than any other group of people. They discovered around the first century AD that a lodestone, when free to pivot, would align itself in a north-south direction. Sometime between the first and sixth centuries the Chinese discovered that a piece of iron could be given the same directional properties by rubbing a lodestone along its length. Magnetic compasses made from iron needles were probably used in China in the 7th century. Needham says that by the 9th century, the Chinese had discovered Earth's magnetic declination, and the magnetic attraction and repulsion of the two poles of magnets.

Gilbert's thinking

In Europe in the 1500's, natural philosophers were aware of electric and magnetic effects. They knew that amber, when rubbed, would attract small bits of matter. Magnetic compasses were in use, and artificial magnets were available in increasing numbers. Some people had pieces of lodestone. Since the attracting effects of amber and lodestone were similar, it is probable that some people thought they were related. One important early step was to identify operational differences between amber and lodestone effects. Cardano in 1550 described 5 differences between magnetic effects and amber effects (Spurgin, 1990). Three of these were that the two effects involve different materials, that magnets always have two distinct poles while amber does not, and that the two different effects are strengthened by different means.

By the end of the 1500s, a number of writers had published accounts of experiments with magnets and beliefs about their causes and effects. Some of these accounts were more reliable than others. By modern standards of science, many of them would be dismissed as laden with superstition. Perhaps to cut through the mounting confusion of reports, William Gilbert published in 1600 his now-famous discussion of magnetism *De Magnete* (Gilbert, 1600). In it he collected together seventeen years of experimental observations involving lodestones and iron. His reported observations were more reliable and attempted to dispel a lot of "old wives' tales" (to use Gilbert's words).

Gilbert identified the two poles of a magnet as "austral" and "boreal" to separate magnetic terminology from geographic terminology. He insisted that the end of a magnet which points north is the "austral" end, because opposites attract. Since the north-pointing end of a magnet is attracted to the North, it must have a southerly, or austral characteristic. The opposite convention is accepted today, as the "north" pole of a magnet is now defined to be that which will point north (which causes some confusion!) Gilbert claimed also that the Earth contained a magnet, or was itself a lodestone. This magnet had its boreal pole in the North.

Gilbert did not detail a mechanism that, by today's standards, could explain how a lodestone works, or how iron must be structured. He described lodestone's action using terms like "harmony" and "discord." Two lodestones which were arranged with one austral end near another's boreal end "harmonized" and created a "pristine continuity." When the two similar ends were placed together, he explained the repulsion this way: "... hence, when all is not rightly ordered according to nature, comes the flight of one from the other's perverse position and from the discord, for nature does not allow of an unjust and inequitable peace, or compromise: but wages war and exerts force to make bodies acquiesce well and justly."

Gilbert identified the region within which objects would be attracted to a lodestone as the "orb of virtue." The region near the lodestone was endowed with some special property due to the lodestone itself, and iron objects within that region were attracted due to this "virtue."

Gilbert did note directional behavior of magnets. He broke a magnet and he found that each resulting piece behaved like a whole magnet, that is, each piece had austral and boreal poles. This was demonstrated in a diagram shown below. Ends C and D will attract, or in Gilbert's language, they "harmonize and combine excellently."

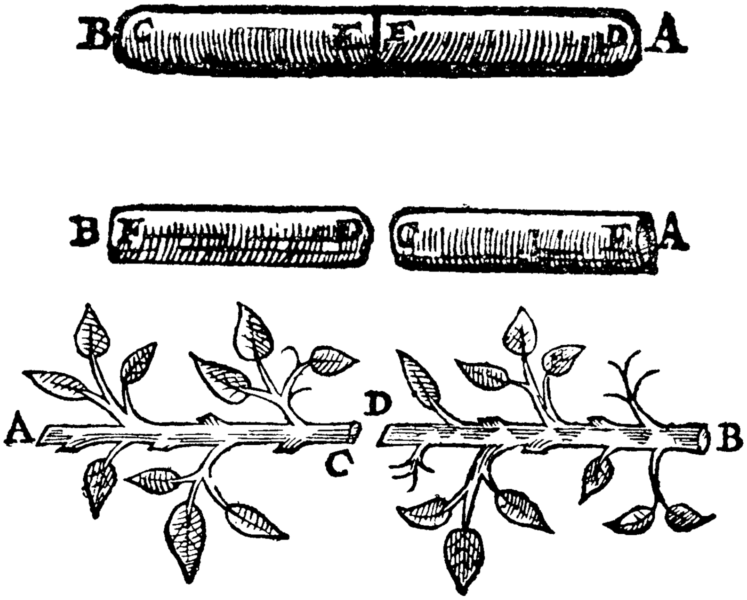


Figure 2-1: Gilbert's diagrams of broken magnet behavior, and his tree grafting analogy.

Gilbert made an analogy between broken magnets and grafting tree branches. In the lower picture, if C is grafted to D, the branch will grow, or if A is grafted to B the branches will grow; but if A is grafted to D the branches will not grow but will die "on account of the inverted and inharmonious arrangement." It seems that what others would later explain by particular mechanisms, Gilbert (and many of his contemporaries) explained in terms of "harmony" and "desire." Still, there is a directionality of a tree branch that is implied by analogy in the magnet as well. It is clear that Gilbert thought that magnets have a direction associated with them.

De Magnete played an important role in "debunking" many unwarranted beliefs about magnetism, and it provided a set of reliable descriptions of magnetic phenomena along with a language which helped to organize them. Gilbert's work also provided an influential example of a new standard for philosophical inquiry, in which reasoning alone was not the primary route to truth. Instead, reasoning had to be coupled with careful and systematic observation. This contributed to the development of modern scientific methods.

The Cartesian aether model

While Gilbert's work may have clarified a set of observations of magnetic behavior, he (perhaps intentionally) did not formulate a mechanism by which the magnet could influence pieces of iron. Then Descartes published *Principles of Philosophy* in 1644 describing his physics, which included a detailed model of magnetism (Descartes, 1644). This model was integrated with Descartes' mechanistic views of the world, in which every phenomenon can be explained by postulating motions and effects of tiny particles of different sizes and shape, which are not directly sensible to humans, but whose effects are noticeable. These constituted "subtle fluids" of two main types, which filled all space in the universe, and were always in motion. He called these "aether." To explain magnetism, Descartes proposed that streams of a third kind of subtle aethereal matter (tiny particles with spiral grooves in them) circulated through magnets, along the magnetic axis through rifled channels that were specially adapted to pass them. This "circulation" model may have been inspired by the appearance of patterns made by iron filings, which, according to Descartes, line up along the paths of circulation.

According to Descartes or later thinkers who used his model, the aether streams in magnets only went in one direction because the channels they passed through had special features - they had little fibers or filaments attached to their inside walls that acted like one-way valves. These tiny little teeth all pointed down the length of the channels. The aether particles, always in motion, could only go one way down the channels. If one went in the opposite direction, it would become entangled in the fibers and stop. Then more particles moving along the magnet's preferred direction would push the stuck particle out in "the right direction."

Attraction between two different magnets could then be explained by a stream of aether particles leaving or entering a magnet. If this stream encountered another magnet with its channels oriented the same way, the streams would zoom right through both of the objects, one after the other. Because the aether particles had well defined paths and were not randomly impinging on the two lodestones, the ambient aether pressure would be reduced in the region between the two objects, and the two objects would be pushed together.

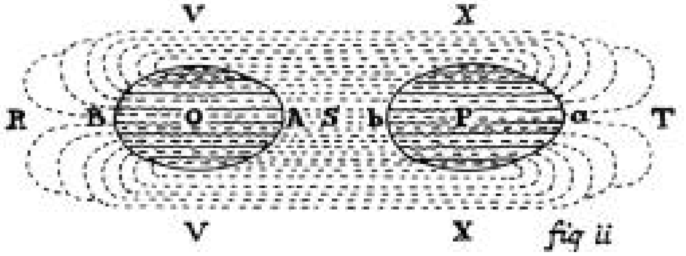


Figure 2-2: Descartes' diagram showing the streams of aethereal matter passing through two lodestones and causing a mutual attraction.

The magnetic repulsion of two boreal ends of a magnet can be explained by two streams of aether, each of which come out of the boreal ends and run into each other in the space between the two poles. The aether has to have some place to go, and it also needs space to flow in, so the magnets can't easily be brought together. The feeling that one gets when pushing two magnets together is certainly suggestive of something invisible "being in the way." Similarly, if two magnets are placed with the aether - streams - entering ends together, there has to be some space for the aether streams to enter, so the magnets cannot easily be brought together.

The alignment of a compass needle can be explained by assuming that the earth is also a magnet, or has a magnet in it (an idea suggested by Gilbert) so that there are also streams of aether coming out of and entering it. There is a pressure involved with these streams of matter. Pressure of these aether streams on the insides of the channels of the compass needle push the needle into alignment with the stream coming out of the earth.

Descartes reasoned that an unmagnetized piece of iron does not show magnetic behavior because the little pores are pointing in random directions throughout the iron, thus there is no preferred direction for aether particles to move inside. They move in and out a little bit, but they mostly get jammed up because they have no clear path. When a magnet is brought near a piece of iron, the aether particles streaming out of it immediately push the channels and their associated fibers into alignment so that, thereafter, the iron is a magnet also. In soft iron, which cannot be strongly and permanently magnetized, the channels are easily reoriented, and they quickly return to a state of randomized positions. In hardened steel, however, once the channels and fibers are aligned, they tend to stay that way for a longer time.

Descartes' model was very influential throughout the following century. In most theoretical treatises on magnetism written during this time, Descartes' basic ideas were employed, with some variations or development of details. While technical improvements were made in the models, the basic idea of circulating aether remained the most compelling explanation. For instance, in 1742 the Paris Academy of Sciences announced a competition for the best explanation of magnetic effects. Three prizes were finally awarded in 1746, to Leonhard Euler, Etienne Du Tour, and Daniel & Jean Bernoulli. All three of these entrants had used Descartes' model as their starting points. Euler's major innovation was to propose that the attraction and repulsion of two magnets was due to pressure differences in the aether itself, rather than in the air surrounding the magnets. But he remained a staunch supporter, as did the others, of the circulating aether theory.

Descartes' natural philosophy organized a lot of phenomena under a single theoretical system. Descartes used a lot of careful reasoning, and he referred often to experimental results. But he had to postulate a complex behavior of completely unobservable objects or materials as an underlying mechanism. There seemed no obvious way that one could prove or disprove Descartes' theories. This bothered some people, particularly Newton.

Newton's philosophy of science

In the late 1600's and the early 1700's, Isaac Newton promoted a different philosophy of science, which took a different epistemological stance from that of Descartes. His philosophy has been summed up in his statement "Hypotheses non fingo" or, "I frame no hypotheses" (Tricker, 1965). Newton claimed that he did not wish to formulate physical models, rather he only wanted to describe relationships between measured quantities. Perhaps he was thinking that theoretical models were invented by people, and as such they might bear little relation to the actual nature of the world. To more reliably access the "truth" about the universe, Newton may have felt that mathematical relationships provide idealized descriptions of relationships in the real world. Newton's law of universal gravitation is an example. It can be used to explain (or at least calculate) the orbit of the moon about the Earth, but it does not propose a mechanism by which massive objects attract each other.

One could argue that in formulating his mechanics, much of what Newton did was modeling, as he practically had to re-define the terms "force" and "mass," but Newton tried to distance himself from those who proposed "occult" (hidden) causes, such as Descartes and his aether model. Newton's program for science became increasingly popular and was applied to fields beyond motion.

The problem with advancing the Newtonian approach in magnetism was that the spatial variation of the magnetic force is complex, and is often confounded with material effects. People tried measuring magnetic forces and varying separations, but they had problems fitting a simple mathematical function to their force - versus - distance data. Researchers often measured the attraction of magnets for unmagnetized pieces of iron, which has non-linear magnetization response. Some researchers may not have been careful about differences in the orientation of the magnet. Another problem involved finding the appropriate place from which to measure the distance between magnetic objects. Since a magnet has two poles, should one measure the distance between the nearest pole and the piece of iron? Or between the centers of the two objects? Attempts to fit data to simple power law curves that made the location of the center of the force a free parameter sometimes yielded centers that were outside the magnet! Also, measurements would somehow have to take into account the presence of two poles in each magnet rather than one. Because of these difficulties it is not hard to see why some researchers may have preferred Descartes' qualitative approach over the Newtonian quantitative approach in magnetism.

But Descartes' theory was not without its detractors. In 1725, Pieter van Musschenbroek suggested publicly that the circulating aether theory was unsupported by available evidence. van Musschenbroek was a very influential magnetic researcher in his time, and he performed experiments whose results he emphatically interpreted as not supporting the circulating aether theory. In one experiment, van Musschenbroek measure the force between two magnets, and then he put a piece of glass in between them. If the glass impeded the circulation at all, the force should have decreased somewhat, just like the amount of light passing through a piece of glass is reduced by some amount. van Musschenbroek found no change in the force at all. He felt that this provided a definite evidence against the Cartesian magnetic model. However, he did not offer another theory, so his complaints about the circulating aether theory did not on their own convince others to abandon it.

From the perspective of Kuhn's theory of scientific change (Kuhn, 1970) we could say that the entrants in the Paris Academy of Science's 1742 magnetism competition were pursuing agendas of "normal science" within a particular research paradigm based on

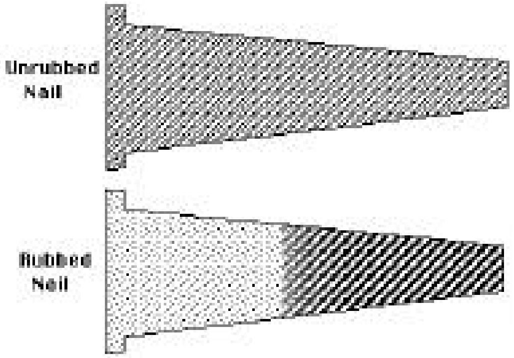
Descartes' model. On the other hand, van Musschenbroek's complaints represent challenges to this dominant paradigm. Because he did not propose an alternate theory (and possibly because evidence against the circulating aether models had not mounted sufficiently) most magnetic researchers did not change their thinking until near the end of the century.

Aepinus's Contribution: Distant action by a magnetic fluid

van Musschenbroek's complaints, however, may have influenced Franz Aepinus. Aepinus proposed in 1756 (Home, 1979) that magnetism involved entities and processes similar to Franklin's theory of electricity. He rejected the circulating aether theory, and suggested instead that magnetic objects have a fluid that is analogous to, but not the same as, Franklin's electric fluid. Benjamin Franklin had some time earlier proposed a one-fluid model for electricity, in which materials that have either excess (+) or deficit (-) are electrically "charged." The electrical fluid exerts attractive and repulsive forces at a distance similar to the attractions that Newton had earlier postulated for all matter. In Franklin's model, two objects which have an excess of electric fluid will repel each other, and similarly, two objects which have a deficit will repel. However, if one object has an excess and the other a deficit, the two will attract. Franklin used the terminology "positive" and "negative" to denote imbalances in quantity of electric fluid relative to a "natural amount," rather than to a category of charge entities as the terms are used today.

Franklin's model, in modified form, is still used today. We say that materials contain protons that are more or less fixed in place, and electrons that sometimes can move about. Materials that have an excess of electrons (more electrons than protons, that is) should be called "positive" in a one-fluid model, while those that have less electrons than protons should be called "negative." When a two-fluid model replaced Franklin's one-fluid model, the positive/ negative terminology was already in place, and it was used to describe two kinds of charges. Unfortunately, Franklin couldn't really tell which electrostatically charged materials actually had deficit of electric fluid, and which had an excess. Later work showed that materials which Franklin had thought developed a deficit of the electric fluid when rubbed actually collected an excess of electrons. But Franklin had already dubbed this condition "negative" (meaning a deficit of electric fluid) so rather than reversing the conditions of many electrified objects, electrons were said to represent negative charge.

Aepinus thought that Franklin's model for electricity could, with modifications, explain magnetic phenomena. Aepinus was particularly inspired by his observations of the mineral tourmaline, a single crystal of which produces an electric dipole at its ends when it is heated or cooled. Aepinus noted that this behavior was very much like that of magnets, and so he refined Franklin's significantly, and constructed an analogous theory for magnetism. In this theory, iron contains a "magnetic fluid." According to Aepinus' theory, there was a kind of magnetic fluid which moved around through the air (similar to Descartes' aether) and which stuck in iron and lodestones. Aepinus said that normal unmagnetized iron contained a "natural" amount of this magnetic fluid - not too much, not too little. If a piece of iron were to contain more than its natural amount, it would repel other pieces of iron that had a similar excess, and it would attract pieces of iron with a deficit. But this rarely happened. Instead, magnets were normally formed by displacing some of the magnetic fluid from one end of a piece of iron to the other. The magnetic fluid would get "stuck" in the end of the iron, and not easily migrate back. The diagram below is a sketch of this idea, using iron nails.



Key:

▨ Magnetic fluid at its normal density

▨ Magnetic fluid compressed to higher density

░ Iron with no magnetic fluid

Figure 2-3: Aepinus' magnetic fluid model in a nail.

Aepinus thought that there was a density gradient of magnetic fluid in a magnetized piece of iron. Here is how the model explained attraction of unmagnetized pieces of iron to a magnet: The presence of a magnet containing excess (or deficit) of magnetic fluid in its near end would induce a corresponding deficit (or excess) in the nearby end of the previously unmagnetized iron. The magnetic fluid would migrate within the (initially unmagnetized) piece of iron. Then the region within the magnet that contained a deficit would attract the region in the iron with the excess of magnetic fluid, and similarly for the other two poles.

Aepinus's model did not exclude the possibility of finding pieces of iron that contained an overall excess or deficit of magnetic fluid. Today we would call these magnetic monopoles. However, Aepinus explained that one normally didn't see any (magnetic monopoles) because they were relatively short-lived. Any object that had a net excess of magnetic fluid would lose some fluid via internal mutual repulsion. Some of the fluid would "evaporate" into the surroundings. Similarly, a magnetic object with a net deficit of magnetic fluid would acquire some from its surroundings.

Finally, one would expect the magnetic fluid concentrated at the point of a magnetized nail shown above to gradually migrate to the head end because of the mutual repulsion between portions of the fluid. Aepinus said this could happen, but at varying rates depending on the kind of iron. Soft iron allowed the fluid to move relatively easily, and thus demagnetize by redistribution of magnetic fluid. Hardened steel, on the other hand, would only allow the fluid to flow very slowly through it. Aepinus noticed that an unmagnetized piece of hardened steel would not attract as strongly to a magnet as a piece of soft iron. However, once a hardened steel object became magnetized, it would remain that way for a longer period of time because the fluid only slowly trickled back to the deficit region.

Aepinus' theory was not completely new. It could be considered a modification of the magnetic thinking of the early 1700's. Aepinus' magnetic fluid was like Descartes' aether particles, because it was present everywhere, and the magnetic fluid not confined to a piece of iron was always in motion. Also, both Aepinus' and Descartes' magnetic fluids had to be physically associated with pieces of iron to cause magnetic effects. However, in proposing this model, Aepinus provided an innovative theoretical mechanism that differed in a very important way from the circulating aether model, because he there was no "stuff" traveling from the magnet to the iron, or vice-versa, which caused magnetic attraction or repulsion. Aepinus proposed instead an "action-at-a-distance" model, in which the presence of special stuff in one place affected other stuff in another place, with nothing actually coming into contact. This is much more in line with Newton's theory of universal gravitation, which also requires action at a distance.

One critical phenomenon that Aepinus' model had to explain was the two - ended behavior of broken pieces of magnets. Aepinus explained it using the diagrams below (Aepinus, 1979):

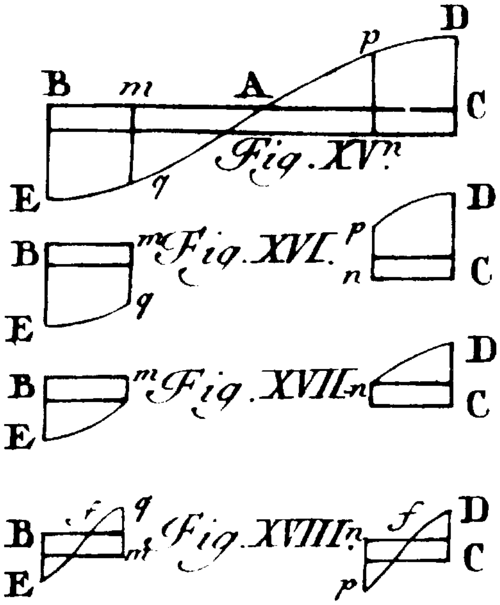


Figure 2-4: Aepinus' diagrams to explain breaking a magnet.

In Figure XV the density of the magnetic fluid is represented along the magnet BAC with the curved line. This actually is a graph of the magnetic fluid density function, although Aepinus did not use these words. Where the curve lies above the magnet, the density of the fluid is higher than its "natural" value. Where the line is below the magnet, the density is lower than the "natural" value. The total amount of magnetic fluid in this magnet is equal to the total amount it would have if it were not magnetized, so no fluid is evaporating from or collecting on it.

Figures XVI, XVII, and XVIII show two pieces that have been cut or broken off of the magnet. The piece labeled "nC", when first cut off, has a net surplus of magnetic fluid, so fluid evaporates from it. To make his model work, Aepinus required that the same amount of fluid evaporate from every point along the magnet, which would result in its magnetic fluid density function merely being lowered by the same value everywhere along the piece! This process is shown in figure XVII. The broken piece stops losing magnetic fluid when its total content of magnetic fluid is equal to that which it would have in its unmagnetized state. For this to happen, the end "n" has to develop a deficit of magnetic fluid. This final state is represented in figure XVIII. The broken piece has become two-ended! A similar but opposite process occurs for the piece from the other end, labeled "Bm", which gradually acquires magnetic fluid uniformly along its length, ending up with a surplus at end "m."

The question of when the fluid moved, and when it didn't move, and how it moved, may have caused difficulties for Aepinus's model. Sometimes the fluid sloshed within a piece of metal, and other times it evaporated or condensed. How did the fluid know which things to do? Using today's ideas of charge motion and of thermodynamics, one would expect the fluid to evaporate more quickly from regions of higher concentration than from regions of lower concentration. Aepinus could not have said this, however, if he wanted to explain broken magnets. The shortcomings of Aepinus' model are easily identifiable through the lens of our current understanding of electricity and magnetism. I state them here to suggest possible reasons for later changes in magnetic theory. However, for the times, Aepinus' work represented a great innovation in models of magnetism. He included mathematical calculations as accessories to this reasoning, which represented a significant change in practice that would be adopted by other researchers.

Acknowledging the tentativeness of scientific models, Aepinus wrote: "I am fully aware that it cannot be certainly concluded from the agreement of an hypothesis with the phenomena that we have reached the true cause. Although the theory I propound here satisfies the majority of magnetic phenomena, I prefer to proceed more modestly than confidently, and to put forward my proposition as probable rather than as certain."

Aepinus' book was published in 1756 in St. Petersburg, Russia. Copies of his book were distributed in Europe, and Aepinus sent a copy to Franklin in America. However, because of the difficulty of distributing a book from a foreign country, and also because it proposed a radically different model of magnetism, researchers appeared to make little use of Aepinus' ideas in Europe until 1777, when Charles Coulomb used Aepinus' theory in a prize - winning entry for another magnetism competition proposed by the Paris Academy of Science.

Coulomb's idea of magnetic molecules

In 1773 the Paris Academy of Sciences announced a prize contest for answers to the questions: "What is the best manner of constructing magnetic needles, of suspending them, of making sure that they are in the true magnetic meridian, and finally, of accounting for their regular diurnal variations?" (A very sensitive compass will point back and forth a very slight amount in a daily pattern.) The contest was announced in 1773, and the award was planned for 1775. But no award was given in 1775 and the contest was set for 1777. Coulomb had not entered the 1773 competition, but he entered the second time around. Jan Hendrik Van Swinden and Charles Coulomb shared the top prize. Coulomb's entry introduced a series of innovations, one of which was the torsion suspension (using a thin silk or other thread) which very quickly afterwards became the apparatus of choice for magnetic measurements. Up to this time, magnetic needles had been supported on sharp points as compasses are today. This support system introduced friction, which put a lower limit on the sensitivity of measurements that could be made. Coulomb's torsion suspensions were capable of providing measurements of unparalleled sensitivity for the times (Gillmor, 1971).

Coulomb's entry in the 1775 competition did not propose a different model of magnetism, and it did not propose the inverse square law force relation for which Coulomb was later to become famous. However, he did suggest that Aepinus' one- fluid model could account for temporal variations of the magnetic direction.

Coulomb went on to become a very influential member of the Paris Academy of Sciences. Later in his life he wrote a series of "memoirs" or papers to the Academy summing up his research in electricity and magnetism. In these memoirs, Coulomb indicated that the "major theoretical concern in magnetical research is the basic question of the 'system.'" The big issue was whether scientists could accept action at a distance as an acceptable feature of magnetic and electric phenomena. Coulomb, following Newton's example, preferred the action at a distance approach. He devoted the opening portions of his first two memoirs to arguments against Descartes' circulating aether model, which was still the dominant theory at this time. Coulomb then went on to report on his work on measuring the electric and magnetic force laws, establishing the inverse square law for both magnetism and electricity. It should be noted that Henry Cavendish established this law first for electricity in 1772, and there were a number of researchers who had proposed, guessed, or measured an inverse square law for magnetism before Coulomb wrote about it in his second memoir in 1785. However, Coulomb's paper was very influential in establishing the relationship once and for all, perhaps because of his precise measurements, his use of mathematics in proofs, or maybe simply because he was already influential in the scientific community.

In measuring the magnetic force relation, Coulomb solved the problem of two poles in each magnet by using very long thin steel needles which separated the poles so that the effect of one could be more easily measured. He used a 27 inch long needle as the source of magnetism within whose influence a much smaller, narrower needle oscillated on a torsion suspension. He located the "center of force" of one pole of the long needle by making a series of measurements of the magnetic force of the needle along its length, and he used the weighted average of these measurements to define the point where the force was centered. In Coulomb's needle, the magnetic centers were about an inch from each end. He also made measurements on a second magnetized needle, rather than using a piece of unmagnetized iron.

About this time, and largely because of Coulomb's influential memoirs, Aepinus' theory began to be more widely known and respected. A two- fluid theory of magnetism was proposed by Aepinus' collaborator Johan Wilcke, and also by Anton Brugmans as a modification of Aepinus' one- fluid theory. Presumably, this theory suggested that there were both austral and boreal magnetic fluids which, when present in equal amounts in iron, would render the piece of iron "magnetically neutral." Separation of these two fluids to the ends of a piece of iron made a magnet. Aepinus' same arguments of evaporation and collection could be used to explain what happens to the pieces when a magnet is broken.

I have found no descriptions of possible dissatisfaction within the 18th century magnetic research community about the awkwardness of the fluid model's explanation for the broken magnet problem, but apparently this was a concern for Coulomb. In his seventh and last memoir, presented to the Academy in July 1791, he described a new model for magnetism that confined the magnetic fluid to tiny regions inside iron. In his paper, Coulomb first introduced the one- and two- fluid theories and then confronted them with the broken magnet problem:

> I believe that one could reconcile the experiments with calculation by making some changes in the hypotheses: here is one which appears able to explain all the magnetic phenomena of which the preceding experiments have given precise measurements. It consists in supposing in M. Oepinus' system that the magnetic fluid is contained in each molecule or integral part of the magnet or the steel; that the fluid can be transported from one extremity to the other of this molecule, which gives to each molecule two poles, but that this fluid cannot pass from one molecule to another. Thus, for example, if a magnetized needle was of a very small diameter, or if each molecule could be regarded as a small needle whose north end would be united to the south end of the preceding needle, there would be only the two ends n and s of this needle which would give signs of magnetism, because it would be only at the two ends where one of the poles of the molecules would not be in contact with the opposite pole of another molecule.

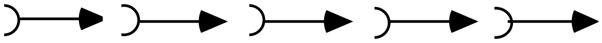


Figure 2-5: Coulomb's diagram of magnetic molecules.

Coulomb's use of the term "molecule" is probably not the same as is used these days. He appeared to be thinking about some kind of little unbreakable containers which held the magnetic fluid.

In proposing this model, Coulomb suggested that magnetic molecules were initially not magnetic, and that magnetizing the object separated the (one or two) fluids to opposite sides of the molecules. In this sense, Coulomb's molecular magnets idea could be seen as simply a modification of Aepinus' theory, because it used similar conceptual objects and processes (a magnetic fluid which migrated to one side of something) but this modification of the model made for a much more satisfying (to us these days) explanation of the behavior of a broken magnet. This modification also made it possible to dispense altogether with the idea of magnetic fluids moving freely throughout space, which seems from our perspective to have been a vestigial remnant of Descartes' model.

In this same memoir Coulomb noted that one could magnetize a thin iron wire, cut it in many pieces, and each piece would still be magnetized. He also noted that one could fill a glass tube with steel filings and magnetize it. Once magnetized, the tube acted like a magnetized piece of steel of the same dimensions, even though the filings were separable. This raises the question of what role steel filings played in helping Coulomb to create his model in the first place. Did he play with a glass tube filled with filings before thinking of his model? One thing that is known is that Coulomb seemed to be thinking of magnetic molecules long before his 1795 memoir. He mentioned in his 1775 competition entry that each point along a magnet could be considered as the pole of a small magnet.

Coulomb's magnetism model appears to have been quickly accepted by the magnetic research community. Poisson used it to formulate the "magnetostatic potential," and with it he proceeded to solve a large number of problems by mathematical calculation.

In his Essay, Aepinus had introduced the application of mathematical calculations to arrive at conclusions as an aid to reasoning about his model. Coulomb's proposal of magnetic molecules permitted a much more advanced mathematization of magnetic theories. Descartes' aether theory, on the other hand, did not neatly lend itself to mathematical modeling. This may be another reason why Coulomb opposed the circulating aether model - he could do calculations much more easily on a magnetic fluid model. With Coulomb's announcement of the inverse square law for magnetism, and his mathematically tractable model, the investigation of magnetism took a much more Newtonian direction.

There is evidence that a scientific revolution (in the Kuhnian sense) took place in the years between 1759 and about 1800 in the field of magnetism. The apparatus and research methods were changed substantially - researchers began using long thin needles on torsion suspensions. The questions of interest had changed - the new research focused on problems that would yield to calculation, and less interest was focused on how the magnetic fluids worked. About the magnetic fluids, Coulomb said to the Paris Academy that "It is almost always more curious than useful to seek to know their causes," Finally, the standards of valid research changed - after Coulomb's work, it would have been more difficult to publish research that didn't include mathematical calculations as part of the argumentation.

Ampére's contribution

The reason why magnetic fluids should be confined to "molecules" or tiny regions was not answered by Coulomb or his contemporaries. But a reason developed after 1820. In this year Hans Christian Oersted finally discovered a connection between electricity and magnetism by placing a current carrying wire above, and parallel to a compass needle. The needle deflected when the circuit was complete. For some time, electrical and magnetic researchers had suspected a relationship between electricity and magnetism and they were hunting for it. There was evidence that there was a connection - it was known that lightning strokes could magnetize pieces of iron that had been nearby. In fact, one magnetic compass on a ship that had been struck by lightning had its polarity reversed. Also, magnetic compasses were known to be affected in electrical storms, even without being struck by lightning (Tricker, 1965). There was also the apparent and suggestive similarity between electric and magnetic phenomena that Aepinus used to advantage in formulating his magnetism model.

Oersted's announcement of his discovery touched off a flurry of research activity in Europe. One of the many researchers who became involved was André-Marie Ampére. He reasoned that if a current in a circuit could cause a magnetic effect, then maybe a current in one circuit could cause a magnetic effect on a current in another circuit. He did an experiment and found that there was indeed a force on one wire by another. There were then three kinds of magnetic phenomena: (1) one magnet could exert a force on another magnet, (2) an electric current could exert a force on a magnet and vice-versa, and (3) one electric current could exert a force on a second electric current. Ampére recognized the value of being able to explain these different effects within a single theory. Constructing this theory was the work that made him famous. The only part of Ampére's work considered here, however, is his thinking about magnetic materials.

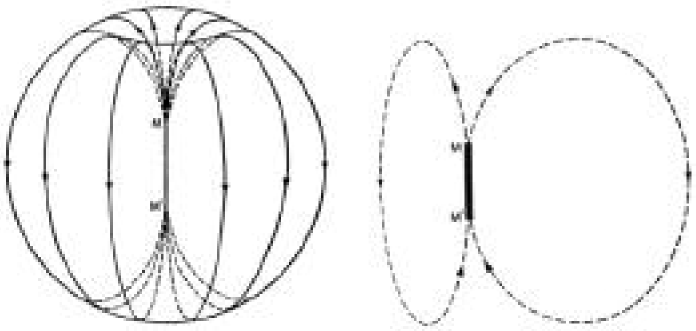


Figure 2-6: Ampére's current loops in unmagnetized (left) and magnetized molecules (right). A single loop is shown on the right for clarity.

Ampére proposed that Coulomb's iron molecules contained electric currents which emerged from one end of each molecule (labeled M in the picture above), flowed around a toroidal surface, and re-entered the other end of each molecule, labeled M'. The molecule on the left was not magnetized because the contributions to any magnetic force from the different currents would cancel each other out. However, when a molecule was magnetized, its electrical circulation was displaced to one side, as illustrated on the right. Only the current flowing in one plane is shown for simplicity. Ampere was able to show that the contribution to magnetic effects was bigger for the large loop than for the squashed loop. Thus, this molecule would be magnetized in the direction perpendicular to the plane shown, with a vector pointing into the page. Ampére's paper describing this model was published by the Paris Academy of Science in 1823.

The final step was the shift from an idea of molecular magnets whose magnetization changes to one in which the magnetic molecule was presumed to be magnetized all the time. If this were the case, then the process of magnetizing a macroscopic piece of iron would involve redirecting a set of initially randomly oriented magnetic molecules into common alignment. This was actually considered by Ampére in a letter written to Michael Faraday in 1822. Also, W. E. Weber later carried out calculations based on this idea, and by doing so was able to explain the magnetic saturation of iron. Saturation is the point at which a piece of steel can no longer be magnetized more strongly. Of course, Ampére's model of deformed molecular currents described above can also explain magnetic saturation. Once all the molecules have had their currents deformed to the maximum amount, there can be no further increase in the magnetization of the iron. Perhaps the increased simplicity of the mechanism was what encouraged Ampére and Weber to consider permanently magnetized molecules. Whatever the reason, this feature of the model eventually became accepted.

Later research showed that the tiny magnetic "molecules" which realign under the influence of an external magnetic field are actually microscopic regions or "domains" containing huge numbers of iron atoms. But these regions do appear to change their direction of magnetization when a sample is magnetized or demagnetized.

The rest of the development of the theory of magnetism (still continuing) is not described here. When physicists began to employ quantum mechanics and statistical mechanics to explain increasingly varied and accurately measured magnetic phenomena, more powerful theoretical and mathematical tools were needed. These ideas, however, are not addressed in introductory physics courses, and will not be described here. Let it suffice to say that ferromagnetism is now seen as a collective phenomenon involving interactions effectively between electron spins, but involving atomic and molecular structure, and thermodynamic considerations.

The seeds and gradual development of models.

Based on the preceding account, it is clear that historical ideas about magnetism emerged in and depended on the cultural milieu of the time. Aepinus used ideas of a magnetic fluid that moved through space, similar to the aether particles of the Cartesian model which preceded Aepinus' model. Also, Coulomb's idea about magnetic molecules appears to have originated as a way to confine Aepinus' magnetic fluid(s). This history suggests that ideas about magnetism, and perhaps other scientific ideas as well, developed and continue to develop gradually over long periods of time, and the changes made were based on then - current models. Early ideas which may seem silly from the perspective of our current beliefs can be seen as providing "seeds" which grew later into more powerful ideas, while less useful parts were abandoned. Thus, even though Aepinus' model is no longer deemed useful, it seems to have served as an important intermediate model which allowed the elimination of problematic aspects of Descartes' model. Intermediate models may be important in scientific modeling.

However, it is hard to tell which parts of a model are really not useful. For instance, Descartes' circulating aether model may seem to have little value in the present day, but recall that Descartes' model of an unmagnetized piece of iron had its "magnetic properties" (the pores and fibers) arranged randomly, and magnetizing the iron caused the pores or fibers to align in a common direction. This is very similar to the alignment idea advanced much later by Ampére and Weber. Also, if Descartes' aether idea itself seems far fetched, please note that the currently accepted quantum electrodynamical explanation for the electromagnetic force involves large numbers of virtual photons which interact at very close range with the object that experiences the force. Virtual photons bear at least a family resemblance to Descartes' aether particles.

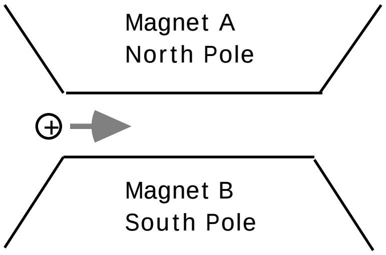
The history of ideas of magnetic materials may also offer a helpful perspective on modern day students' ideas on the same topic. These are described in the next section.

STUDENT THINKING ON MAGNETIC MATERIALS

A small number of research papers describe the ideas that students generate about magnetic materials and magnetism in general. The results of these studies are described below.

Studies on student thinking

Students in college level introductory physics courses generate a variety of ways of thinking about magnetized objects. (Goldberg and Johnson, 1998). These students have some ideas before any formal instruction in magnetism, and they develop others in response to instruction in magnetism. Many students talk about "positive and negative charges" in magnets both before and after regular physics instruction. They use these terms when describing what they think is inside magnets or when they are trying to explain magnetic phenomena. Students use charge terminology loosely but they seem to be referring to something similar to static charge. This was found by Maloney (1985), when he attempted to find strategies that students consistently used when answering questions about forces on charges moving in magnetic fields. After traditional instruction in electricity and magnetism, many university physics students apparently used strategies that were consistent with the idea of electric charges replacing the poles of magnets. Students commonly thought that positive charge was at the north pole and negative charge was at the south pole. Maloney carefully analyzed students' answers to electromagnetism problems such as the one diagrammed below:



Choose an answer:

A) Will move toward magnet A
B) Will move toward magnet B
E) Will not move toward magnet A or B

Figure 2-7: A question from Maloney's instrument.

In the above picture, a positively charged object is shown moving between the poles of two large magnets. According to the accepted Lorentz force, this charge should be deflected in a direction perpendicular to the plane of the paper. Two different groups of students (in two semesters) were given a number of these kinds of questions. About 40% of the students chose answers A and B in patterns consistent with the idea that a north pole attracts + charges, or the north pole attracts - charges. About 30% of the students chose answers that could not be matched with a particular strategy. Thus, the idea that charges attract to or repel from magnetic poles seemed to be the most popular idea in both classes. The situation diagrammed above involves a magnetic force on a moving electrical charge, and thus it is not just a question about magnets themselves. However, students seem to use ideas of charge in other situations involving magnets also. The Physics Education Group at the University of Washington is also doing research on this topic. They have also found that students talk about "charge" when describing magnets (Harrington, 1997).

The first in- depth report on student and others' models of magnetism was written by Borges and Gilbert (1998). They compiled and characterized "mental models of magnetism" expressed by people from different walks of life in Belo Horizonte, Brazil. The subjects fit into five categories of experience, including secondary school students (before and after taking physics course), technicians with no formal schooling in magnetism, physics teachers, and electrical engineers. There were about ten subjects from each level of education. Each subject was interviewed in an interactive format, in which they were shown some magnets and other things. They were then asked to predict a magnetic phenomenon, observe the phenomenon, and then explain it. Borges and Gilbert then formulated a set of models which could explain the different subjects' explanations. These models are described below.

Borges and Gilbert did not focus on subjects' understanding of magnetic materials, but on their explanations for magnetic effects, and on subjects' understandings of the field concept. Still, their five model categories are useful because they constitute a starting point for further research. The categories are listed below in order of increasing similarity with the accepted view of magnetism.

1. Magnetism as pulling

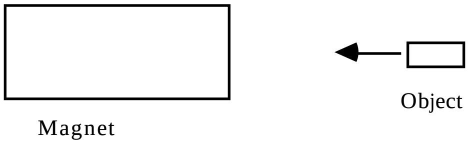


Figure 2-8: Magnetism as pulling.

Magnetism is seen as an attraction exerted on objects near the magnet. This is a property of a magnet - it attracts things. Borges and Gilbert found that people who express ideas in this category don't show concern for explaining the cause of the attraction. To these people, there is not much more to explain, they are just showing that attraction happens.

2. Magnetism as a cloud

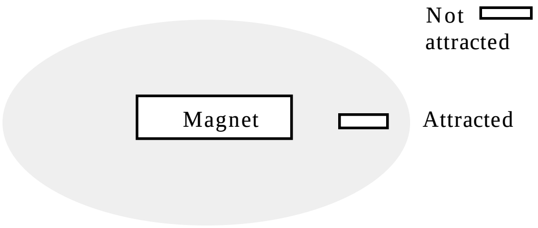


Figure 2-9: Magnetism as a cloud.

In this model, magnetism is thought of as a "sphere of influence" surrounding a magnet. People using this model talk about the effect of the region, rather than of the effect of the magnet itself. Outside of the field region, there is no attraction. This model may have partial origins in the popular idea of "force fields."

The difference between this model and the one above is that this one shows a mechanism to explain the attraction. The magnet creates this "sphere of influence" and things within it are attracted. However, there is no causal explanation for how the magnet does this.

The "pulling" model and the "cloud" model together were used by 13 of the 19 subjects in the study who had not taken a course in magnetism. This is almost 70 percent. In other words, these first two models are commonly used only by "naive" people, who have not had formal education about magnetism. Only 3 of the 37 subjects who had studied magnetism used the cloud model.

3. Magnetism as electricity

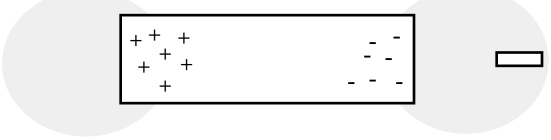


Figure 2-10: Magnetism as electricity

This model includes a mechanism within the magnet to explain magnetic attraction. The poles of magnets are thought to have charges, often opposing ones, which cause the attraction. This model clearly shows that the two ends of magnets are somehow different or opposite. It seems to be based on some ideas about electricity, quite likely including "likes repel, opposites attract." Borges and Gilbert claim that the main concern of those who use this model is to explain the two-endedness of magnets, which this model does.

This magnetism as electricity model is similar to those described above by Maloney (1985), Harrington (1997), and Goldberg & Johnson (1997). Borges and Gilbert did not explain how students come up with this model and they didn't discuss details that different students or other people explained the origins of the charges. A student model similar to this one is discussed at more length in Chapter 4.

Borges and Gilbert said that 14% of their subjects used this model to reason about magnets. One of them was a physics teacher.

4. Magnetism as electric polarization

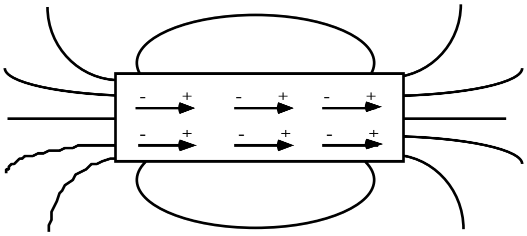


Figure 2-11: Magnetism as electric polarization.

This model uses charge polarization to explain magnetism. It appears to use electric charges to provide a causal mechanism for the magnetic domains that students are taught about in school. Or it could be the result of a confusion between magnetic and static electric concepts. Significantly, this model was only expressed by people who had taken a course in electricity and magnetism. It seems that people may develop this model when trying to make sense of school teaching on magnetism.

This model was used by an additional 12% of Borges and Gilbert's subjects.

5. Field model (close to the accepted model)

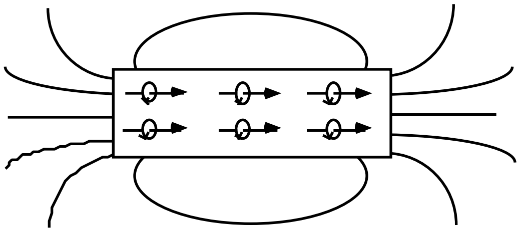


Figure 2-12: Field model.

In this model, the magnetic domains are thought of as being caused by the atomic motion of electrically charged particles. Subjects explained that effects caused by the magnet were mediated by the magnetic field. This model is closest to that which physics teachers would like their students to learn. However, Borges and Gilbert found their subjects were sometimes able to only describe parts of what would be a complete explanatory model. Also, the only people who used this model had heard about it in a physics class. Only 28% of the subjects used this model, even though about 60% of the subjects had taught or taken a physics class in which this model should have been presented, and another almost 20% worked with magnets on a daily basis and should therefore be expected to understand the accepted theory of magnets.

Borges and Gilbert pointed out that there apparently is some effect due to instruction, as the models expressed by students did have some mechanism (in contrast to the "magnetism as pulling" model which has none. They surmised that the three intermediate models represent students developing better models as a result of what they heard in school. While these models do not agree with the model that teachers would like them to have, still there is evidence that students try to make sense. The authors also suggested that the striking use of electric charges to explain magnetic phenomena may be due to the fact that, these days, people have more experience with electric phenomena than with magnetic phenomena.

Summary of reported findings

College students' understandings of magnetic materials have been studied only a small amount. Borges and Gilbert published the most extensive study, on a range of ninth grade students, teachers, and technicians. They found that a lot of these people seem to use charges to explain magnetic effects. They offered part of an explanation why students' use charges to explain magnets- they suggested that people encounter many more static effects than magnetic effects in their daily lives. Also, their suggestion that students use the common or salient terms positive and negative to explain magnetic mechanisms supports a view of learners as people who try to make sense of things they are told, but who use pieces of it in ways that physics educators might not anticipate.

Borges and Gilbert explained that students use charges to explain magnetism because they encounter so much static phenomena in their daily lives. However, my own feeling is that people also encounter plenty of magnetic *effects* in their daily lives.

Practically all of the mechanical devices that we use are powered by electric motors, which involve magnetic forces. But people may not notice these motors or think much about how they work. Maybe a reason why people use charge to explain magnetism is that they have had more encounters with *model-oriented representations* of electric phenomena. That is, they see + and - symbols relating to static charge on advertisements and other visual media, and they have learned to align batteries using the + and - symbols on electrical devices. To even the lay person, those plus and minus charges seem to explain something. But in our culture we tend to see few depictions of magnetic effects beyond some zigzag "lightning" zaps that are sometimes shown emanating from magnets. And these zaps do not seem to show how a magnet works, but just to show that the magnet is indeed working. There seem to be many fewer model-oriented representations of magnetic phenomena in everyday life.

Borges and Gilbert's research detailed the models that students and others actually offer in discussions about magnetism. Their goal was not to explain in any complete way how students develop these models, or what is the next step for those who move towards better models of magnetism. In the papers discussed above, the question of how students *change* their thinking about magnetism has barely been addressed at all. That is the focus of this dissertation.

Relation of historical ideas to student thinking

There are some striking similarities between the ideas about magnets that students propose in physics classes and the ideas that developed historically. For example, Aepinus (1979, 1759) explained magnetic effects by making an analogy with Franklin's electric model, and students today also make analogies to electric models. There are also important differences between models that scientists proposed and those that students propose. Perhaps the most important differences are the reasons for introducing particular ideas. These differences highlight differences in prior knowledge, and different culture, goals, and social roles of the two kinds of investigators.

Similarities and differences in cloud models

As noted above, the "magnetism as a cloud" model is similar to William Gilbert's idea of an "orb of virtue" surrounding a magnet. In both models, the magnet only attracts the things inside the orb or cloud, and the attraction is by "virtue" of the cloud. Students (and other people) might construct this idea using similar reasoning as that used by William Gilbert (1600), who noticed that he could separate a piece of iron and a lodestone to a particular distance beyond which the iron no longer jumped to the lodestone. It is more difficult, however, to draw parallels between the reasons that Gilbert had for magnetic effects and the reasons that beginning students (who use the cloud) model will offer.

Gilbert wrote at great length about "harmony," "virtue," and "proper order" as reasons why magnets do what they do. He lived during the Renaissance, when those concepts may have been believed to have more causal nature than they do now. In comparison, Borges and Gilbert (1998) suggest that students' ideas of a "sphere of influence" arise from hearing about gravity, and science fiction type "force fields." These theoretical supports are similar primarily because both had their origins in the culture of the day.

Similarities and differences in electric separation models

The main similarities lie in the basic types of models that were used. Borges and Gilbert's "magnetism as electricity" category bears a striking similarity to the two fluid models proposed by Wilcke and Brugmans in the late 1700s. This model, a variation on the one-fluid model of Aepinus, is conceptually very attractive because it clearly explains the two ended behavior of magnets.

However, the reasons for accepting such a model are different for modern-day physics students than they were for ancient scientists. In 1759, magnetic researchers were quite aware of a range of magnetic phenomena. In particular, they knew that a broken lodestone would still be two ended, so a two fluid model could only be acceptable to scientists of the time if it could account for the broken magnet phenomenon. It was important for Aepinus to offer a plausible explanation for this phenomenon, because without it his model would not have been acceptable to members of the scientific community of his day. Also, in their appropriation of analogies from electricity, eighteenth century scientists probably made sure they clearly understood an electric model before applying it to magnetism.

In comparison, one would expect that modern day physics students are not aware of a wide range of magnetic phenomena. Many students (prior to instruction) may not feel compelled to explain how each piece of a broken magnet can still be two ended, even if they are aware of this behavior. Also unlike scientists, students appear to use the idea of charges without completely understanding the accepted static electric model.

These social concerns provide part of the motivation for studying social aspects of students' activity in a classroom. More motivation is offered in the last major section of this chapter.

No historical record of an electric polarization model of magnetism.

I have found no record that any scientists in history proposed a model of magnetism with magnetic domains made of positive and negative electrical charges. This seems to be an artifact of instruction in modern electricity and magnetism. One might guess that students hear about magnetic domains or they see a picture of them, and they try to make sense of them by including charges in their explanations.

No modern expressions of a circulating aether model

I have also found no reports that any students think of something circulating around or through magnets to explain magnetic effects. Reasons for this probably include the fact that, these days, most people (besides historians and philosophers of science) don't talk about aether as scientists did in the 1700's. Still, it might be rather surprising that a model that was held in the highest regard for a hundred years is not expressed by any students these days.

Summary of similarities and differences

There are important differences in the approach used by modern-day physics students and early scientists in appropriating electrical concepts for magnetic explanations. These differences are due partly to different social positions and roles, and different prior knowledge of the two kinds of investigators. Scientists or natural philosophers in the 1700's knew some things that most twentieth century physics students do not know. Eighteenth century scientists working in this area were familiar with differences between electric and magnetic phenomena. Once the two phenomena had been clearly differentiated (probably by 1550), early scientists would have considered it an error to "confuse" electric and magnetic phenomena and explanations.

With regard to social positions and roles, Aepinus wrote his essay on magnetism for the international (European) scientific community of the middle 1700's. When introducing his model, Aepinus very carefully emphasized that the magnetic fluid was *like* electrical fluid but *not the same* as electrical fluid. He knew that the analogy had limitations, and he tried to lay these out clearly. As a scientist, he had a reputation to protect. He could gain a bad reputation very quickly if he appeared to not have thought things through before presenting his ideas. In comparison, physics students seem to suggest notions of electric charge relatively casually because they may not have thought carefully about the differences between electric and magnetic phenomena. They don't have the same social stakes to worry about. And if they do think carefully, they don't have as much time as Aepinus had to consider the issues.

Something has been left out of much of the above discussion of historical and student models of magnetic materials. That is how such models came to be created. To understand the model development process I believe one has to look at the effects of culture and social interactions on groups of people. How to do this is discussed in the next major section.

COGNITION IN INTERACTION

This last major section will flesh out ideas about "making sense" as an activity rather than as a result. After an introduction to ideas from activity theory in general and distributed cognition in particular, two particular foci will be introduced. The first is a particular way of thinking about peoples' use of "inscriptions" (text, graphs, pictures, and so on) as simultaneously social and cognitive tools. Latour and Woolgar's (1979) perspective will be employed here. The second focus will be the social norms in a classroom, and how they can be understood as affecting students' interaction in terms of their participation in the class. The main theoretical influence here will be that of Yackel and Cobb (1996).

Distributed cognition, activity theory, and communication

Physics teachers sometimes claim that they occasionally develop deep insights while preparing and/or delivering lectures. This could be called the "explanations effect" (Chi, et. al. 1989; Chi & VanLehn, 1991). However, the attempts of Chi, et. al. to explain the explanations effect in terms of internal mental structures alone seems to leave something out. After all, the normal reason for making an explanation is to offer it to someone else. The subjects in Chi's study, who constructed explanations ostensibly for their own benefit, learned how and why to construct explanations via social interaction. Social interaction has a pervasive influence on cognition.

Turning this statement around, researchers are beginning to recognize that cognitive processes fundamentally involve interactions between people and their social and physical environments (Brown, Collins, & Duguid, 1989; Shore, 1996). Accepting this claim requires a fundamental change from the conception of cognition as an "internal" process which operates on representations of "external" objects (Cobb, 1996b) to something more inclusive of the role of environment and interaction. If one accepts the idea that people utilize structure in their surroundings for cognitive purposes, it becomes apparent that theoretically separating internal cognitive process from external events may not be fruitful or faithful to the character of human interaction. Admittedly, theories of cognition may be easier to formulate when one assumes that mental activity is neatly separable from social interaction, but doing so reduces one's ability to make sense of cognition.

Sociocultural perspectives see the mind not as a symbol processing device separated by a skull from the world outside, but as an active participant in the world and a manager of human activity. Cognition is seen as an emergent property of the interaction of mental systems with physical and social systems. The thinking is that, because people structure their environment to their (sometimes cognitive) benefit, and because the structure of the environment affects how people do things, it does not make sense in most cases to think of a mind separate from its surroundings (Cole, 1996). In particular, Hutchins (1995) claims that it makes sense to analyze cognition using a different boundary than the limits of the skull to define the cognitive system. Bateson (1972) gave a now-classic example:

> "Suppose I am a blind man, and I use a stick. I go tap, tap, tap. Where do I start? Is my mental system bounded at the handle of the stick? Is it bounded by my skin? Does it start halfway up the stick? But these are nonsense questions. The stick is a pathway along which transforms of difference are being transmitted. The way to delineate the system is to draw the limiting line in such a way that you do not cut any of these pathways in ways which leave things inexplicable."

In general, the boundary of the unit of cognitive analysis (traditionally the skull) is a matter that should be considered in each situation. In some cases, a group of people can be thought of as a cognitive system, or a person plus tools in surroundings can be thought of as a distributed cognitive system. Much of the structure that traditional cognitive scientists attribute to the human mind can be attributed instead to a system of person(s) plus tools in a setting.

For example, consider a group of students working in front of a computer. The memory of each student is augmented (at least) by the computer screen. To guide their actions, students can look at the screen or talk to each other instead of having to recall the assignment and any diagrams from memory. But the screen can do more than make the student's memory better. It actually changes what can happen in the group, because the processing of representations takes place not only inside the heads of individual students, but it takes place on the computer screen as well. Fingers point to relevant features of a picture, students make suggestions for changing wording in text while it is being typed. The cognitive activity in this situation (or in any other) is not restricted to the heads of individuals, but much of it is constituted in their actions, interactions and interpretations. It is probably much easier to track and make sense of these interactions by considering a cognitive system larger than an individual brain.

Understanding the cognitive aspects of interactions requires careful thinking about the nature of tools. Tools do not merely "amplify" human abilities (as might be inferred from the statement that the computer screen can act as another type of memory) but they change the task faced by the tool user (Norman, 1994). That is, tools do not just make a job easier, but they change the job that has to be done.

The electronic calculator is an example. To do an arithmetic calculation using paper and pencil requires knowledge of some particular algorithms and a set of basic multiplication and addition facts. Performing the calculation involves writing symbols (numbers and operation symbols) in particular locations on a piece of paper and applying an algorithm to the written numbers (or doing something similar in one's head). Using a calculator to do the same calculation requires knowing a different algorithm for entering numbers and actually performing the calculation involves pressing appropriate keys in the appropriate sequence. When the numbers are large or the calculations are extensive, a calculator generally offers a quicker solution, but it doesn't accomplish this by helping us move our pencil differently or by helping us apply the long division algorithm faster. Rather, the calculator is faster in some cases because the job of operating it is completely different (and often easier). To extend this example one step farther, note that a person using a calculator may still use pencil and paper as well, but is not likely to use them the same way as without a calculator. Thus the use of a calculator changes an arithmetic task completely, and it can change the task setting.

When a tool changes a cognitive task in this way we say that the tool *mediates* cognition. Activity theorists (Cole, 1996) claim that mediation is a fundamental aspect of cognition, that people naturally make use of the cultural means available to them to accomplish their ends. Accepting this requires recognizing that many aspects of culture can be thought of as media. Language, for example, is a very powerful medium in a number of ways, one of which is that it provides a way for a person to offer her views to another person. In the classroom I studied, however, the computer screen provided students with another tool for communicating. Along with language, it also mediated students' conversations. The particular features of those mediated conversations are described in Chapter 5.

The concept of mediation is useful because it provides a way of clarifying the cognitive roles played by culture and social interaction. It also provides a way to begin trying to make sense of interactions. Thus this dissertation will take the perspective that mediation is a fundamental feature of human cognition- that it is always taking place, therefore studies of thinking and learning can profitably identify important mediating artifacts and explore their effects on the activity of interest.

Language was mentioned above because it mediates communication. This dissertation attempts to identify some of the ways that communication mediated cognition in the classroom. But language plays complex roles in human interaction. Work by Lemke (1990) and Garfinkel (Heritage, 1984) clarified the nature of communication in science classrooms and in everyday discussion. Some of their ideas, discussed below, contribute to a sense of the role of language in science learning.

Communication and science talk

Constructivist epistemology problematizes communication. The notion that one person can't transfer ideas to another requires that we look more closely at what happens when people talk to each other (von Glasersfeld, 1991; Bettencourt, 1993). The basic idea proposed by radical constructivists is that each member of a conversation constructs an interpretation of what the other is saying, and each listener continually checks this interpretation's validity against her prior knowledge and the unfolding conversation. People seem to be very good at this, because communication seems to succeed reasonably well in normal everyday circumstances, or so participants in conversations may believe. However, research evidence shows that students often have great difficulties interpreting statements by physics teachers (McDermott 1984; 1991), which suggests that the processes of communication and the subsequent construction of acceptable ideas do go awry in physics classrooms more often than we would like.

What should remain surprising to a thoughtful person, however, is how infrequently people sense breakdowns in communication. At the same time, one should wonder why students in physics courses do not often sense that their understanding of physics is not what the teacher intended. An explanation for both of these phenomena, and probably many others, was offered by Garfinkel in the 1960's (Heritage, 1984). While working on sociological problems associated with the coexistence of social order and free will, Garfinkel proposed an interpretation of prior theories of social order which involved a "reciprocity of perspectives." This phrase suggests that a listener interprets a speaker based on the listener's understanding of the topic *and* the listener's current, developing interpretation of the speaker's understanding of the subject. Each person does this, it is a "reciprocal" situation. Notably, a great deal of every discussion is "taken as shared" by the participants and not explicitly spoken. In Garfinkel's words, in any two party conversation, "much that is being talked about is not mentioned, although each [member of the conversation] expects that the adequate sense of the matter being talked about is settled" (Garfinkel, 1963).

Why do people structure their conversations this way? According to Garfinkel, we do it for the sake of economy. It would not be possible for each member of a conversation to explicitly state every piece of information that is commonly taken as "background knowledge." This omission in conversation of all but the critical pieces of new information, said Garfinkel, is supported by powerful social norms. Through a series of experiments in which experimenters intentionally breached the norms of standard conversation, Garfinkel showed that people tended to become righteously indignant when a partner in a conversation asked for more details than were commonly expected. Garfinkel's interpretation was that people develop and maintain working understandings of the "normality" of events and conversations, and that breaches in this perceived normality lead to serious reprisals by the other participant(s). Maintaining the "reciprocity of perspectives" is thus not only a cognitive activity, but "one in which each actor trusts that the other will accomplish as a matter of moral necessity" (Heritage, 1984, page 82). Maintaining a taken-as-shared sense of understanding is a moral feature of cognition. This issue is particularly salient for classroom settings because prior expectations of the students may not support the kinds of sense-making conversations that can be beneficial in science classrooms. It also suggests that norms relating to conversation are closely tied to processes of making sense.

There is certainly room for plenty of questions, now, in understanding how students in a small group or in a whole class establish or maintain a reciprocity of perspectives when they all begin with slightly or wildly different ideas, and when they are charged with the task of developing the main ideas of physics. This interesting but huge question can only be touched on in this dissertation.

A possible entry to an explanation about how students can construct reciprocities of perspectives in a physics class is to consider the use of language in scientific communication. Science is spoken differently from everyday language. It seems that one of the norms of scientific communication is for speakers to be more explicit about assumptions and background information than in normal casual speech. As will be seen below, scientists also enlist text and diagrams in support of a shareable set of assumptions. In other words, applying Garfinkel's ideas, science explicitly requires the development of its own "reciprocity of perspectives" which members of the community are required to explicitly support. It is needed because scientific topics are often beyond the range of common experience. This requirement for explicitness may simultaneously explain why it takes a long time to become a scientist (it takes a long time to develop background knowledge for a robust scientific reciprocity of perspectives); and why students have difficulty learning to talk explicitly about particular detailed issues in science classes (possibly because they may not at first value the explicitness which they perceive as a threat to commonly accepted conversational norms supporting a reciprocity of perspectives).

Maintaining a scientific reciprocity of perspectives involves different kinds of talk. Lemke showed how a semantic analysis of talk in science classrooms reveals patterns of social processes (negotiations of power and values) and patterns of scientific meaning which are also negotiated between teacher and students. Lemke claimed that much of learning in science is learning to talk the talk, that "mastery of a specialized subject like science is in large part mastery of its specialized ways of using language." (Lemke, 19990, p.21) Because language is so closely tied to thinking, mastering language is also a process of developing ways of thinking.

Lemke described a scientific concept or model as a "thematic pattern of semantic relationships in a subject, one that is reconstructed again and again by nearly all the members of a community." In other words, a semantic analysis of statements made by different people about the same topic should show similar semantic structures if the two people agree. They might use different words, and use terms in different order, but the fundamental semantic relationships would be similar. Learning to construct particular accepted semantic structures is for Lemke what people do when learning science.

This dissertation takes a different path from Lemke's work. Lemke studied only the use of language, and primarily speech, in his analysis of science learning. This dissertation instead focuses on larger features of interaction including, but not restricted to speech. Also, Lemke analyzed discussions from science classrooms which used more or less traditional models of teacher - student interaction. The teacher was the social and content authority, whose job was to convey scientific ideas to students. The CPU classroom, on the other hand, places teachers and students in roles that are different from traditional one. How students in a CPU course establish meaning by all means of communication, not only speech, is part of the concern of this dissertation.

Use of inscriptions

Another avenue to studying scientific communication is to focus on drawings, charts, pictures, text, and so on. Scientists, after all, make heavy use of these to make their points. Reporting on an ethnographic study of a biology laboratory, philosopher Latour (1979) introduced the term "inscriptions" to indicate the wide variety of representations, most of which could be put on paper, and which he observed scientists using in their work. Latour included diagrams, pictures, and graphs in the category of inscriptions. Written text has some important characteristics that make it similar to inscriptions so text will be included in this dissertation as another kind of representation that influences cognition.

Latour saw that much of the activity of scientists was centered around obtaining inscriptions that could support their claims and move their ideas closer to acceptance as scientific facts. By focusing on inscriptions as the objects of scientific activity, Latour also drew attention to the activity itself which he claimed is enabled by inscriptions. According to Latour, much of scientific activity involves arranging and connecting various inscriptions which together can be seen to form a logical whole.

Part of the task of learning science, then, would seem to be learning the uses of paradigmatic inscriptions, which are different for different topics. In the case of magnetism, important inscriptions are tables of test results and magnet model diagrams. Students' written explanations are also important. But learning to use inscriptions is not an end in itself. They are tools whose use can contribute to understanding.

How do inscriptions contribute to understanding? Perhaps by being used in sense-making or rhetorical activities. Latour pointed out a number of useful properties that inscriptions share (Latour, 1986). Among these is the property of flatness. A two dimensional inscription can be accessed easily, pointed at and often moved and changed, and thus can be made to serve a person's needs. Another property is their flexibility. Inscriptions can be recombined, superimposed, and combined with text. These properties are what makes inscriptions extremely useful in making connections and in making points. Inscriptions can play important roles in rhetoric. These two properties are particularly important to analyzing students' sense-making conversations.

Theoretical perspectives that focus on inscriptions integrate cognition and social interaction. (Roth & McGinn, 1998). Roth and McGinn pointed out that the meaning and use of inscriptions depend on social practices, and at the same time influence them. They wrote that paying attention to the use of inscriptions by students changes the focus from individual accomplishment to the interaction surrounding inscriptions. But the above discussion of communication suggests a way to understand how inscriptions also influence cognitive activity.

My interest for this dissertation is to understand ways that inscriptions mediate face-to-face interactions between people, and how those conversations consequently mediate development of ideas. That is, two people talking about a magnet can both look at a picture of a magnet and use it in their discussion. They may literally "make points" with their fingers by gesturing at features of the picture. It seems that inscriptions can provide opportunities for two people to compare their understanding by providing a shared space within which they can negotiate a shared understanding. Here may be part of the origin of inquiry students' scientific reciprocity of perspectives. But if inscriptions are important to learning, to what uses do students put them? Also, what sense can be made of the ways that inscriptions influence conversations? A few researchers have begun to address these questions.

Research on students' uses of pre-made inscriptions

Some researchers have analyzed the process of students' making sense and making use of representations that were presented to them. Kelly and Crawford (1996) noted that the presence of a computer displaying real-time MBL graphs significantly structured the activity of a group of students studying motion. The authors found that the computer representations had two "paths" of entry into the group's conversations. One path was by presenting a new graph or an interesting feature which had to be interpreted by group members. In this way the computer could be seen as initiating discussions. At other times, students making claims to each other would refer to some part of the graph on the screen in attempts to persuade or influence. In this way the computer was enlisted into a rhetorical role in the group's discussion. This is Latour's role for inscriptions, described above. The computer screen can be seen as providing inscriptions for students' benefit and use.

Kelly and Crawford found that the difference in intellectual roles of computer and students was flatter than has previously been appreciated. The computer could be seen to play roles that complemented the students' roles. Sometimes the graphs initiated discussions by presenting new shapes. Other times, the students enlisted the MBL graphs as rhetorical support of claims. At still other times, students engaged in sense-making discussions about details of graphs.

Kelly and Crawford found a number of cognitive processes that took place within the group, and which explicitly included the computer. By doing this analysis, Kelly and Crawford were able to illustrate some of the "nuts and bolts" mechanism of group interaction at a computer. Most importantly, the computer screen served as a tool for communication, by providing common objects of discussion for which students might not yet have had shared words. This can be seen by imagining how students might make claims, predictions, or demonstrations. A student could point to a graph feature and say "this will go like that." Such talk can be seen in this perspective as part of a cognitive process.

Other researchers have also begun to illustrate the ways that pre-made inscriptions support or take part in cognition or communication. Enyedy, Vahey, and Gifford (1997) studied the ways that the "Probability Inquiry Environment" supported communication in a classroom. These authors documented how students used graphical representations on screen as resources for communication and problem solving. The students pointed at or counted various states in a probability tree, and their reasoning was supported by animations showing the current state of three flipped coins. By tracing paths through an animated probability tree, students developed understandings of compound probability.

Wolff-Michael Roth investigated the way that a teacher used Interactive Physics^{TM}, a simulation program, in a high school physics class (Roth, 1995). Assuming that much of the learning of physics involves learning to talk physics, Roth noted "that inscriptions and talk mutually organize each other such that it is misleading to investigate scientific and technological products without accounting for the social and material settings in which they came about" (page 330). Roth investigated the classroom role played by computer - generated diagrams and animations. Since he believed that such diagrams themselves do *not* convey meanings unambiguously, he wanted to find out how Interactive Physics^{TM} might be valuable. Roth focused on "affordances" that the simulation software provides the teacher for eliciting and evaluating students' understanding. These included identifying students' ways of seeing and thinking, making forces visible, and coming to terms. This last category represents ways that students converged on a "shared way of talking" within the group. The simulator supported this because it presented a single view to three students who had to find a way they could talk about it together. It seems likely that, along with generating a common terminology, the students were also generating a more robust reciprocity of perspectives.

Roth's paper provides glimpses into ways that a teacher can use computer simulations to support science learning. We now need to better understand the actual activities that students engage in, and the relationships between their knowledge growth and their interaction with inscriptions. Again, this dissertation is intended to add to such an understanding.

This section has explored some research perspectives on uses of pre-made inscriptions by students. They were made by a computer, and students used them in a variety of ways. However, students also construct inscriptions of their own. This might require certain skills. Students might show different kinds of involvement while making inscriptions than when interpreting inscriptions that are provided to them. Constructing inscriptions might lead to characteristic patterns of conversation, or of cognition. The following section addresses these issues.

Research on students constructing inscriptions

In order to understand students' abilities to use and construct meaningful diagrams, diSessa and others studied the process by which a group of sixth grade students invented graphing (diSessa et al., 1991). The students, of course, didn't call it that. They were trying to find ways to represent the motion of a car. In the middle of a course on motion involving computer programming, a group of students spent a few days constructing, suggesting, critiquing, and improving static representations of a particular motion. These were all drawn on paper or a chalkboard. At the end of about four hours spread over five days, the group of students developed and accepted a representation scheme that had a lot of the features of a velocity - time graph. diSessa, et al. emphasized that their sixth grade students developed sufficient meta-representational expertise to critically examine each others' diagrams. Such expertise is necessary for the development of ideas via construction of representations in a collaborative setting. Since this type of expertise has been demonstrated, the door is open for examining how collaborative construction of representations draws on the abilities and knowledge of the collaborators, and how it contributes to their learning.

The work by diSessa, et al. remains unique in its focus on representations constructed by students who were not told what kinds of diagrams to make. However, one other study by Lehrer, et. al. investigated the relationship between representing ideas via inscriptions and conceptual development in science (Lehrer, et al, in press). They reported on two design tasks in which second or third graders had to 1) design a Lego car which would travel the fastest or slowest down a ramp or 2) design a set of experiments about plant growth. In the Lego Car task, students had to address issues of speed measurement, of ramp standardization, and of the slope of ramps. Each of these issues posed problems which the students had to deal with, and which the teacher hoped to use to teach about measurement, about central tendency of a group of measurements, and about representation of slopes.

Lehrer et al. noted a "progressive mathematization of ideas" and identified connections between the evolution of student- generated inscriptions and the evolution of students' thinking. For instance, in the Plant Growth task, the authors say that a "cascade of inscriptions" for describing plant growth was accompanied by a "cascade of individual and collective conceptual growth." What the authors mean by this is that the students produced series of representations with increasing sophistication and informational value. Each of the representations were developed with the support of the teacher, but the interesting feature for the authors was the relationships between inscriptions and development of thinking in the classroom. Students constructed tables of plant height measurements, which forced discussion and decisions about what measurements were appropriate to make. With the teacher's help, they then graphed these tables, and had to discuss what would make a "typical" graph of a "typical" plant. This required discussion of what "typical" means. Further investigations required the development of measures of volume taken up by the plants, and a second round of discussion and drawing of "typical" graphs. Questions about the variation between growth conditions led to the construction of histograms to represent the variation. As students made representations (particularly graphs) which they could use to summarize growth, they developed more sophisticated ideas about plant growth, and discovered questions which led to the next use of increasingly sophisticated inscriptions.

This is the way in which the process of representation seemed to be connected reflexively to concept development. The students' changing diagrammatic and recording schemes influenced what they thought, and their questions and new understanding influenced how they drew diagrams and kept new records.

The second and third graders in Lehrer's study did not invent everything. Their teacher probably introduced graphing ideas when they were needed, supported student's use of tables, and may have offered ideas about measuring plant size. The teacher provided authoritative support. In a study of the construction and use of inscriptions *without* the support of an authority, Luciano Meira placed pairs of eighth graders in problem solving situations involving linear functions (Meira, 1995). Meira took an activity centered approach in analyzing the students' work. He proposed (and provided supporting evidence) that "cultural conventions, such as notational systems, shape in fundamental ways the very activities from which they emerge, at the same time that their meanings are continuously transformed as learners produce and reproduce them in activity." He closely analyzed the inscriptions produced by the students, and their use of these in solving problems.

The student pairs used one of three kinds of linear function mechanisms; either a spool that wound up a string when a crank was turned, a spring on which masses could be hung, or a computerized "function machine" which returned numbers when a number was typed in. Each instrument allowed easy measurement of numerical input and output values. Each pair of students was asked to answer a set of questions intended to require thought about the numerical relationships involved. The main inscriptions produced by students in all three situations were tables of input/output values. Students used or modified their tables in different ways when solving problems. These tables often helped students to make connections that they might not have made in their heads. For instance, one group hung one and two weights on one spring and found lengths of 2 and 4. Then they did the same thing with another spring and found lengths of 8 and 10. They were asked to say whether there would be a weight for which the two springs would be the same length. The two students were not sure how to answer this question until one of them wrote the measurements down in a table format:

2	8
4	10

Upon seeing this, one student said "So it's just a difference of six!" After this realization, the student was able to explain why the ends of the two springs should stay the same distance apart regardless of the weight applied. The rudimentary table which was drawn (perhaps intended only to be a record of the measurements) became a guide to thinking about the relationship between the two springs.

Using this and other data, Meira found evidence that students' inscriptions organize their activity and sense making, and that children's designs of inscriptions depend in essential ways on the immediate setting of their activity. Meira found that children have multiple and sophisticated ways to use and organize information, and that the emergence of problem solving strategies may depend on the existence of specific displays in a situation.

Meira's work shows that there are important interactions between students and the inscriptions they create. His work suggests further research on the development of ideas. Is the development of *ideas* , rather than problem solving strategies, also dependent on the existence of specific material displays? That is, do students get ideas based on things they are looking at? In Chapter 5, I will explore the types of activities associated with construction of inscriptions, and the relations of these activities to development of models. It will be seen that particular inscriptions seem to lead to particular ideas and discussions.

The research described above has established that children and other students develop skills in using and constructing inscriptions, and that inscription use has a reflexive relationship with the development of knowledge. The term "reflexive" implies, for one thing, a two-way relationship. Students use inscriptions in developing their knowledge and they employ their knowledge in using inscriptions. However, the term "reflexive" also means an even closer relationship, that the one does not exist without the other. Without sufficient knowledge, an inscription would be a meaningless collection of lines. Without an appropriate inscription or set of inscriptions, it would be difficult or impossible to develop some particular kinds of knowledge.

This section has shown ways that the concept of inscriptions can help organize observations of groups when they create or interpret text and pictures. Inscriptions are not inert objects but they are aspects of the environment that are intimately connected with students' thinking and learning processes. Research on the process of learning can't ignore the inscriptions that, for students, are the objects of their efforts.

But relating inscriptions to learning processes only partly explains why students do things the way they do. Just because students draw pictures, interpret text, or decide what to write does not imply that they are therefore developing better ways of thinking. Groups could type text and draw diagrams without really thinking too deeply about what they are doing. A group that is thoughtfully engaged in course work has some commitment to being engaged. The members take it seriously enough to put thought and effort into it. Willingness to take part in a course in certain ways seems necessary to making progress in the course.

Such willingness may be motivated by senses of obligation on the part of students. Obligation to engage in productive course work is evidence of explicitly social influences. Social considerations are increasingly becoming recognized as important in science (Kuhn, 1970; Latour & Woolgar, 1979). Similarly, social structures seem to be important in classrooms (Yackel and Cobb, 1996). In a classroom, social structures such as norms affect more than just willingness to engage in tasks, but in fact provide structure for much or all of the activity that takes place. Social norms, for instance, influence a wide range of behavior, from sitting quietly in seats (or not) to use of evidence (or not) in support of a model of magnetism. Norms influence how groups use inscriptions. Clearly, understanding norms in a classroom can lead to better understanding of the processes of idea development in that classroom. The following section explores classroom norms in more detail.

Social norms in a classroom

As suggested above, social norms are thought to provide much of the structure for activities in a classroom. They may support certain actions or discussions, and discourage others. In turn, the kinds of actions and discussions that take place influence students' development of ideas. Norms might be seen as providing a continually evolving framework within which a class takes place. This section will explore the importance and effects of classroom norms.

Physics inquiry involves learning how to perform experiments and evaluate their results, judging the validity of an explanation, differentiating between observations and models, and determining the characteristics of a "good" physical model. Students in the class studied for this dissertation had to learn these "science processes." They gradually began to engage in them at the same time they were developing physics models. Classroom expectations for model use and standards for acceptable explanations gradually developed in the context of groups making sense of the teacher's and other students' statements. Such expectations and standards may be called classroom norms.

In studying a second grade mathematics teaching experiment, Yackel and Cobb (1996; Yackel, Cobb & Wood, 1991) and Bowers, et. al. (1999) chose to evaluate social norms that pertain to the development of mathematical understanding by children. These authors developed the concept of classroom norms so that they could talk about the networks of obligations and expectations that the teacher and students construct, negotiate, and continually renegotiate in a classroom. They noticed that some patterns of mathematical behavior came to be steady after a few weeks, and some standards for mathematical explanations were continually renegotiated.

In the language of Yackel and Cobb, norms are interactively constituted by participants in classroom discourse. The term "interactively constituted" implies that the teacher and students together develop norms in a classroom, and much of this process is not intentional or explicit. The teacher may declare expectations for students' work, and then different members of the class may interpret these expectations in somewhat different ways, and respond in individual ways. Students' different actions that are oriented towards' the teacher's statement constitute simultaneously their sense of obligation and their ways of responding. The teacher then responds to students' actions in a cycle of negotiation by interactive constitution.

Students and teachers rarely, if ever, talk explicitly about classroom norms. Rather, their actions constitute normative influences. Norms are researchers' constructs which provide a way to organize observations of obligations and expectations. Yackel and Cobb divided their observations from the second grade classroom into a set of categories based on both social and individual perspectives. Yackel and Cobb use the word "psychological" to imply a focus on the development of individuals. Taking the social perspective requires a shift in focus to the "social background" which provides the structure within which individuals and groups act. A table of their major categories is shown below (Cobb, 1996.)

Table 2-1: Cobb & Yackel's categories for classroom interactions

Social Perspective	**Psychological Perspective**
Classroom social norms regulate classroom activity. Similar norms could arise in any course with similar students.	Beliefs about one's own role, others' roles, and the general nature of mathematical activity in school
Sociomathematical norms define standards of mathematical action. They are specific to the content of the class.	Mathematical beliefs and values
Classroom mathematical practices are the common ways that students in the class tend to do math.	Mathematical conceptions These, along with mathematical practices, are typically the topics of math instruction

In the above table, entries across a row are reflexively related. For example, classroom social norms are reflexively related to individual students' beliefs about their roles in school. This means that students' beliefs about how they should act in class lead to the development of social norms, and simultaneously, social norms can influence students' beliefs about how they should act in class. The two can't be considered separately. Classroom norms come about partly via students' beliefs and values, while at the same time, beliefs and values may be affected by particular obligations and expectations that have been negotiated in the classroom, and which compose classroom norms.

The two sides of the table are complementary. The social perspective allows one to think about influences on individuals in the class, but does not directly address how social influences on any one student led to development. The psychological perspective can address how a student's thinking developed, but by itself can't explain the origins of the influences that led to this development. The two perspectives taken together can be used to tell a more complete story than either one taken separately.

In order to clarify the distinctions between classroom social norms, sociomathematical norms, and classroom mathematical practices, examples from Cobb's work are detailed below.

Classroom social norms

These are general patterns of expectation and obligation which influence activity in a classroom. They do not depend on the particular topic of the class, and so might be found in a class on any topic. However, social norms found in one classroom might only bear a family resemblance to norms found in other classrooms because of differences in teachers, pedagogical strategies, and the particular students in the class. One could probably identify many social norms in a given classroom, for example, there might be norms for how the class got started in the morning. Yackel & Cobb described classroom social norms that characterized the "inquiry oriented" structure of the classroom they studied and which seemed to be connected to the development of mathematical knowledge. For example, in this classroom, students were obliged to explain and justify their reasoning. At the same time, the rest of the students were obliged to listen to and attempt to understand their classmates.

Similar norms might have arisen in a physics class, or in a history class. The norms described by Yackel and Cobb may be common to inquiry classrooms, but they do not depend on the topic of instruction. Yackel and Cobb identified other types of norms that do depend on the topic. Social influences on the relative value of mathematical explanations, for example, were called sociomathematical norms.

Sociomathematical norms

Sociomathematical norms are those patterns of obligation and expectation that are connected with particular mathematical activity in a math class. For instance, Yackel and Cobb identified a sociomathematical norm for what constituted an acceptable explanation of a problem solution in their classroom. By the end of the school year, acceptable explanations had to be descriptions of actions on experientially real mathematical objects, that is, students had to say how they obtained their answers in terms of "tens" and "ones" which the class had come to accept. In general, the class developed particular ways to evaluate explanations or solutions so that when a student spoke in class, other students were able to decide whether that statement was acceptable or not, whether it was different from the others or not, and whether it was elegant compared to the others. Sociomathematical norms provided criteria for judging mathematical solutions or explanations. However, they were not the same as "standards" because they were not formulated or enforced by an authority external to the class, but were negotiated interactively by participants. Even though the teacher was the main promoter of standards, the responses of the students partly determined the expectations and obligations that later influenced student (and teacher) behavior.

Sociomathematical norms represent aspects of the culture of mathematics as it develops in a classroom. These norms define what is mathematical, what is good and what is not good, and in what ways. Hopefully they eventually resemble corresponding values within the larger mathematical community. By promoting particular sociomathematical norms, the teacher introduces aspects of the culture of mathematics into the classroom.

Sociomathematical norms, like classroom norms, are interactively constituted. Yackel and Cobb described an example of how a sociomathematical norm gradually developed. Recall the norm that "acceptable mathematical explanations had to represent actions on experientially real mathematical objects." When adding two digit numbers, some students did not accept another student's explanation when she talked of adding numbers in the tens column as if they were ones. One student wrote

$$\begin{array}{r} 12 \\ +\ \ 13 \\ \hline \end{array}$$

in vertical format and during his explanation said that one plus one equals two. Another student did not accept this and said "no, they are tens! Two tens are twenty!" The teacher's acceptance of this protest promoted students' later referral to digits in the tens place as representing tens. For instance, the character "2" in the number "25" was called "twenty." This pattern of speaking was only gradually adopted in the class, and students and the teacher were responsible, via their actions, for its adoption. This is another example of the "interactive constitution" of norms, and simultaneously, of the construction of a more robust "reciprocity of perspectives."

It seems that similar interactions in the course studied for this dissertation may have introduced features of the "culture of physics" so that norms for physics activity, or "sociophysics norms" developed in the course along similar lines. This dissertation investigates both classroom norms and sociophysics norms.

There were other aspects of the classroom activity that seemed to be "normative." Sometimes most of the children used the same algorithm to solve a particular kind of problem when another algorithm would also have worked. This may have been the result of the teacher responding positively to a particular solution offered by a student. Other students may have noticed and decided to do the next problem that way also. Yackel and Cobb named common methods of solving problems which developed by interactive constitution "classroom mathematical practices."

Classroom mathematical practices

Classroom mathematical practices were the actual mathematical methods that students used in the classroom to solve problems and answer questions. They became classroom practices once they were taken as shared, that is, when many of the children used similar methods and would have said that they were solving the problems the same way. These were different from sociomathematical norms because they were very specific, but they still had a normative character because particular classroom mathematical practices were "the way they did those problems in the class."

Consider a teaching experiment reported by Yackel and Bowers (1997) which involved an imaginary "candy factory" scenario. Children in the class packaged (hypothetical) candies in rolls of ten, which led to discussions of place value and pedagogically useful situations for discussing addition and subtraction. Some classroom mathematical practices involved counting by tens and ones to evaluate collections of candies, or grouping ten candies mentally when evaluating collections of candies. Eventually, most of the students in the class used these methods to count candies. Grouping collections of ten candies into rolls became accepted practice in the classroom.

Why study norms?

Cobb's research has taken the position that social aspects of classrooms must be considered when trying to understand individual learning, and vice-versa. Consideration of norms is important to understanding both social and learning processes in a mathematics classroom. Whether students ever listen to and try to understand each other's statements, for instance, determines in part whether they will be able to build on each others' ideas. Sociomathematical norms in particular are important in a mathematics classroom because they are the criteria by which students decide what is good or not good mathematics, which can eventually lead to adoption of "desirable" mathematical activity. Sociomathematical norms can represent a microculture of mathematics as it has developed in a particular class. From this perspective, a teacher promotes the development of sociomathematical norms that are reflective of values found in the larger community of mathematics.

Also, Cobb's framework intentionally places beliefs and values as "psychological correlates" of social processes. Students' beliefs and values have received attention lately because of their perceived influence on physics learning (Hammer, 1994). Physics educators might be interested in beginning to understand how students epistemological and other beliefs and values can be changed. According to Cobb and Yackel, these things are reflexively connected with the social system of the classroom, and could affect and be affected by particular social classroom norms.

Summary

The theoretical perspective taken in this dissertation includes a view of learning as processes of active reorganization of adaptive systems (Hutchins, 1995). In this case, the "adaptive systems" of interest are sometimes individual students with tools such as pencil and paper, other times small groups working at a computer or a whiteboard, and at still other times, the whole class. The kind of reorganization which was recognized in the course I studied involved developing abilities to talk, write, and draw meaningfully and productively on the topic of magnetism. Doing so required development of more explicit discussion of assumptions which led to a scientific "reciprocity of perspectives." Constructing and interpreting inscriptions seem to support communication within small groups, and simultaneously support the active reorganization seen as learning. Finally, the social components of interaction have strong and pervasive influences on what things students do, and why and how they do them. Studying social norms can help one make sense of a classroom.

The next chapter describes the course setting, students, and data collection, and also details my analysis methods. Chapters 4 and 5 offer results of these analyses.