

USING MULTIMEDIA
TO TEACH COLLEGE STUDENTS
THE CONCEPTS OF ELECTRICITY AND MAGNETISM

by

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Table of Contents

I.	Introduction to the research	1
A.	Context	1
B.	Purpose of the Study	8
C.	Research hypothesis	10
D.	Definition of terms	10
E.	Delimitations and limitations	11
F.	Significance of the study	11
II.	Research on student understanding	12
A.	Cognitive research	12
B.	Student difficulties as reported in the literature	13
C.	Different approaches to teaching electricity and magnetism	36
D.	The role of multimedia	38
III.	Theoretical framework	45
A.	The choice of the field concept	45
B.	The quantitative research paradigm	49
C.	The qualitative research paradigm	50
D.	Combining research designs	50
E.	Data collection	51
IV.	Pre-instruction	53
A.	Data collection procedures	53
B.	Data analysis procedures	58
C.	The pre-instruction data	58
i)	existence of fields	59
ii)	source of electric fields	69
iim)	source of magnetic fields	71
iiie)	representation of electric fields	72
iiim)	representation of magnetic fields	73
iv)	superposition of fields	74
v)	relationship between electric and magnetic fields	77
vi)	relationship between gravitational and electric fields	81
vi)	relationship between gravitational and magnetic fields	81
viii)	behavior of magnets	83
D.	Conclusions from pre-instruction data	85
V.	Multimedia lessons	88
A.	Batteries and bulbs	88
B.	Electric charges, fields, and forces	92
C.	Electric fields and potentials	94
D.	Magnetic fields and electric current	96
E.	Electric and magnetic fields	97
F.	The ratio of electric charge-to-mass for electrons	99
VI.	Post-instruction	101
A.	Post-instruction data	103

i) existence of fields	103
ii) source of electric fields	107
iim) source of magnetic fields	110
iiie) representation of electric fields	111
iiim) representation of magnetic fields	112
iv) superposition of fields	113
v) relationship between electric and magnetic fields	114
vi) relationship between gravitational and electric fields	121
vi) relationship between gravitational and magnetic fields	121
viii) behavior of magnets	124
B. General results from the post-instruction interviews	126
C. Multimedia versus lecture	128
VII. Summary and suggestions	132
VIII. Personal postscript	137
Appendix	141
References	165

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I. INTRODUCTION TO THE RESEARCH

A. Context

A serious concern for the quality of teaching has long been a part of the careers of physics faculty members. From the beginning it was seen that being a physics scholar does not necessarily qualify one as a good teacher (Richtmeyer, 1933). Teaching, for Richtmeyer, is an art; and in preparation for teaching, a person needs to be trained in more than subject content:

The teacher shall first acquire a thorough knowledge of his subject – a knowledge which extends much beyond those parts of his subject which he is initially to teach. ... The teacher, say, of science, must remember that though as a *teacher* he may be an artist, he is at the same time a *scientist*. He must approach the subject matter in his field *always* in the latter capacity. Without that approach he can never be a successful teacher. But he must approach the *presentation* of that subject matter as an artist; without *that* approach he can scarcely become a successful teacher. (Richtmeyer, *ibid.*, p. 3)

Nevertheless, the primary concern of physicists when they considered teaching was the mastery of physics content.

In short, physics is physics; history is history; education is education. And there is not much to be gained by mixing them, so far as methods of teaching are concerned. Teaching, like charity, begins at home. ... Again I repeat: “Physics is Physics.” And if we leave the selection and training of physics teachers to the physicists, and place upon them the responsibility for doing a good job, we need never fear, I fancy, that subject-matter requirements will be neglected. (Richtmeyer, *ibid.*, p. 5)

In the 1950s, a dissatisfaction with the state of high-school physics led a group of physicists at the Massachusetts Institute of Technology to initiate a project to reform high school physics. They formed the Physical Science Study Committee, which developed PSSC Physics with the following goals (Haber-Schaim, 1967):

- (1) To present physics as a unified yet living and ever-changing subject.
- (2) To demonstrate the interplay between experiment and theory in the development of physics.
- (3) To have the students learn the basic principles and laws of physics by interrogating nature itself, thus learning not only the laws but also the evidence for them as well as their limitations.
- (4) To extend the student's ability to read critically, to reason and to distinguish between the essential and the peripheral, thereby improving his learning skills in general.
- (5) To provide a sound foundation for those students who plan to study science or engineering at the college level.

PSSC Physics was created “in response to a widespread dissatisfaction among physicists and physics teachers with the state of secondary-school physics in the United States” (White, 1960). The course was intended to help students understand the concepts rather than memorize information. Lab equipment was simple, sturdy, and inexpensive when possible. Films were used to show things that could not always be done in the classroom. Laboratory work was used to generate ideas, not just verify them. PSSC physics had two primary criticisms in the 1960s: there was too much material with too little guidance for the teachers, and there was little effort made to get the students to learn the words and language of physics (Arons, 1960). From the perspective of the 1990s, PSSC

physics focused too much on physics content and too little on student capabilities.

The criticisms of the PSSC project led physicists and others in the 1960s, once again, to attempt reform of high school physics. Harvard Project Physics was begun by a high school physics teacher (F. James Rutherford), a university physicist (Gerald Holton), and a professor of science education (Fletcher G. Watson). This project had three goals: “to design a humanistically oriented physics course, to attract more students to the study of introductory physics, and to find out more about the factors that influence the learning of science in schools” (Project Physics Course Text and Handbook, 1970). This led to the design of a course with the following intended effects:

- (1) To help students increase their knowledge of the physical world by concentrating on ideas that characterize physics as a science at its best, rather than concentrating on isolated bits of information.
- (2) To help students see physics as the wonderfully many-sided human activity that it really is. This meant presenting the subject in historical and cultural perspective, and showing that the ideas of physics have a tradition as well as ways of evolutionary adaptation and change.
- (3) To increase the opportunity for each student to have immediately rewarding experiences in science even while gaining the knowledge and skill that will be useful in the long run.
- (4) To make it possible for teachers to adapt the course to the wide range of interests and abilities of their students.
- (5) To take into account the importance of the teacher in the educational process, and the vast spectrum of teaching situations that prevail.

The Project Physics curriculum sought to introduce all students to physics, to make physics more than just a college preparatory course, and to nurture the

"hidden" physicist in each student. Hence, a concern for the capabilities of the students began to attract the attention of physics educators.

An additional shift of physics educators from primary concerns about content to student capabilities occurred in the 1970s. The abilities of students to do mature reasoning in physics was beginning to be examined. The assumption that entering freshman college students think logically was tested by McKinnon & Renner (1971). They found that the college experience did not teach one how to think; colleges and universities "look at their primary purpose as the transmission of information." A review of several research studies led McKinnon & Renner to suggest the use of inquiry-based courses. They hypothesized that "(1) The secondary educational experience does not now promote logical thinking in students. (2) An abundance of inquiry-oriented courses taught by teachers who are products of college and university professors who practice and profess inquiry must come into being before an alternative to the [transmission of information (ed.)] hypothesis can be accepted." Unless courses are taught by teachers who learned and use inquiry-based methods, the secondary educational experience will not promote logical thinking in students.

Students can develop more advanced reasoning patterns with the help of teachers who are aware of reasoning patterns needed to understand a particular science course and who can identify the conceptual emphasis and demands of the subject matter (Karplus, 1977). If students are to learn to do more than memorize, they must have experiences that force them to think about what they have observed and compare that to their preconceptions (Fuller, Karplus, and

Lawson, 1977). This type of learning requires that the teacher have some understanding of how the students are reasoning prior to and during instruction.

The concern for the development of reasoning led Swiss scholar Jean Piaget (Inhelder & Piaget, 1958) to conduct some of the early studies of formal thought. His use of semi-clinical oral interviews using physics tasks forms the foundation for much of the research being done on college student reasoning and learning. Lawson and Wollman (1975) applied some of Piaget's ideas to the solving of physics problems. Fuller, Karplus, and Lawson (1977) adapted Piaget's work to explore the differences in reasoning between students who had completed a term covering Newtonian mechanics and students who had not. Arons (1982, 1983, 1984a, 1984b) also explored reasoning and patterns of thinking in physics.

The concern for better knowledge of how students understand physics concepts started with extensive studies of topics of kinematics and mechanics and has gradually spread into other physics topics, such as light and optics and electricity and magnetism. Much of the early research into college student understandings of physics was conducted by the Physics Education Group at the University of Washington, led by Dr. Lillian McDermott. The student understanding of the concepts of velocity and acceleration in one dimension were investigated by Trowbridge & McDermott (1980 and 1981). McDermott (1984) published a paper on research on conceptual understanding in mechanics. Grayson, Trowbridge, & McDermott (1987) investigated using computers to identify student conceptual difficulties. McDermott, Rosenquist, & van Zee (1987) explored student difficulties in using graphs in physics. Grayson, van Zee, &

McDermott (1986, 1987) investigated how students understand graphs of motion and how computers can be used to overcome student difficulties. Rosenquist & McDermott (1987) discussed a conceptual approach to kinematics. Lawson & McDermott (1987) investigated student understanding of the work-energy and impulse-momentum theorems. Goldberg & McDermott (1986, 1987) studied student understanding of the formation of images by mirrors and lenses.

McDermott discussed teacher preparation in the sciences (1990) and the match between how physics is taught and how students learn (1991). The successful use of the semi-clinical interviews to understand college students' preconceptions in mechanics was duplicated in studying students' understandings of electric circuits (Evans, 1978) and electricity and magnetism (McDermott and Shaffer, 1992).

Since one of the early experiences children have with electricity is the use of a flashlight, it was reasonable to begin an investigation into student understanding of electricity with some exercises with batteries and bulbs (Evans, *ibid.*). It was found that *college* students have substantial misconceptions about electric currents. For example, many college students were not able to construct a complete circuit. They believed that current was "used up" in a circuit. They thought that the arrangement of components in a simple series circuit changed the behavior of the circuit. A number of experiments to explore simple circuits were developed to confront and challenge students' ideas. These experiments began with making a light bulb glow with just a battery and a single wire, and progressed to more complex circuits. Concepts such as current, voltage, and power were developed in this process (Evans, *ibid.*).

Given the successes in teaching simple circuits based upon the results of research into college student conceptual understanding of electric current (Evans, *ibid.*, Shaffer and McDermott, 1992), it was decided in this research to extend such research into student knowledge of electric and magnetic fields. Once student difficulties in this area are known, it may be possible to develop effective instructional materials to teach the concepts of electric and magnetic fields. Since the field concept is more advanced and abstract than the electric current concepts, the broad range of interactive, multimedia teaching strategies will be employed in this project to help students learn the field concept better.

Multimedia teaching can bring phenomena from the outside world into the classroom where it can be analyzed in new, interactive ways. For example, one can use video to study and model the motion of an athlete, something not easily done in a conventional classroom setting (Zollman, Noble, and Curtin, 1987). Computers and video can be used together to explore real motion data (Dengler, Luchner, and Zollman, 1993). Computers can provide immediate feedback, individualized instruction, and facilitate learning (Bork, 1979 and 1984). Graphics, animation, video, and sound (essentially, video and computers) can increase both the knowing of physics and the motivation of the learner (Fuller, 1993a). This combination of computers and video is known as multimedia, and is central to the work being done by the University of Nebraska's Research in Physics Education Group.

Within the current research literature that discusses student misconceptions in physics, a few papers report on a single aspect of electricity and magnetism: simple electric circuits. Almost no research has been done in

trying to understand student difficulties in learning the concepts of electric and magnetic fields. In addition, there has been little research on how the use of multimedia laboratories can improve students' reasonings and their understandings of physics.

B. Purpose of the study

This mixed-method research study had three parts: The first part was to explore the common preconceptions of undergraduate students about the fundamental concepts of electricity and magnetism using personal interviews, personal observations, and written instruments. This information was used to develop written pre-instruction instruments to gather additional data to aid in designing the multimedia activities that were developed in the second part of this research. The exploration of student preconceptions is based on the work and follows the trends of other physicists in relating research to the classroom (McDermott and Shaffer, 1992; Goldberg and McDermott, 1987; Reif, 1987).

The second part was to develop multimedia activities to teach electricity and magnetism based on experience, existing research data, and the data gathered in the first part of this study. These multimedia lessons were organized as Learning Cycles (Karplus, 1977).

The third part of this study was to analyze the effectiveness of these multimedia activities in helping students develop mature conceptions of electric and magnetic phenomena. Post-instruction tests were administered in order to determine to what degree students' preconceptions were changed. These tests

were the written instruments created in the first part. Some post-instruction oral interviews were also conducted.

The multimedia lessons can be described as having some or all of the following multiple parts: a traditional hands-on approach, a microcomputer-based laboratory, and an interactive video portion. The dependent variable, students' understandings of electric and magnetic fields, can be described as the concepts students use to explain phenomena of electric and magnetic effects. The results of this study will measure the effectiveness of these multimedia laboratories and will be used to suggest improvements in laboratory activities to help students improve their understandings of electric and magnetic fields.

C. Research hypothesis

Effective instructional materials can be developed through the use of research into students' understandings.

D. Definition of terms

preconception: any idea or meaning for a concept which precedes formal instruction. In many instances students' preconceptions are greatly different from physicists' conventional explanations of phenomena.

misconception: any idea or meaning for a concept which does not agree with the operational definition (McDermott, 1992). In this thesis, this term is reserved for students' unconventional explanations, usually after instruction.

multimedia: a system of nonlinear, or non-sequential reading and writing, including graphics, video, animation, and sound (Fuller, 1993).

semi-clinical interview: for this research, the interviews had a protocol (certain items that were a part of every interview), but no pre-determined structure. The interviews were demonstration-oriented, with subjects asked to predict, observe, describe, and explain some phenomenon.

E. Delimitations and limitations

This study will confine itself to tests, observations and interviews to determine students' conceptions about electricity and magnetism. These students were enrolled in an introductory algebra-based college general physics course. The results of this study may be generalizable to other uses of multimedia lessons with college physics students.

F. Significance of the study

Improved methods of instruction in a physics laboratory should change students' current perceptions of the world in which they live. The multimedia approach may provide a better method of instruction by bringing examples from the outside world into the laboratory where they can be examined with modern technology, thereby improving student understanding of natural phenomena and their logical reasoning. This study reports on students' understandings of electric and magnetic fields and examines the effectiveness of the multimedia activities for teaching concepts in physics.

II: RESEARCH ON STUDENT UNDERSTANDING

A. Cognitive Research

Cognitive research is the study of knowledge acquisition and use.

Cognitive researchers try to understand the initial state of the learner, the process of teaching and learning, and the desired final state for the learner (this varies from one field to another; in physics, one desired state would be a learner with improved reasoning). While cognitive research has grown in recent years, many college faculty remain unaware of the results of this research. The implications of cognitive research for physics teaching was discussed by Mestre and Touger (1989). Physics instruction ought not be based on the absence of prior knowledge in the student, rather it must acknowledge the existence of naive theories that most students bring with them. Such theories have been developed to help the student explain the world as the student experiences it, but may contain misconceptions. Such misconceptions are not easily replaced, and may remain strong in the student's way of thinking (see also Redish, 1994, for example). Suggested changes in the way physics is taught include changing the traditional physics textbooks to rely less on quantitative paper-and-pencil problem solving and to rely more on qualitative explanations, and providing students with diverse examples that show the range of a concept's applicability (Mestre and Touger, *ibid.*). This change requires a concerted effort, and it must be sustained in the daily practices of the teacher.

For the purposes of this paper, *misconception* can be defined as any idea or meaning for a concept which does not agree with the operational definition

(McDermott, 1992). Operational definitions assign “meaning to a variable by specifying the activities or operations necessary to measure, categorize, or manipulate the variable,” (McMillan & Schumacher, 1993, p. 83). In other words, a physics concept can be defined operationally by how it is observed and measured.

B. Student difficulties in learning the concepts of introductory electricity and magnetism as reported in the literature.

When one considers student difficulty in learning the concepts of introductory electricity and magnetism, there are many aspects of electricity and magnetism that can be labeled as concepts, where a concept can be defined as “an abstract or generic idea generalized from particular instances,” (Webster’s Ninth New Collegiate Dictionary). Once specific concepts are identified for students to learn, student difficulties regarding these concepts can be investigated. A look through undergraduate textbooks (Serway, 1994; Hecht, 1994; Giancoli, 1991; and Tipler, 1991, for example) reveals the concepts that have traditionally been regarded as important. Examples of such concepts are electric charges, magnetic poles, electric and magnetic fields, electric potentials, and electric circuits. Other concepts in electricity and magnetism build on these; flux, for example, is a measure of the number of field lines penetrating an area. It is important that a student have a good understanding of *field* before that student can have a useful understanding of *flux*. It follows that researchers need to understand the difficulties students have learning the concept of field before studying student difficulties in learning about flux.

Research has indicated that college students have several misconceptions about electricity (Evans, 1978). Such misconceptions included that current is "used up" in the circuit, and that the battery was a constant current device. Students had difficulty with the concept of a complete circuit (students often tried to make a bulb light by running a single wire from one terminal of a battery to one terminal of a bulb, but not completing the circuit). The usual textbook treatment of electricity was too abstract for many students. A program of instruction was designed for students' classroom encounters with simple electricity in either high school or college. The theme was a model for electricity in which the necessary abstractions were introduced only as the student saw the need for them. Only simple equipment (batteries, light bulbs, and wires) and a qualitative model were used at first, then quantified. In the process, students developed operational definitions for such things as resistance and current. Only common words such as "obstacle" and "flow" were used until their operational definitions were satisfactory, at which time the technical terms "resistance" and "current" were introduced. The first project for the student was to make a simple circuit with a single battery, wire and light bulb. Once this was completed, the students could begin to distinguish between insulators and conductors by inserting samples of various materials in the circuit. Then more bulbs and wires were included. Students proceeded to more complex circuits and developed the concept of current. They learned to compare resistances by the relative brightness of bulbs in the circuit. In the process, misconceptions were challenged. The students developed rules for this model which could predict the outcome of many experiments. At some point, it became necessary

for the students to define some amount of resistance as one unit of resistance, then base all future measurements on that definition. Rules for adding resistances in series and parallel were developed by experimentation, so that more complex circuits could be reduced to combinations of simple circuits which could be easily analyzed. A standard unit for current was defined, followed by potential difference. These three quantities (resistance, current, and potential difference) form the basis for simple electricity. In summary, instructional methods were developed for exposing misconceptions in simple electric circuits, and offering a model for correcting these same misconceptions. One of the methods used was that the concept names were not introduced until they were needed. This helps avoid the common problem students have by confusing terms such as power, energy, and voltage. It is useful for the student to have a concept to which to apply a label, rather than having a label and searching for a place to put it (Evans, *ibid.*).

The choice of current as the fundamental concept in simple circuits was challenged by Cohen, Eylon, and Ganiel (1983). They studied (the equivalent of first-year college) students' conceptions of potential difference and current in simple circuits. In their view, potential difference is the prime concept, and current is secondary. While Evans' choice of current might work well at the introductory level, Cohen et al. felt that this may be a cause for misconceptions at later levels. For example, students learn that potential difference can be defined by $V=IR$. They can reason that if $R=0$, then $V=0$. Similarly, they reason if $I=0$, then $V=0$. However, the latter is not necessarily true. Students can become skilled at performing algorithms while still not qualitatively understanding

simple circuits. For example, a student may show mathematically that adding a resistor in parallel reduces total resistance, but still be surprised when it happens experimentally. In this situation, students tend to resort to “local” thinking, and do not take into account that a change in one part of a circuit may cause changes in other parts of the circuit. Students also indicated a belief that batteries are a source of constant current, and had trouble with the concepts of power and internal resistance. By making potential difference the primary concept, perhaps such reasoning errors could be avoided (Cohen et al., *ibid.*).

Similar misconceptions were found to be held by French students (Dupin and Johsua, 1987). This study examined 920 students, ranging from 12 years of age to the fourth year of university, in an attempt to find the source of the misconceptions about electricity. For example, students were taught that current in a series circuit is constant everywhere in the circuit. Then, a student may reason, the battery is a source of constant current. Some common misconceptions often sufficed for the situations most students encountered. Therefore it was concluded that teachers need to focus on the roots of these misconceptions and the possible effects of teaching methods (as with the battery-as-constant-current-source problem just discussed). Teachers must extend the types of problems given to pupils in order to challenge the concepts the students may have, e.g., problems that require reasoning using potential difference (Dupin and Johsua, *ibid.*).

In the Netherlands, the same common student difficulties as found in the above studies (batteries supply constant current, current is “used up” as it flows through circuit elements, local thinking, using different concepts

interchangeably) were reported by Licht (1991). A five-block procedure for teaching electricity was suggested: (1) a phenomenological orientation, (2) a qualitative macroscopic treatment, (3) a qualitative microscopic treatment, (4) a quantitative macroscopic treatment, then (5) a quantitative microscopic treatment including the concept of the electric field. It is this last step, concerning the electric field, which sets this study apart from the previous studies. No prior study was concerned with the field concept – every study was concerned with the circuit concepts. In block 1 (phenomenological orientation), a descriptive style for simple circuits, where no technical physics terms are used, was proposed. Block 2 (qualitative macroscopic treatment) addressed the students' desire for something to be "used up," namely energy. Energy is more closely related to phenomenological observations than current or voltage, according to Licht. Current should be introduced shortly thereafter in order to highlight the differences between current and energy. Students developed functional relationships at this stage, such as relating the number of batteries in series to the energy produced. The concept of voltage was introduced at this stage as well. Electrons were introduced in block 3 (qualitative microscopic treatment) as the material that composes the current flow, and electron density as the cause for the flow (electrons flow from high to low density in his model). Block 4 (quantitative macroscopic treatment) began with a test to indicate their qualitative development. Ohm's law was introduced at this stage to relate previous concepts. However, the student had to develop the relationships themselves; they were not just given a formula to memorize. Block 5 (quantitative microscopic treatment) was used to explain the nature of the

interaction between electrons (from block 3) using the electric field. Typically, students apply the field concept only in situations using charged spheres and the like, rarely making any connection to circuits. Combining fields and circuits can lead to a better understanding of the three concepts this study was designed for: electrical energy, voltage and current.

Licht also made the point that it may not be the misconception that causes the learning difficulty, but the lack of any related concept. Redish (1994, p. 799) stated that "It is reasonably easy to learn something that matches or extends an existing mental model." If there is no related concept, a student may have a difficult time learning a new concept. Therefore, Licht recommended a progressive approach using hierarchical levels as outlined above. This approach can connect concepts that students may not connect on their own.

A two-part study, closest to the process of this research, was conducted on the physics of simple electric circuits by McDermott and Shaffer (1992). The goal of the study was to examine student difficulties and to offer instructional tutorials that address these difficulties. In the first part, their investigations contributed to a research base from which a curriculum could be developed. Interviews were conducted to identify specific areas of difficulty, then laboratory activities and class discussion, as well as homework and tests, were used to provide additional information about student reasoning. Students often used several different terms (current, voltage, energy, and power) interchangeably. Students failed to distinguish among related concepts (such as current and energy), lacked concrete experience with real circuits, failed to understand the concept of a complete circuit, believed that current is "used up" in a circuit, and

believed that a battery is a constant current source. Students had difficulty with potential difference, series and parallel circuits, and had a tendency to focus attention on the number rather than the nature of the elements and their function in the circuit. Students had trouble reasoning qualitatively about circuits, even if they could solve numerical problems. Students often have misconceptions that present methods of instruction fail to address. Specific examples were given illustrating the symptoms of such misconceptions.

Shaffer and McDermott continued their analysis in the second part of their study. The method they outlined for exposing the errors in the misconceptions was very similar to the method used by Evans: simple circuits were used to demonstrate inconsistencies in the misconceptions, then circuits were used to develop new concepts and rules. A qualitative description was developed, with terms introduced only after the concept was sufficiently developed.

The students began, as in Evans' study (above) by trying to make a bulb light with a battery and a single wire. Only four similar arrangements work (touch either terminal of the bulb to either terminal of the battery and touch the other bulb terminal to the other battery terminal). By comparing the circuits which work with the circuits that do not work, the students discovered that there must be a complete path from one battery terminal, through the element, and back to the battery – a complete circuit. Recall that one of the student difficulties with circuits is “failure to apply the concept of a complete circuit.” Thus one learning difficulty is specifically addressed in this approach.

When the students connected the terminals of a battery with a wire, the wire got hot. Students were guided to conclude that something must be flowing

from the battery into the wire. This flow was compared to complete circuits, where bulb brightness indicated the amount of flow. The flow was identified as electric current (although the nature of this current was not specified yet). Thus a concept was developed before the technical term was used.

The students connected two identical bulbs in series and observed that the bulbs were of equal brightness, although less bright than a single bulb. This implied that current is not “used up” by the first bulb. If two different bulbs were placed in series, it may have appeared that one bulb used up current, causing the second bulb to be dim. However, when the bulbs were reversed, it became clear that the current was not used up, the order of the circuit elements did not matter, and current direction was not important.

Connecting two identical bulbs in parallel across a battery showed that each bulb would glow as brightly as the other, and both would be as bright as a single bulb. The students recognized that this meant the current through each bulb was the same, therefore the current through the battery must not have been constant, but it depended on the circuit arrangement.

The concept of resistance arose from the observation that a bulb dimmed when a second bulb was added in series. By connecting more complicated arrangements, students realized that local reasoning is not sufficient for most circuits. An ammeter was introduced as a way to quantify the amount of current flowing.

When the role of the battery was investigated (by adding batteries in series and across a single bulb) the concept of potential difference was introduced. The increase in bulb brightness with the addition of each battery

showed the need for the new concept. A voltmeter was used in place of the bulb to quantify potential difference. At this point, there was very little to show students the difference between potential difference and current. By using the ammeter and voltmeter, the difference was shown.

Additional experiments with the meters allowed students to develop Ohm's Law (where ohmic materials must be used, of course). By requiring that students articulate their reasoning, Shaffer and McDermott helped the students to maintain clear mental models. Repeated practice with schematic diagrams helped students learn that such diagrams may not represent the physical arrangement of the circuit elements.

Shaffer and McDermott noted that student difficulties are not always due to misconceptions. Sometimes the problems were with incorrect reasoning or inability to understand diagrams. However, for overcoming misconceptions that are persistent, they recommended the process of *elicit*, where the error is exposed, *confront*, where the error is challenged, and *resolve*, where the error is corrected. This teaching method exposes the underlying difficulty so it can be directly challenged. This method matches the statement by Redish (1994, p. 801) that "In order to change an existing mental model the proposed replacement must have the following characteristics: (a) It must be understandable. (b) It must be plausible. (c) There must be a strong conflict with predictions based on the existing model. (d) The new model must be seen as useful."

Many of the misconceptions found for simple circuits are explicitly addressed by this approach. Real experience with circuits is an integral part of the method. This approach is based on research in student learning (the first part

of the study was such research): conceptual understanding comes first, followed by the formalism.

Shaffer and McDermott also described how to adapt their laboratory-based curriculum into a tutorial for use in a standard lecture course, and described how their curriculum was more successful than the traditional approach. In particular, they noted that the development of the concept may be more important than the ability to do numerical problems. A short-term assessment of their tutorial was conducted with about 500 students in four courses: a lecture-based course with tutorials, a parallel calculus-based course without tutorials, a lab-centered calculus-based course at a liberal arts college, and an algebra-based course. The students were asked to rank five bulbs in a simple circuit in order of brightness, and to explain their reasoning. Students who did not have the tutorial answered correctly less than 50% of the time (there was little difference in results from the calculus-based lecture course and the algebra-based lecture course). Students who had completed the tutorial answered correctly about 65% of the time at the liberal arts college, and more than 75% of the time in the calculus-based course with the tutorial.

A longer-term assessment was carried out with about 100 students in the third quarter of a calculus-based physics class. The material on DC circuits was covered in the second quarter of the course. About half of the students had worked with the tutorial. On a qualitative question, the correct response was given by approximately 15% of the students who did not use the tutorial, whereas 45% of the students who had used the tutorial gave the correct response

together with acceptable explanations. This makes this approach appear successful.

They concluded with a statement that there was a need for an ongoing investigation into student difficulties in all areas of the standard introductory course, including the development of effective instructional strategies.

Notice that Shaffer and McDermott chose to use current as the basis for concept building, rather than potential difference or energy. They pointed out that if potential difference is chosen as the primary concept, then students realize that there must be something flowing due to this “pressure.” Thus the concept of current is brought out quickly anyway. This makes it more likely that students will confuse the two concepts (current and potential difference). When current is used first, students do not need the concept of potential difference immediately. (Shaffer and McDermott say that students are not bothered by the lack of something causing the flow of current, whereas a physicist would be bothered.) If energy is introduced too early in the development of the model, students have trouble with the dissipation of energy and the conservation of current. Therefore, it is reasonable to begin with the concept of current.

A different approach that builds on research was taken by Berg & Grosheide (1994, 1995). They were interested in overcoming student difficulties in differentiating current, voltage, and energy, as well as the idea of current consumption in a circuit. Their approach was also intended to provide long-term retention of these basic concepts. They decided to use an analogy to which students could easily relate. The water analogy is popular, but Berg & Grosheide decided that students are likely to be at least as unfamiliar with water pressure

and hydrodynamics as they are with voltage and electrostatics. Therefore, they chose to model “current particles” as little creatures. Energy was carried by the creatures in backpacks, just as current particles carry energy. Voltage was introduced as the energy per particle, or the energy per backpack. As the little creatures passed an appliance, they gave some of the energy from their backpacks to the appliance. This was intended to keep the concepts of voltage, current, and energy separate. Also, this analogy was acted out in the classroom using students and beans. This helped the students form a concrete mental model of what was happening. At the same time, the analogy was not so life-like as to be taken seriously. The students realized that it is just a tool to help them learn.

Two Dutch schools were used in this study; School A served students that are regarded as being in the upper 30%; School B spanned the entire ability range. The students used were 14 to 15 years old.

There were 45 students used from School A, with six of these followed through a pre-interview, two midterm interviews, a post interview, and a retention interview 18 months following the post interview. When first introduced to this model, the students were asked if they believed this model was real; none of them did. When asked why it was being used, the students replied that it was being used because it was simple. So it was clear to the students that this was just a model to help them form a mental model for understanding electric circuits. During the retention interview, all six students immediately remembered the model of creatures with backpacks, and with the model they could distinguish current from energy. Some associated voltage with

the size of the backpack. When asked “Do you believe that there are little creatures in the wire?” one student responded “No (decidedly), but I imagine particles going through the wire. But I think the model with the creatures is very useful.” Another student thought it was childish - they needed the model then (when first introduced to circuits) but not anymore (at the time of the post interview).

When these six students were asked questions related to specific misconceptions during the retention interview, they demonstrated that this analogy worked well for them in some areas, but not others. All six strongly supported current conservation (stating that current in is equal to current out). They also remembered that current transports energy to appliances, where the energy is transformed, but the current is not consumed. However, many students continued to think of a voltage source as a source of constant current or constant energy. Berg & Grosheide suggested that the cause for this was that the teachers did not sufficiently stress the differences between current, voltage, and energy.

At School B, 130 students were pre- and posttested. Also, retention interviews were conducted with six students from School B three years after they studied circuits; three students were science majors and three were not (the Dutch school system specializes earlier than the American system). The three science majors had studied circuits more in-depth since being introduced to the model being studied here. Two of these students vividly remembered the model, although one had to reconstruct his knowledge about the differences between voltage, energy, and current using the model during the interview. The third

student recalled the model, but preferred to use the more formal approach from a school book. Details were not given about just how well they remembered the concepts, except for the one who had to reconstruct his knowledge during the interview. The implication was that these three students remembered the concepts correctly.

The three non-science majors from School B elected not to take physics in senior high school. One student was taught by a teacher who had the class pretend to be these little creatures and walk through the class carrying beans (energy units) and going through constrictions (resistance). This student recalled the need for a complete circuit and could connect current and energy correctly, but could not relate these to voltage. The other two non-science majors could relate current and energy transport, but could not explain differences between current and voltage.

The results for the 45 students from School A and the 130 students from School B on the pre- and posttests were good, if not complete. On the pretest, only 50% supported current conservation, compared to 80% on the posttest. It was stated that “the idea of a current which is conserved and which transports energy which gets transformed in the appliances” was strongly supported by the students from the two schools. The students showed the same problems on the posttest as were found in the retention interviews: students continued to think of a voltage source as a source of constant current or constant energy. While students seemed to understand the contrast between current and voltage or energy, many students had trouble with the difference between voltage and energy.

For a basic conceptual model, this analogy works well. Students develop a good mental model for current. However, other student difficulties are not resolved - voltage and energy are still confusing to the students. Berg & Grosheide believe that many teachers used in the study taught in their former style and did not use the analogy properly. Whatever the cause, the model as a whole met with limited success; students understood the role of current in simple circuits, but not much else.

This model does not discuss that current is the flow of charges; therefore, the manner in which voltage causes current to flow is not at all clear. The model seems appropriate for use only with students who have not encountered electricity in school, as only the most basic concepts are learned. Certainly this model is not sufficient for developing deep understanding, but it may be a good place to begin so students have learned at least the idea of current conservation early on in the study of circuits.

Since only six students from each school were interviewed, it is probable that these results are not typical. However, for early research on this method, it does not seem unreasonable, given the difficulty of tracking students for a period of years.

Research on students' understanding of electric fields and potentials has been done in Sweden by Tornkvist et al. (1993). Students were administered a written test, consisting of a drawing of electric field lines between three conductors. More than five hundred second-year college students (all of whom had studied calculus) were tested as part of the final exam for a compulsory

nonmajor course in electricity and magnetism at the Royal Institute of Technology in Stockholm (see Figure 1).

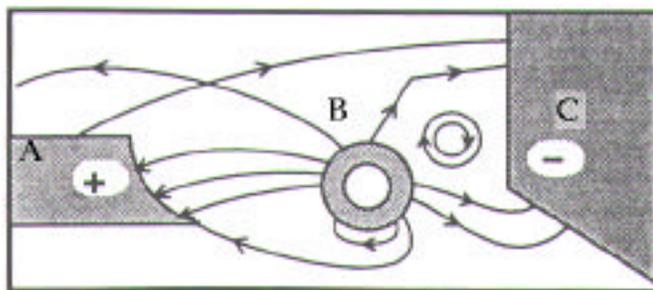


Figure 1: The figure above is a perpendicular cut through long, parallel pieces of metal. A and C are charged, B is neutral. There are no currents; the system is stationary. In this figure a number of electric field lines are drawn. Find all the errors in the figure and explain why the field lines cannot be drawn this way.

There were several errors in the way the lines were drawn. The students were asked to identify all errors in the drawing and explain why these were errors. 85% of the 545 respondents did not react to field lines crossing, and 96% did not notice that field lines do not have sharp bends. Therefore, a vast majority of the students did not “master the mathematical concepts of continuity of a function and its derivatives well enough to apply them in a non math context.” (p. 336). Many students do not take knowledge gained in one subject (calculus) to another (physics).

Oral interviews were conducted shortly after another group of college students finished their examination for the electricity course (Tornkvist et al., 1993). The students were provided diagrams of field lines and asked to draw force vectors, field lines, and trajectories for charges. Rather than using mathematical reasoning, the students treated field lines as real objects, not curves depicting the vector nature of some quantity in some location. Many of the

mistakes students made were not related to the field concept, but to the representation. For example, 21% of the students drew vectors with curved arrows. When asked to predict the trajectory for a charged particle in a given electric field, 76% of the subjects predicted that the particle would follow the field lines. This showed that students did not understand the vector representation for electric fields.

This study shows how difficult it can be to probe student understanding of the field concept when the students do not understand the representation used for the field. The students have trouble using the mathematical, analytical, and representational tools of physics, and this makes understanding difficult for the students.

Improper representations can cause additional difficulties for students (Iona, 1990). For example, many textbooks contain pictures that are meant to represent particular phenomena, but the pictures themselves are lacking in clarity; to illustrate sources of larger electric fields, a book may show a larger number of charges, while the truth may be that it is the charge *density* that is larger. These types of errors need to be avoided to prevent the student from forming misconceptions. Students also have trouble extending two-dimensional representations into three-dimensional space (Freeman, 1995).

Superposition of fields is another concept with which students have difficulty (Viennot and Rainson, 1992; Rainson, Transtomer, and Viennot, 1994). Two obstacles to student understanding were suggested in preliminary research. One is that students may think there is no field present if there is nothing for the field to act on; or, in a similar manner, since the charges in an insulator are not

free to move, there must be no field in an insulator. This is referred to as *field if mobility*. The other suggested obstacle is that students often think that the terms on the right-hand side of a formula cause the terms on the left. This is called *cause in the formula*. This study was undertaken to determine the impact of these obstacles to student learning.

Ten students were interviewed, after which four test questions were created, each associated with one or both of the obstacles. A total of 1145 college-level students in France and Sweden were tested. All students had, at a minimum, had a course in electric circuits and an introduction to electrostatics. Indeed, a majority (over 70% in some samples) of students expressed a belief consistent with the statement that an insulator cannot have an electric field inside since charges are not free to move. This confirmed the first obstacle. Questions regarding the nature of the electric field near a conductor indicated that students thought that the surface charge density causes the electric field, since the equation for the electric field has the surface charge density included. The students (it is not easy to determine from this study how many, but it seems a majority) do not see the surface charge as a reaction to the applied field. These results confirmed the presence of the second obstacle. Another test question concerned electric fields in the wires of a simple circuit. Students were asked to draw the electric field vectors in various parts of the circuit, identify the sources of the fields, and explain the change in direction of the field in different parts of the circuit. They were also asked if they had thought about that before. Students expressed the belief that the current itself caused the electric field. Other

answers included the battery as a source for the field. Only 6% of the students said they had ever thought about it before.

Rainson et al. concluded that an underlying problem is that students do not make the connections between related concepts; the information from one course is not associated with information learned in another course. In this specific case, students do not make the connections between electrostatics and electric circuits (that is, steady-state fields drive currents), topics which may be covered in the same course. (It should be noted that simple electric circuits can be explained adequately at the introductory level without electrostatics. Nonetheless, electrostatics is necessary for a deeper understanding of the operation of simple electric circuits.) So it seems that students do not even transfer knowledge from one topic to the next.

None of the questions used in these studies concentrated solely on the *concept* of superposition. Each question was complicated by the presence of macroscopic bodies, either insulators or conductors. Some of the questions depended on the ability to understand or manipulate equations, rather than simply understand superposition. The two obstacles mentioned, *field if mobility* and *cause in the formula*, indicate that it was (1) the production of fields and (2) the use of equations that may have caused student difficulties, not superposition. In fact, the abstract for one of the studies (Rainson, 1994) indicates that the article presents “an analysis of the difficulties experienced by students when applying the principle of superposition,” not an analysis of student understanding of the concept itself.

Student difficulties learning concepts of magnetism have not yet been studied extensively. Various sources (Twiest & Twiest, 1992; and Haupt, 1952, for example) have listed several suspected misconceptions. (The following list is compiled from various sources, based on people of various ages and educational backgrounds, and is not meant to be exhaustive.) Student difficulties may include the following:

- failure to understand the Earth as a magnet
- failure to understand the operation of a simple compass
- failure to understand the attraction of magnets to some (but not all) metals
- failure to understand the attraction of opposite poles and the repulsion of like poles
- belief that north and south magnetic poles are the same as positive and negative electric charges
- belief that poles can be isolated (monopoles)
- belief that magnetic fields are the same as electric fields
- belief that magnetism holds objects to the Earth

Also, there is considerable student difficulty concerning the forces felt by moving charges in magnetic fields (as well as forces felt by charges in electric fields).

To overcome student difficulties in learning concepts, students must see the need for a concept and develop operational definitions before applying a technical term. In learning about circuits, current was the primary concept used by Evans. Everything in circuits was built upon the current concept.

Conceptual learning was important to Cohen et al., but in their view, the primary circuit concept was potential difference, since that caused everything to happen in a simple circuit.

A five-block model for teaching, starting with qualitative descriptions and proceeding to quantitative descriptions was developed by Licht. Start students with the concepts; afterwards they learn the formalities. Energy should be taught first, since that is the concept most familiar to students. Learning is easiest when new information can be connect to existing mental models (Redish, 1994).

No single method of teaching electric circuits has been clearly shown to be best. All show the importance of addressing specific student misconceptions directly. If these research and development techniques are to be successful in teaching electric fields and magnetism, then a study of student preconceptions of these phenomena must be done. A few of the difficulties students have in these topics are becoming known. Fields are often too abstract for students. The methods used to represent fields cause confusion for them. Add the use of other representations (force vectors on top of field lines, then add trajectories) and students get overwhelmed.

From the research currently being done on student understanding of fields, it is known that the field representation is a problem. Students have been exposed to fields before they encounter electric fields, since most students have studied gravitational fields. But the concept of a gravitational *field* may not be stressed enough. When electric fields are introduced, they seem like a new concept. Certainly students have been taught about gravitational potential energy, but few are aware of gravitational potential. Perhaps teaching that concept would make learning the concept of electrical potential easier. This is an area for research that deserves attention.

The same can be said for magnetism. Magnetic fields are related to electric fields, but many students fundamentally misunderstand the relationship. This causes many problems, such as when to apply a Right Hand Rule, and when not to. Magnetic poles and electric charges are not separated well enough in the mental models of many students. Research on how students think about these concepts is needed so they can be taught more effectively.

Also mentioned above are concepts that build on other concepts. Take electric flux, for example. Assuming a student understands integration (and many introductory physics students are not well-versed in calculus), calculating flux means very little if the student does not know what a field is. Once again, there exists a situation where students can do the algorithm and have no idea what it means. So before researching flux (and related concepts like Gauss' Law), students' understanding of fields needs to be known. Otherwise, the results will be a mixture of student difficulties with fields, dot products, integrals, and elemental surface areas.

The same is true for other relations, such as the Biot-Savart Law. If students do not understand the nature of a cross product, the Biot-Savart Law cannot be meaningful to them. The list goes on: Ampere's Law, Faraday's Law, Lenz's Law, Maxwell's Equations, etc. Student difficulties in the fundamental areas need to be known before investigations into the more advanced areas will be meaningful.

C. Different approaches to teaching the concepts of introductory electricity and magnetism.

The field concept is important in physics. Gravitational, electric, and magnetic interactions all use the concept of a field extensively. An approach that uses the field concept as the central concept has been developed (Chabay and Sherwood, 1995). This was an attempt to explain a broad range of phenomena using a small number of powerful ideas. (For a discussion of the effective use of a small set of basic models, see Wells, Hestenes, and Swackhamer, 1995.) Electric and magnetic interactions are present in many parts of everyday life. Radios, televisions, computers, and even plastic cling wrap depend on these interactions. At the atomic level, the electric and magnetic interactions are the key to physics and chemistry. Chabay and Sherwood combined active learning, qualitative reasoning, microscopic models, and the unification of electrostatics with circuits, where the field concept is well-developed and tightly integrated. Their textbook is based on research in student learning. According to Sherwood (1996),

Our textbook is indeed heavily based on educational research. The most basic influence is the very general result of educational research that it is vitally important to keep students active in their learning, hence the workbook format of the textbook. Compared with the large amount of specific research on student difficulties with mechanics, there is rather little research on E&M, and the great bulk of this research deals only with simple circuits, which is a small portion of an E&M course. For that reason much of the research on which our book is based is our own detailed observation of student difficulties with our own materials. The book went through ten revisions before publication, each revision heavily based on observations of what students could and couldn't do.

It can be seen that specific learning difficulties were addressed as each revision was completed. However, the difficulties that were addressed were largely based on the authors' observations, and not difficulties reported in the literature. This makes it difficult to evaluate this approach. Recall, however, that Mestre

and Touger (discussed earlier) suggested writing new textbooks. Since the text is a new approach, it is difficult to compare it with other courses.

A major innovation of this approach is that the basis of the textbook is the concept of the field. The operation of circuits is explained in terms of the electric field, a connection between electrostatics and electric circuits that is often lacking (see discussion of Rainson et al. (1994), above). To check for (and compare) current flow, magnetic compasses are used. This approach introduces students to the magnetic field generated by a current. This is an example of students gaining experience with a concept before being introduced to the formalism.

There is evaluation material available on the World Wide Web (at <http://cil.andrew.cmu.edu/emi.html>). At this Web site, it is reported that, after instruction,

Many standard misconceptions are absent. For example, students do not think that current is used up in a light bulb. In fact, many students give a detailed dynamical argument for why the currents in and out of the bulb become equal in the steady state.

Students not only perform well on new, qualitative problems but also perform well on traditional quantitative problems, confirming our expectation that solid qualitative, conceptual understanding would contribute to improved performance in quantitative problem-solving.

It would appear from these statements, as well as the claim that often as much as a quarter or a third of the class performs at an “A” level on difficult exams, that the approach taken by Chabay and Sherwood is successful. Being a new text taught in a new way, and having no standard evaluations for electricity and magnetism, strict evaluation is difficult.

One last point needs to be made when discussing new approaches to teaching concepts in physics. If teaching is to promote conceptual learning, the

tests need to be changed to account for it (Tobias, 1995, 1996). Students know well that physics tests are quite often similar to the problem sets found in many undergraduate textbooks. Since students are test-driven, they will concentrate on passing the test. If the tests are quantitative, one cannot expect students to devote their time to learning concepts. Tests need to change if the instruction is to change. That makes evaluation of methods such as the approach taken by Chabay and Sherwood difficult until an appropriate test is developed.

D. The role of multimedia

Multimedia is a combination of video, graphics, sound, and animation, often with the use of a computer (Fuller, 1993a, 1993b). A typical multimedia arrangement (or station) has a computer, a CD-ROM drive, a videodisc player, and various software packages for manipulating video and sound. Probeware for interfacing the computer with experiments, and the necessary software, is also used in physics classrooms.

In the last decade or so, there have been many changes that make multimedia particularly attractive. Computer prices have fallen while capability has increased. With faster computers, more storage space on a hard drive, the popularity of the CD-ROM, and user-friendly graphical user interfaces, computers are a viable option more than ever before. Probes for taking real-world measurements are getting better, and new probes are being developed.

The drive to use computers in instruction is not new. Bork (1979) said that the “current method of publishing textbooks is antithetical to cultivating exciting new approaches” (p. 5). As an alternative, he discussed some of the advantages

to using computers in education. The first, and to Bork the most valuable, advantage is for interactive learning. This makes the student a participant rather than an observer. With interactive learning, the students can get immediate feedback on their performance. Another advantage is individualization; for every different input from a student, the computer can give unique feedback, records of input can be maintained, and the computer can change its feedback to match the previous actions of the individual student. The third advantage Bork mentioned is that computers “can amplify everyday experiences” and “create worlds which are not available in convenient form for the students to play with,” (Bork, *ibid.* p. 8); as an example, he suggests that the computer can give students a new view of the way charges behave by plotting electric fields and potentials - something that the student cannot get by manipulating equations. Other advantages promote the computer as an intellectual tool (using numerical methods), student control of pacing, time and sequence control, and student control over content. Also, testing can be turned into a learning situation, since the computer can tell a student when their answer is correct and suggest other methods for answering the question, or for telling a student when their answer is wrong and why it is wrong. The computer is also unbiased; it treats everyone the same.

The multimedia techniques can be used to examine systems that can be difficult or impossible to examine otherwise; for example, electric and magnetic fields can be shown in space as the fields change in time. A CD-ROM (Chabay, 1996) is available for graphically displaying electric fields, magnetic fields, and electromagnetic radiation. The electric fields due to a positive charge, a negative

charge, and a dipole (which rotates about multiple axes and can also oscillate) can be shown, as can the magnetic fields due to a moving proton, a current-carrying wire, and a wire loop. In addition, the electromagnetic radiation from an accelerated positive charge can be displayed in either two or three dimensions. There is also a representation of a traveling electromagnetic wave. All of these displays can be used to help students learn the representation used by physicists for fields, as well as how the fields depend on location and time.

The multimedia activities developed in this study used the following process (Grayson, 1996):

1. Select topic (content area) and target group;
2. Identify student conceptual difficulties;
3. Write preliminary version of the program;
4. Try it out with students - observe what they do and how they interact with the program, test what they learn, and solicit students' comments and suggestions.

This thesis reports on these four stages. Future work uses the next three steps:

5. Modify program on the basis of step 4;
6. Try it out with students again;
7. Repeat steps 5 and 6 until the program is reasonably robust and fairly stable.

It is important to keep the students interested in any instructional setting.

The work of Malone (1981) can be applied to the use of multimedia in the classroom. Malone investigated what properties of computer games made people want to play the games. His study showed that there are three main ingredients common to the games his subjects enjoyed playing the most: challenge, fantasy, and curiosity. Malone suggests that these three elements help form a coherent framework for intrinsically motivating instruction.

Multimedia lessons may have a beneficial effect in physics teaching. Hands-on activities can certainly be enhanced by the use of other media. Computers can allow students to do things not easily done otherwise in a laboratory or classroom. For example, motions that are too fast or too small to observe normally can be videotaped (possibly digitized) and slowed down or

enlarged for ease of measurement. Some phenomena, such as lightning, are not safe to observe closely, or difficult to arrange for scheduled lab sessions. Others are too expensive or too messy. Some experiments simply do not work well at all times (such as many electrostatic labs during times of high humidity). Real-world events, such as athletic or large-scale events, can be analyzed in the lab via multimedia. This lets the student see that physics is not just something that happens in the lab or is discussed in lecture. With multimedia, it only needs to be captured once, and then can be used repeatedly. Measurements can easily be redone, so results can be checked.

When students are studying electric or magnetic fields and potentials, multimedia can be extremely valuable. Presently, there is software available to calculate and display potentials and fields (*EM Field* and *Electric Field Hockey* available from Physics Academic Software, for example). Such simulations can be useful when it is not easy to show something clearly. The flexibility of simulations makes them especially attractive. These can be used in lecture as well as in labs.

Taking measurements from video images has other advantages. At the University of Nebraska-Lincoln, introductory physics labs are using images of charged spheres to investigate electrostatic repulsion. Since Nebraska gets rather humid in the spring and summer, this is an activity that is well-suited to multimedia. This same experiment is one that would be difficult to perform in lab, as charge would leak off the spheres before the students could make very many measurements. Another problem is that it is difficult to perform this experiment in a crowded room where air currents agitate the spheres.

Multimedia labs can provide other benefits. Computers can be used to eliminate the drudgery of analyzing data. Computers can be used to record data faster and easier than ever before. Modeling is an important learning tool that can be done much faster and easier now. For example, using Interactive Physics™, the Coulomb force between two electric charges can be modeled. With modeling, students can quickly and easily see the effect of changing quantities and dependencies in equations. They can investigate which models seem to fit experimental data. Calculations can be done by the computer, allowing students to concentrate on the physics.

The use of multimedia for education purposes is being studied in many places around the world. The University of Bremen (Germany) is finishing a study in the use of multimedia with students. The preliminary results are promising (based on a site visit, 6-7 December 1995).

The United States Air Force Academy in Colorado Springs is using their network and a web browser in innovative ways. Cadets can access class materials from any computer on campus. This use of multimedia includes text, movies, graphics, and sound.

The multimedia approach may be able to provide a better method of instruction by bringing examples from the outside world into the laboratory where they can be examined with modern technology, thereby improving student understanding of natural phenomena. Multimedia may be more effective for teaching than computer-based teaching.

A large number of meta-analyses¹ have been done on computer-based teaching by Kulik et al. (1994, 1991, 1986a, 1986b, 1985, 1983, 1980). In general, computer-based instruction raised student scores a small but significant amount, sometimes as much as 0.30 of a standard deviation. Another positive effect in these studies was that computer-based instruction reduced the amount of time needed for instruction. It has been shown that multimedia presentations, with the ability to deliver instruction with different media, provide the means to meet the needs of a wide variety of learning styles (Hoffer, Radke, & Lord, 1992; Larsen 1992).

The field concept is fundamental to the study of physics. Given the importance and abstract nature of the field concept, it seems wise to use all the tools available to help students understand fields. Combining the power of multimedia with the research techniques for investigating student understanding, it may now be possible to create instructional materials that can teach this fundamental concept in new and effective ways.

¹ A meta-analysis is an analysis of analyses; it is a method of integrating findings from a large collection of results from individual studies into a single statistical analysis (Glass, 1976).

III: THEORETICAL FRAMEWORK

A. The choice of the field concept

The concept of a field is fundamental to the study of physics. It is through the field that interaction-at-a-distance is described (Karplus, 1969). For physicists, fields are incredibly useful constructs. It has not always been this way, however.

Isaac Newton was not comfortable with the idea of action-at-a-distance:

It is inconceivable that inanimate, brute matter should, without the mediation of something else, which is not material, operate upon, and affect other matter without mutual contact, as it must be if gravitation, in the sense of Epicurus, be essential and inherent in it. And this is one reason why I desired you would not ascribe innate gravity to me. That gravity should be innate, inherent, and essential to matter, so that one body may act upon another at a distance through a vacuum, without the mediation of anything else, by and through which their action and force may be conveyed from one to another, is to me so great an absurdity that I believe no man who has in philosophical matters a competent faculty of thinking can ever fall into it.¹

Despite the observation of electric and magnetic phenomena by the ancient Greeks, the concept of a *field* to describe action-at-a-distance was not introduced until the early 1800s by Michael Faraday. Maxwell's equations summarize and describe all electromagnetic phenomena. In vacuum, these are (Jackson, 1975)

$$\begin{aligned} \nabla \cdot \mathbf{E} &= 4\pi\rho & \nabla \times \mathbf{B} - \frac{1}{c} \frac{\partial \mathbf{E}}{\partial t} &= \frac{4\pi}{c} \mathbf{J} & \nabla \cdot \mathbf{B} &= 0 & \nabla \times \mathbf{E} + \frac{1}{c} \frac{\partial \mathbf{B}}{\partial t} &= 0 \end{aligned}$$

Using these four equations, one can see the source for both electric and magnetic fields as well as the relationship between them. Static electric charges give rise to electric fields. Electric currents cause magnetic fields. An electric field with a nonzero time derivative creates a magnetic field, and a magnetic field whose time derivative is nonzero creates an electric field. For physicists, these

equations are almost all one needs in order to demonstrate an understanding of electric and magnetic fields.

The field concept is important to the study of physics. All forces are governed by the *field particles* or *field quanta*. These include the photon for electromagnetic interactions, the graviton for gravitational interactions, the gluon for the strong force, and the vector bosons for the weak force. Indeed, the field concept is so important that this study concentrated on how students understand fields, especially in the realm of electricity and magnetism. Introductory students cannot be expected to discuss fields in terms of field quanta or Maxwell's equations. They may not easily be able to put the concept in words at all.

The definition for a field can be difficult to express in words, especially for students in an introductory physics course – many students lack the necessary language. Therefore it is necessary to use operational definitions when investigating student understanding. At first, introductory college students may have naive theories to describe action-at-a-distance; but as their experience and vocabulary grow, their understanding may approach the formal definition for a field.

Without the language to define a field, students may demonstrate understanding of the field concept by describing various properties of fields. As shown by Maxwell's equations, electric and magnetic fields are represented by vectors. They have magnitude and direction. The net electric or magnetic field at any point is the vector sum (superposition) of the individual electric or

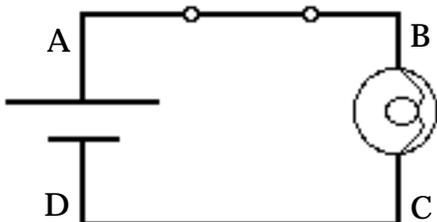
¹ Isaac Newton, Third letter to Bentley, Feb. 25, 1692, from Tipler (1991)

magnetic fields. While electric and magnetic fields share some properties, they are not identical to each other. These properties of fields allow for several different categories of understanding, including the following seven: the existence of fields (the field concept or construct for action-at-a-distance), sources for fields, representation of fields, superposition of fields, relationship between electric and magnetic fields, and the relationship between the gravitational field and electric or magnetic fields.

Fundamental to the study of electricity and magnetism is the field concept. A search of the literature revealed that only one aspect of electricity and magnetism had been widely researched: simple circuits. Yet introductory physics courses typically teach many topics in electricity and magnetism, such as the following: electric charge, electric field, electric potential, electric potential energy, electric flux, electric current, capacitance, resistance, magnets, magnetic fields, electromagnetic induction, and magnetic flux. Flux, whether electric or magnetic, is defined in terms of the field. Potential and potential energy are related to the field strength.

Ideally, one would have a concept inventory (an instrument to measure conceptual understanding) to administer to the prospective subject, the results of which would point to certain preconceptions. An example of such a test is the Force Concept Inventory (Hestenes, Wells, & Swackhamer, 1992). While no such instrument exists for electricity and magnetism, one is under development (Maloney, 1997).

The concept inventories usually consist of multiple-choice questions. Each answer corresponds to different preconceptions. An example from simple circuits is the following:



- A. The current is largest at A.
- B. The current is largest at B.
- C. The current is largest at C.
- D. The current is largest at D.
- E. The current is the same everywhere.
- F. The current is the same in AB and smaller than in CD.
- G. The current is the same in AB and larger than in CD.
- H. None of these is true.

With little previous research into student understanding of the field concept, it has not yet been possible to create such a concept inventory for fields. There have been some attempts to create an electricity inventory, but they have been quantitative in nature - “What is the force on an electron in an electric field of strength 100 N/C ?” Such questions depend on a knowledge of the formula, and may not reveal a conceptual understanding of fields.

Research in physics education tries to account for progress from naive to mature thinking. Test instruments to investigate student understanding need to measure this progress. Since there is no reason to expect college physics students to quantitatively understand electric and magnetic fields prior to instruction, test instruments must have a qualitative aspect. To explore whether students understand electric and magnetic fields after instruction, quantitative measures may be used. Therefore, investigations into student understanding of the concept of the field must use both the qualitative and the quantitative paradigms.

B. The quantitative research paradigm

Quantitative research presents statistical results with numbers. This approach assumes that there is an objective reality, not open to various interpretations from different researchers. Quantitative research establishes causes and relationships, with an established set of steps and procedures. Variables are kept to a minimum and controlled when possible. The researcher seeks to be unbiased and “attempts to establish *universal context-free generalizations*,” (McMillan & Schumacher, 1993, p. 15).

The quantitative paradigm is “an inquiry into a social or human problem, based on testing a theory composed of variables, measured with numbers, and analyzed with statistical procedures, in order to determine whether the predictive generalizations of the theory hold true,” (Creswell, 1994, p. 2). A quantitative design is useful for area in which research has already been done and the variables are known.

C. The qualitative research paradigm

Qualitative research uses a narrative to give results. Multiple realities are assumed. Qualitative research seeks to understand a phenomenon from the perspective of the participants. The data collection techniques may change during the course of the study. Bias and subjectivity are allowed, but accounted for. Data is collected by a person rather than an instrument. The results may be affected by the context (McMillan & Schumacher, 1993).

A qualitative study is a “process of understanding a social or human problem, based on building a complex, holistic picture, formed with words, reporting detailed views of informants, and conducted in a natural setting,” (Creswell, 1994, pp. 1-2). A qualitative design is especially useful for exploratory research, in which the variables may be unknown.

D. Combining research designs

Both quantitative and qualitative research paradigms have strengths and weaknesses. A study that uses both paradigms can use the strengths of both to develop a more complete understanding of the phenomenon under study. Since little research has been done on student understanding of the field concept, the qualitative design allows exploratory research to discover patterns. These data can be used to create instructional materials that take advantage of known student conceptions. Quantitative measures can then be used to describe the effectiveness of the materials.

The instruments used in this study were written pretests, written posttests, and oral interviews. The instruments have different forms, but use open-ended questions. The subjects are free to respond in ways different from the researcher’s expectations. This can create a more complete understanding of how students think and learn about electric and magnetic fields, as well as a measure of the effectiveness of the instructional materials.

E. Data collection

The data collection method is rooted in the methods used by other physicists doing research in physics education. As mentioned in Chapter I, the Physics Education Group at the University of Washington has done extensive work on the conceptual understanding of college students. One of these studies, on students' understanding in introductory electricity (McDermott & Shaffer, 1992), was reviewed in Chapter II. Goldberg (1986, 1987) has explored students' understanding of optics. At the University of Maryland, Redish (1997) has studied the effectiveness of active-engagement microcomputer-based laboratories, and is presently investigating student understanding of quantum mechanics and student understanding of mechanical waves. The Force Concept Inventory was developed by physicists (Hestenes, Wells, & Swackhamer, 1992) at Arizona State University for studying student understanding of Newtonian mechanics. Reif (1987) has studied the application of technology to the teaching of physics. Laws has discussed using physics education research in introductory physics courses (Laws, 1997) and has investigated the use of computers for teaching introductory physics (Laws, 1991). Beichner (1990, 1996) has investigated using graphs and motion analysis to improve student learning of kinematics.

The purpose of this study is to enlarge the research base on the concept of the field and to verify the hypothesis that effective instructional materials can be created through the use of research into students' understandings. This research will use the methods that have been used successfully by physicists to study other concepts and to also study the use of multimedia to teach college students concepts in electricity and magnetism.

IV: PRE-INSTRUCTION

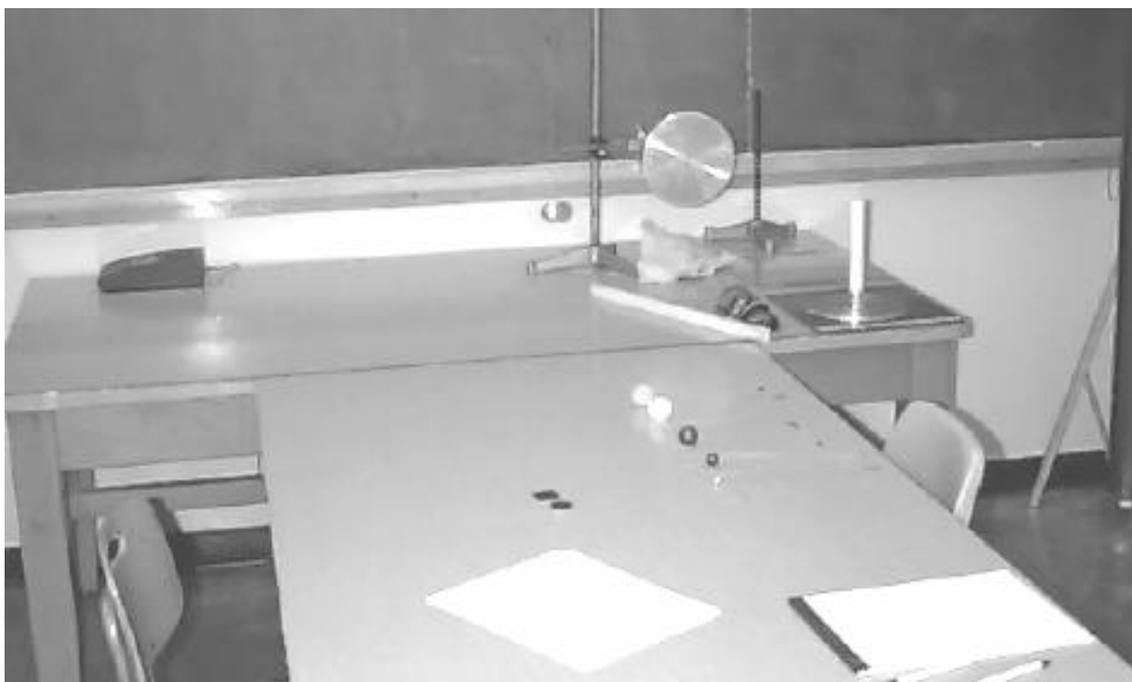
A. Data collection procedures

The data collection began by administering lab quizzes to all students in the Fall 1994 semester Physics 142 class. These quizzes were designed based on observations and earlier test questions. The quizzes were analyzed to determine the nature of the questions that cause students the most difficulty. Some students were interviewed at the end of the semester to see what concepts remained troublesome to the students. Given its fundamental importance, the field concept was selected as the central concept for this research. These data served as a basis for later data collection. See Appendix A for a tabular summary of the data collection. A concise summary of the collection and analysis of a subset of these data appears in Appendix B.

Two primary procedures for collecting data were chosen: written instruments and semi-clinical interviews. A pretest was administered to all 66 students enrolled in the Summer 1996 session of Physics 141. It should be noted that no electricity and magnetism concepts are formally introduced in Physics 141. The results of these tests provided additional understanding of the conceptions held by students prior to formal instruction, and allowed further development of the multimedia lessons.

Using all data collected to that date, a format for semi-clinical interviews was chosen. The semi-clinical interviews were conducted at a table (shown on the next page) with the interviewer sitting opposite the interview subject. A

string, approximately 2 meters in length, was suspended from the ceiling above the table. Several objects were on the table and could be hung from the string during the interview: a hollow aluminum sphere, an ordinary Ping-Pong ball, a pith ball, an aluminum-covered pith ball, a steel marble, a Styrofoam ball, and a graphite-coated Styrofoam ball. The string was suspended in a “V” to keep all motion limited to one dimension. Also available were a plastic ruler, wool, various magnets (a horseshoe magnet and a small number of bar magnets), a compass, and iron filings. Paper was provided to allow subjects to sketch or write.



Subjects were encouraged to use the provided objects to explore electrostatic and magnetic phenomena. They were asked to predict what would happen and explain their reasoning. The interviews were designed to encourage the subjects to explain any aspect of their observations of electrostatic or

magnetic phenomena. Guidance was provided from the interviewer through probing questions. No technical words were used unless used by the subject. The format for the interview was constant throughout the investigation. The interviews were videotaped and professionally transcribed for later analysis. The transcripts were compared to the original videotapes for accuracy by the author. Every interview subject in this study was asked to explain an example of electrostatic attraction or repulsion. If the subject did not suggest using electric charges to cause action-at-a-distance, the interviewer would demonstrate the effect of a charged ruler on a pith ball and ask the subject to explain the interaction. A typical interview began as follows (the letter “I” represents the interviewer and the letter “S” the subject):

- I: The system in question consists of a string suspended from the ceiling, from which we can hang any of several objects, including a pith ball, a Styrofoam sphere, a steel marble, and a hollow aluminum sphere. The first question I would like to ask you is this: can you think of a way we can affect this system without touching it?
- S: Yes, you can induce a charge on [the pith ball] and with that charge you could move it in just about any direction depending on how much charge you used.
- I: How would you go about inducing a charge on this?
- S: What we did in lab was use the plastic ruler which was, I believe, a negative charge and held it underneath the pith ball to make the positive charge on the lower half of the ball and the negative charge on the top half of the ball. We touched the top of the ball to remove the negative charge and left positive charge on the ball.
- I: You used something just like this [plastic ruler]?
- S: Right.
- I: If you were just to charge this up and bring it close what would happen first?
- S: ... I would say that it would attract.
- I: Why do you think it would attract? Draw pictures if you want.
- S: Because of what I said ... that [ruler] is charged where this [pith ball] isn't.
- I: Ok let's see what it does.
- S: They attract.
- I: Now that you know it attracts, can you explain why it attracts?
- S: ... back to the old saying that opposites attract

After this subject also observed electrostatic repulsion, the interviewer asked why they now repelled.

S: I don't know why they repel each other, other than 'like charges' ... I guess I don't know how to put it in words.

It was important that the interviewer used the same vocabulary as the subject. For example, once the subject used the word "field," the interviewer would ask for clarification, and thereafter use the word in the same manner as the subject. When possible, the subjects were asked to provide sketches. A complete interview transcript can be found in Appendix C.

Nine pre-instruction interviews were conducted with Physics 141 students. The subjects were entirely self-selected and were offered nothing more than tutoring in exchange for participation. The subjects displayed a wide range of understanding and ability to communicate their ideas. It should be noted that none of the subjects asked for the tutoring, but most expressed a desire to assist in the improvement of physics instruction. The final course grades for these nine subjects was a little above average, consisting of 3 C's, 2 B's, 3 A's, and a single A+.

Using the information gathered on the previous tests, as well as from these interviews, a pretest was administered to 39 students at the beginning of the Summer session for Physics 142. This test was the final written instrument to affect the development of the multimedia lessons.

Thirty-five of the 39 Physics 142 students agreed to be interviewed. These 35 interviews were conducted as the course progressed; some may be considered as pre-instruction, and some as post-instruction, but the majority are

a mixture (see Appendix A, Table A1). This allowed examination of how student thinking changed as instruction progressed. The multimedia lessons were finished during this same time period, and were modified with information gathered from these interviews.

Pretests were administered to both the Fall 1996 (80 students) and Spring 1997 (177 students) Physics 142 classes. Post-quizzes were administered every three weeks during the electricity and magnetism part of the course. The concepts covered on the quizzes were the same as the concepts from the three most recent lessons. A post-instruction interview was conducted from the Fall 1996 class to compare the fall students with the summer students. The final data collected in this study were a set of questions included on the final exam for the Spring 1997 Physics 142 class.

TABLE 2.1. A summary of pre-instruction data collected. Not all instruments asked the same questions; the data reported may not reflect all instruments.

Instrument	Pre- or post-instruction	When	Number of subjects
written test	pre	summer '96	66
oral interview	pre	summer '96	9
written test	pre	summer '96	39
written test	pre	fall '96	80
written test	pre	spring '97	177

B. Data analysis procedures

The tests and quizzes were graded for correct answers along with correct explanations of the procedure necessary to arrive at that answer. The interviews were professionally transcribed, then the transcripts were compared to the original video for accuracy by the author. The transcripts were studied to analyze the common misconceptions held by the informants.

C. The pre-instruction data

The student understandings can be discussed in seven categories: i) the existence of fields, ii) source of fields, iii) representation of fields, iv) the superposition of fields, v) relationship between electric and magnetic fields, vi) relationship between gravitational and electric fields, and vii) relationship between gravitational and magnetic fields. An eighth category was also chosen for examination: behavior of magnets. It was discovered during the interviews that a large fraction of pre-instruction students believed that one end of a magnet will repel anything that the other end attracts. Explanations from students often indicated that they believed that the ends of a magnet had “opposite charges,” and thus must have opposite effects. While this may be a confusion of electric phenomena with magnetic phenomena, it was treated as a separate category since the reasons behind the preconception were not completely clear.

i) existence of fields

The definition of an electric field can be difficult to express. One subject who had finished Physics 211, 212, and 222, and was taking Physics 223 said “My concept of an electric field doesn’t readily manifest itself in English. (No, I’m not trying to be funny – just can’t think of words to describe one).” This lack of a language to describe such an abstraction was not uncommon. Almost all students involved in this study were aware that “opposites attract and likes

repel.” That knowledge alone was not sufficient to indicate that the subject had a mental construct of a field. For this study, a subject had to communicate a knowledge of something more, such as the vector nature of fields, dependence on distance, or superposition, for example.

A pretest was given to 177 Physics 142 students in the first week of classes in January, 1997. For the majority of these students, the pretest came before any instruction on the field concept. On this pretest, 85% (150 of 177) of the students indicated that they had used a compass. 83% (147 of 177) indicated that a compass measures something magnetic (the fraction of students answering in this way was independent of any indication that they had used a compass before). Overall, 83% (350 of 422) of the students used in this study claimed to have used a compass prior to college instruction on electricity and magnetism.

When asked “What does the term ‘electric field’ mean to you?” 51% (91 of 177) of the students indicated that an electric field is an area or place. Typical answers were “The area that surrounds electrical charge,” and “The area where the electricity has an effect.” Another 15% (27 of 177) thought it was a collection of charges. Only 7% (12 of 177) supplied answers that resembled a physicist’s operational definition; for example, “the force around a charge,” “can create a force without physical contact,” and “disturbance caused by electrons.” The remaining 27% (47 of 177) supplied no information, either leaving the question blank or writing answers that could not be categorized.

The same question was used with smaller sample sizes and similar results were found. When all responses to the question are considered together, 50% (108 of 216) of the students indicated that an electric field is an area or place.

Another 17% (37 of 216) thought it was a collection of charges. Only 6% (12 of 216) supplied answers that resembled a physicist's operational definition. The remaining 27% (59 of 216) supplied no information.

TABLE 2.2. A summary of the pre-instruction responses

Number of subjects	Correct	Misconceptions		
		Area	Charge	Blank/ no information
39 100%	0 0%	17 24%	10 26%	12 31%
177 100%	12 7%	91 51%	27 15%	47 27%
total: 216 100%	12 6%	108 50%	37 17%	59 27%

On these pretests was the question “Do two magnets need to touch to affect each other? Why or why not?” Virtually 100% of the subjects correctly indicated that magnets do not need to touch, but the reasons given included magnetic fields, electric fields, electric charges, “opposites attract,” and more. The results were not tabulated, as some answers were correct but gave no indication of the subject's concept of a field. Of interest is that many responses included electric phenomena rather than magnetic. This was typical for students prior to instruction – they confused electric and magnetic effects.

A similar question involving electric charges was also included on the pretest, but results were not tabulated for the same reasons as above.

The pre-instruction oral interviews supplied data on how students think and talk about action-at-a-distance and fields. Excerpts from nine pre-instruction oral interviews follow.

Prior to using any equipment, subject S2 was trying to describe how objects can affect each other without physical contact. In the process, this subject used the word “field,” at which point the interviewer asked for clarification:

Int: When you say “field,” what do you mean?

S2: I don't know, they're just kind of... there's some chemistry either something electr ... either something electric or magnetic or maybe there would be an electrical field or even if you could just put another, I'm mean theoretically you know, you got two objects, they should be gravitationally attracted to each other.... I am thinking primarily of like an electromagnetic field. I know on a particle level their going to be, I'm trying to remember exactly the name that they have, a response to, like if you fired particle, and you've got this difference ... if you've got like an electric current going they're going to respond, they'll be attracted or repelled sort of the same way as to an electromagnetic field. ... I don't know if it's the I don't know if I can really adequately explain that. I think it's ... I understand the big concept, but I don't know if it's something that I could really specifically explain.

This last sentence makes it clear that this subject could not express the concept. Based on the interview, it was decided that this subject had a reasonable mental model for fields.

This next subject could only express action-at-a-distance as a result of a force field. Subject S43 suggested that charges could be used to affect a pith ball without physical contact. After observing a charged plastic ruler attract a pith ball, subject S43 discussed how the charges on the ruler could affect charges on the pith ball without touching.

Int: How can one of the charges put a force on one of the others?

S43: I guess they all got their own sorta force field. I mean from here to here it'd be stronger or it's repelling charge.

The next subject also describes a force field. The subject had just used a magnet to attract a steel marble:

Int: How would you describe that effect, what would it be?

S10: An attraction. Forces I guess, magnetic forces.

Int: How do you think the magnet put a force on this marble before actually touching it?

S10: I don't know. I really ... Have like a force field around it.

Int: How would you describe the force field?

S10: Kinda like the area around the object, in which the force is present.

Int: Would you say that force field is around this magnet even if there's nothing around here to affect?

S10: Yeah

Another subject noticed that a magnet had a smaller effect on a steel marble if they were far apart, as compared to close together. This subject thought that a magnetic field was a cloud of ions surrounding the ends of the magnet:

S7: But then if you move the magnet back farther it's just the force in between them. The magnetic field goes away.

Int: You said magnetic field, can you tell me what you mean by magnetic field?

S7: Like the ions and the electronegativity, which is negative. They're giving negative and positive electronegativity like this. If one end's greater ... if the north end is greater than the south it would be positive and if the south end is greater than the north it is going to be negative.

Int: How would you describe a field?

S7: It's like a group of something within this certain space. These are ions, probably sort of like a cloud I would say or like a cloud.

This next subject knew that invisible forces were involved in action-at-a-distance. In response to the opening question about affecting a sphere without touching it, subject S16 suggested gravity:

Int: Even though the sphere would be hanging here and the earth is affecting it, the earth isn't touching it, right?

S16: No the earth's not touching it. Magnetic field I'd say.

Int: It's a magnetic field?

S16: That's what I'm guessing.

Int: Now when you say a field ... ?

S16: A magnetic force, that attracts or repels the atoms in one molecule, away from or towards another one.

Int: So what properties would a field have?

S16: Force in a unit, some magnetic unit. We're dealing with an invisible force. Gravity's the only thing I really know of. It's an invisible force.

After the interviewer moved an electrically charged disk, which sparked when it was taken off its acrylic base, the subject added more:

S16: There's electrostatic fields too besides.

Int: So what made you think of that?

S16: Cause when you peeled that off I heard this.

Int: OK. So ...

S16: There's electric fields.

Int: What can you tell me about electric fields?

S16: I think they might be caused by friction between two objects, maybe. One example would be if you rub a piece of plastic on the carpet and then put it up to your hair it attracts your hair. I'm not real sure of how it works, but I think that there's electric fields too.

When asked to explain what was meant by electric fields,

S16: The field would just be an area over which the energy acts. Where you can actually measure an attraction or repulsion.

In the end, this subject thought that the field was an area over which energy acts.

After watching a bar magnet attract a steel marble, the following subject knew that forces exist without physical contact, but did not have any mental model to explain this:

Int: How can this magnet actually affect this steel ball without touching?

S30: I really don't know.

Int: I could phrase it a different way ... you have the magnet here and the ball's there ... how can they interact without touching?

S30: Right.

Int: Is there something that the magnet does to that?

S30: Far as force, something to do with the energy or is ... ?

Int: Anything that you can think of that allows it to pull something without actually touching it.

S30: Well I don't know why it would.

Later, the same subject seemed to lack the language to describe the phenomenon:

S30: So whatever is in it that allows ... magnetic force I guess.

Int: How would you describe this magnetic force?

S30: Just some kind of a deal that repels it ... I mean that would not repel but attract.

Later in the same interview, the subject observed the effect of a bar magnet on a compass. The subject was not able to form a mental model to explain the action-at-a-distance:

Int: What do you think a compass measures?

S30: A compass measures basically your ... ah ... the magnetic force of the earth. And that's why generally in the north direction there is apparently a pull up there north. That the magnet poles point to where you're at. That I don't know is it in the air or something; I don't know.

Int: I'll go back then to the question – how do you think the earth can put a force on this, a magnetic force, and not touch it? What do you think is the medium of interaction?

S30: I don't ... something in the atmosphere? That's ... I have no idea what it would be.

Another subject could only suggest gravity as a way to affect objects without touching them. When magnets were suggested, the subject displayed some knowledge, but mostly confusion between magnets and electric charges. This particular subject did not use the word “field” until the end of the interview, after observing and discussing magnetic and electrostatic interactions, and then only when asked:

Int: Have you ever heard of a magnetic field or an electric field?

S5: Yeah, I've heard of them.

Int: Do they mean anything to you? Any idea what they might be?

S5: No, just the field around the object. But as far as like the flow of magnetic field around the object. That's all I can think of.

Int: Okay, do you have any idea what the shape might be? What it looks like, if you could see it?

S5: Mmm, probably be the same shape as the object.

Another subject, after seeing the equipment but before using any of it, also suggested gravity:

Int: Is there anything affecting this now without touching it?

S17: Gravity.

Int: How do you suppose gravity is acting on it, what is the source of the gravity?

S17: The pull from the earth... the mass of the earth.

Int: OK, so the earth is pulling on it without touching it, right?

S17: Right.

Int: How do you suppose it does that? It's gravity but it's not touching. How can it put a force on it?

S17: I don't know. It's just the mass of the earth pulls that smaller mass toward it then it creates movement.

When shown a magnet attracting a steel marble, this subject still appeared to lack the concept of a field:

Int: Any idea how that could have happened? How a magnet could affect something?

S17: I don't know how magnets work.

Int: OK, any idea what this magnet must do between itself and this ball?

S17: Right, I think maybe it's the electrons between the two but I'm just guessing.

Later, after observing an electrically charged ruler repel a hollow aluminum sphere:

S17: There's a flow of electrons around the ruler and a flow of electrons around this aluminum ball, so when you get them close enough to one another then they exchange electrons and that probably causes them to stick to one another but maybe as you get them close they can exchange, but if you get really far away then their clouds are not close enough to exchange their electrons.

In the end, the subject thought that the only way objects could affect each other without contact was if they got close enough to exchange electrons.

The final pre-instruction subject interviewed prior to any instruction in electricity and magnetism seemed to have an adequate mental construct for fields. Before using any equipment, the subject suggested gravity as a means to affect something from a distance. The following is from the discussion on gravity:

Int: Do you have any idea how something can affect something else without touching?

S36: Oh, field of force around it.

Int: OK, field of force. Could you tell me what you mean by that, when you say field of force?

S36: Well, like the object may be concentrated right there, but the field of force that acts around the object and things in this field of force can be affected by the gravity of the object. If you get a great enough distance away, it's going to lessen and lessen and lessen.

Int: Are there any other types of these forces, fields, that you can think of?

S36: Electromagnetic, possibly. I don't know much about that.

Of the nine subjects interviewed prior to any formal college instruction on electricity and magnetism, only four (subjects S4, S16, S36, and S43) had the

mental construct of a field, using the guidelines described above. When asked how to affect a system without touching it, four of the nine suggested gravity, and five said magnets (but one of those kept saying “charges”). None suggested using electric charges without some prompting by the interviewer. However, the confusion between electric and magnetic phenomena makes the distinction less clear – some subjects said magnets, but discussed charges. The confusion between electric and magnetic phenomena will be discussed below.

ii) source of electric fields

With only four of the nine pre-instruction interview subjects having the mental construct for a field, it became difficult to reach a conclusion as to whether they knew what produced the fields. Generally, all subjects knew “opposites attract and likes repel,” but most did not have any mental model for *how* that attraction or repulsion takes place. Since such a small fraction (less than 10%) of the students taking the written pretests gave responses that showed they have the mental construct for a field, it was not determined what they thought the source was. Pre-instruction subjects knew that forces exist between charges, but they generally did not have a model for explaining the forces.

Before using any equipment, subject S43 suggested that charges have something to do with objects affecting each other without contact. This subject demonstrated the difficulty of trying to understand what creates a field:

Int: What could I do to affect it (a pith ball) without touching it?

S43: I guess each one would give off a certain charge.

Int: When you say “give off a charge,” what do you mean?

S43: Like magnets, with a positive and a negative. I mean if you charge something you probably move it cause you're moving all the ... I mean they're all scattered – positive, negative all the way around. If you put a charge next to it, it scatters and separates different charges on whatever object you're gonna put up there.

Int: You mentioned bringing charges near (the pith ball). How might we go about bringing charges near?

S43: Electrostatic charge maybe.

Int: How would you like to generate one?

S43: This would be a ruler or something. And rub it up against the fabric.

While this subject clearly understood that charges affect other charges, it is not clear what was meant by “charges,” since magnets were mentioned specifically. This was typical of the responses given by the students. The preconceptions of the students were not often well-defined.

One interview subject did express a belief that a separation of charges was needed for forces to exist between objects. When a charged disk touched the hollow aluminum sphere, the sphere became charged and was repelled from the disk:

Int: OK, all right, so the sphere is repelling without touching the disk anymore.

S2: Uh huh (yes).

Int: How would you think it could do that?

S2: I think possibly it's transferred some of the charge from If this electric... (inaudible) it kind of... I'm trying to remember... I think that in terms of static electricity kind of similar to... I mean... I don't know I just describe it similarly to how I described the magnetic fields in terms of...I don't know, separation of charges. I know you've got some like electrons but I don't remember what ... but they were more inclined to travel.

ii) source of magnetic fields

When magnets were discussed on written pretests or during interviews, the majority of the subjects said that the ends of a magnet are oppositely charged. While “charge” may be an arbitrary term, it means something specific to physicists. Pre-instruction students do not have such a specific meaning for “charge” and thus it is not clear whether they mean magnetic poles or electric charges. None of the pre-instruction subjects, either on written pretests asking about the source for magnetic fields, or during oral interviews, indicated that magnetic fields are produced by moving electric charges.

iii) representation of electric fields

When 216 Physics 142 students were asked to sketch an electric field on a pretest, only 5 were able to sketch something that resembles the vector representation physicists use for electric fields; one of the sketches included the caption that the field was “the flow of electrons.” Many of the sketches that were drawn were sketches of fields surrounding bar magnets. This is not surprising, since most people have experience with magnets and metal objects, whereas most experiences with electric charges are not controlled.

During the pre-instruction oral interviews, the subjects were asked to sketch the fields or to draw a sketch representing the force due to charged objects. Only one drew something resembling an electric field. After using a charged plastic ruler to attract and repel an aluminum sphere, subject S36 was asked to sketch the field around the ruler:

Int: You drew a magnetic field for a magnet. What do you suppose the field around this (charged ruler) looks like?

S36: Looks like it's all going away from it, or all going in the same direction out or into it. There doesn't seem like there's separate poles.

The sketch appears exactly as described, a ruler with lines radiating away. There were no arrows to make it a vector representation. No other interview subject attempted to sketch an electric field.

Again, there is the difficulty that most of the students did not know what an electric field was, so they could not draw anything resembling a physicist's representation.

iiim) representation of magnetic fields

No written pretests asked students to sketch magnetic fields; however, many students sketched the magnetic field due to bar magnets when they were asked to sketch an electric field.

When asked to sketch a magnetic field, two subjects sketched the pattern observed when iron filings are sprinkled near a bar magnet, giving no indication of field lines or vectors. One of these subjects, after observing a magnet attract a steel marble, described a force field:

Int: You described a force field around these magnets. Could you draw what that field might look like?

S10: Ah, yeah. I've seen with the iron filings they seem to go like this formation.

A third interview subject sketched field lines for a bar magnet, but gave no indication of direction or vectors.

After using a bar magnet to attract a steel marble, and discussing how the magnetic field is responsible for the interaction, subject S16 was asked to sketch what the field might look like. When the subject tried to sketch a representation for a magnetic field, the result was a bar magnet with a cone projected outward, opening onto a sphere that was being attracted. There were no arrows and no indication of force, just a cone that may have indicated an area of influence. The explanation given was as follows:

S16: Oh there's a field throughout. It's strongest ... The closer ... I'd say it resonates outward from the point of origin like this is the point source. I'd say I guess there's magnetic attraction or magnetic field in front of the magnet, but probably not behind the magnet, cause you have the opposite ends here. Actually there's a magnetic field all around it but it's not the same.

Three interview subjects could draw no sketches at all. The remaining two (of nine) pre-instruction interview subjects sketched clouds of charge surrounding the ends of a bar magnet.

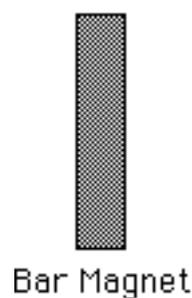
iv) superposition of fields

One question on more than 250 written pretests asked about magnetic field strength and superposition. This question is shown on the next page.

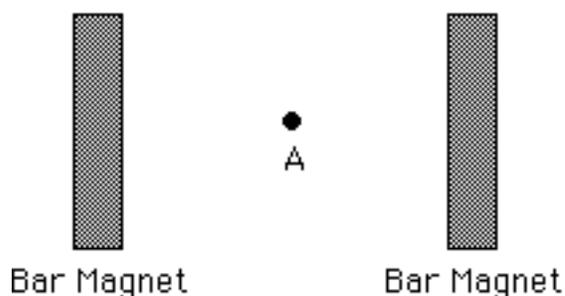
The answers were difficult to interpret. No single answer dominated the responses, which included the following: zero, half the original value, unchanged, double the original value, decreased, and increased. Many answers discussed the magnets affecting each other and ignored point A entirely, others suggested point A would move. Only four responses were correct together with a correct reason, and three of those indicated that the relative orientation of the

magnets was important. The data from this question showed that students did not have an adequate understanding of either the field concept or superposition.

Suppose you had a bar magnet and you measured the magnetic field strength at some point A.



How would you expect this measurement at point A to change if you placed a second, identical magnet on the other side of point A?



During the oral interviews, one subject spontaneously attempted to superpose the fields from two magnets in order to cancel the forces on a steel marble. This subject used two bar magnets on either side of a steel marble and demonstrated (after many attempts) that it was possible to position the magnets such that the marble was not affected.

Int: Why do you suppose it canceled? You said the forces canceled.

S16: If you look at the attraction in the north direction and the attraction in the south direction are equal, it's being pulled by an equal force in each direction. So it stays in equilibrium.

Int: Would you say there's a field at that point?

S16: Yes, I'd say there's a field in front of this magnet pulling the object to the south and there's a field in the front of this one pulling the object to the north.

Int: So each have their own field?

S16: Right and these fields are equal distances from the ball so the ball remains in equilibrium.

Int: How do these fields interact with each other?

S16: If you have a stronger magnet it's gonna have a stronger field therefore it's gonna act at the same distance. It's gonna attract the ball where the weaker magnet won't.

Int: So in this case were those roughly equal?

S16: Right.

Int: And then you canceled them at the point where the ball is. Would you say there is a field or there's no field? There's field due to each of them...

S16: Sure I'd say there's still a field ...Yeah, there is a field for sure. Course I guess when I get to the ball the stronger it gets too, there's a field between them and as I get closer to the ball it gets stronger.

Int: There's a field between them but there's apparently no force at the ball, right? It's not moving?

S16: Yeah there is ... no the force would cancel out, right there's no net force.

Int: There's a field but no force?

S16: Right.

v) relationship between electric and magnetic fields

255 students were asked the following question on a pretest:

Compare electric fields with magnetic fields. In particular, discuss similarities (if any), differences (if any) and the sources for these fields. Please include sketches to clarify your meaning.

As described above, the sketches were not in agreement with what physicists would use. 47% (120 of 255) of the answers were blank or simply “?” or “I don’t know.” The remaining 53% (135 of 255) of the answers showed much confusion. The common answers included “I thought they were the same,” “they operate on the same principle: likes repel,” “they both deal with charges,” or “they both can attract or repel.” A few mentioned that fields can act without contact. Given the small fraction of pre-instruction students that seem to have the mental construct for a field, and the large number of blank responses to this question, the data from this question is not quantifiable. The overall conclusion from this would be that students have difficulty differentiating electric fields from magnetic fields, and electric charges from magnetic poles.

During the oral interviews, most subjects did not discuss how one type of field is related to another, often because the subjects did not have a good concept of a field. The few subjects that did describe both electric and magnetic phenomena were often not sure of the differences.

For one subject, a charged aluminum sphere was attracted to a bar magnet held by the subject. When the sphere touched the magnet, it gave up some of its charge and was attracted to a nearby charged disk. After touching the disk, the sphere was again charged and attracted to the magnet. The sphere bounced back and forth a few times in this manner.

S2: It’s just going from one pole to the other.

Int: Ok, why do you think it’s doing that?

S2: Because it’s kind of trying to counter balance the charge each time. It gets big, it accepts the negative then it wants to compensate for

the attraction to the positive charge to balance out that extra negative charge and goes back and forth and then gets extra positive charges attracted to extra negative charges to balance out.

Int: You were saying something about charges. Do magnets have anything to do with charges?

S2: I think so, yeah. I'm pretty sure.

Another subject was trying to explain how objects can be affected from a distance. Before using any equipment, subject S43 suggested charges, but it was not clear what was meant:

S43: I guess each one would give off a certain charge I guess.

Int: When you say "give off a charge," what do you mean?

S43: Like magnets, with a positive and a negative. I mean if you charge something you probably move it cause you're moving all the ... I mean they're all scattered positive, negative all the way around. If you put a charge next to it, it scatters and separates different charges on whatever object you're gonna put up there.

Another subject used some of the correct words for magnets, including calling the poles "north" and "south," but still confused these with electric charges. Subject S7 observed that a bar magnet had no effect on a charged aluminum disk, but that the magnet had affected a similar magnet moments earlier. The subject thought electric charges are the same as magnetic poles, so that a magnet has both types of charges (poles) and an electrically charged disk has only one charge (or pole):

Int: Why do you suppose these two magnets will interfere with each other, but not with this disk?

S7: Ah, cause they're the same magnet.

- Int: The same magnets will affect each other. Will different ones, do you think?
- S7: Actually there is a difference. But when you have see, the ends are different – one has north and south. So if a magnet has a north and south end and another magnet has north and south end, the north and south will attract each other.
- Int: Why do you suppose they didn't attract this disk?
- S7: It doesn't really have a north and south end, it just has one big electric magnet. So actually it's gonna affect anything with a negative or positive charge. But since this magnet has both of them they cancel out.

Another subject needed some prompting to discuss static electric effects after discussing gravity and observing magnetic interactions:

- Int: Are there any other systems you can think of where objects are attracting or repelling or something like that, that maybe you encounter from time to time?
- S36: Oh, electricity kind of goes along with electromagnetism.
- Int: OK, so..
- S36: So static friction or static electricity.
- Int: How do you suppose static electricity relates to a magnet? Do you think they're the same kind of thing?
- S36: Well yes because there is like positively charged particles and negatively charged particles and they're attracted towards each other like little sparks like lightening.
- Int: How do you suppose they're attracted to each other? What causes the attraction, do you suppose?
- S36: Differences in the charge balance?

This was the same subject discussed earlier who sketched a magnetic field different from an electric field:

- Int: You drew a magnetic field for a magnet. What do you suppose the field around this (charged ruler) looks like?
- S36: Looks like it's all going away from it, or all going in the same direction out or into it. There doesn't seem like there's separate poles.

Considering this explanation, and the belief that static electricity and magnets are the same, it seems that for this subject an electrically charged item is identical to a magnetic monopole.

As stated earlier, it seems that the most significant conclusion is that students do not know enough prior to instruction to discuss the relationship between electric and magnetic phenomena.

vi and vii) relationship between gravitational and electric or magnetic fields

One question used on many (over 200) written pretests asked “How are people affected by the Earth’s magnetism?” The range in answers indicated that many, perhaps most, students did not understand the question. At that stage of their physics education, it appeared that many thought the Earth’s magnetism was gravity; they did not seem to think the question meant the Earth’s magnetic field. The word “magnetism” is used in the English language for things other than magnetic fields; “animal magnetism,” for example. The question was worded as it was in order to avoid giving students the vocabulary to answer another question on the same pretest (asking what compasses measure). Therefore, many students said that the Earth’s magnetism keeps us grounded.

Many simply said it does or does not affect people. While this may indicate that students confuse gravitational and magnetic fields, the results are not conclusive.

The topic was discussed in a few oral interviews. The following subject indicates that magnetic fields are the same as gravity. No equipment had been used, and the subject was discussing how the Earth was affecting a hanging sphere at the beginning of the interview:

Int: Even though the sphere would be hanging here and the earth is affecting it, the earth isn't touching it, right?

S16: No the earth's not touching it. Magnetic field I'd say.

Int: It's a magnetic field?

S16: That's what I'm guessing.

Later, to clarify the conception, the interview returned to the same topic:

Int: And you described gravity as a magnetic field, right?

S16: Right.

Int: Do you think it's the same as, basically the same as these (magnets)?

S16: I think it works on the same properties.

Int: OK.

S16: I think it... yeah, I think it works on the same general idea.

Most subjects simply did not know enough to discuss different types of fields. Subject S36 suggested gravity as a way to affect something from a distance. This subject mentioned a “field of force” for gravity. Before observing any electric or magnetic interactions during the interview, the subject was asked if there were other types of fields:

Int: That's for gravitational field of force, right? Are there any other types of these forces, fields, that you can think of?

S36: Electromagnetic, possibly.

Int: OK

S36: I don't know much about that.

viii) behavior of magnets

One other interesting preconception that surfaced during interviews was that students think that one end of a magnet will attract an object, while the other end of the same magnet will repel the same object. The following question was asked on pretests with 252 subjects:

Suppose you brought one end of a magnet near a paper clip, and observed some reaction (attraction or repulsion, for example). How should the other end of the magnet affect the same paper clip? Why?

Three-quarters (75%; 190 of 252) of the subjects said the reaction to the other end of the magnet would be opposite that for the first end of the magnet. More than one-fifth (23%; 59 of 252) correctly answered that the reaction would not depend on which end of the magnet was used, with some answers giving very thorough explanations. The remaining (3 of 252) responses were either blank or non-committal. This question was a variation of an earlier pretest question. The earlier version had the magnet touch the paper clip; in practice, paper clips can be magnetized on contact, making results sometimes contrary to expectations. While this question does not concentrate on the field concept, it was still used in the test instruments and was used to create some activities for the multimedia lessons.

This topic was addressed in many of the pre-instruction oral interviews. At the start of the interview, and before using any of the equipment, subject S7 suggested a magnet could be used to attract metal objects:

Int: So you can attract it?

S7: Ah huh (yes).

Int: Can you do anything else to it with that magnet?

S7: You can repel it.

Int: Why did you think it might repel?

S7: Cause having a negative and a positive end of the magnet. And it gives off ions in here. This is the negative ... negative ion is gonna attract to the positive side of the magnet, but it doesn't seem like this has a north or south end or negative and positive ends.

After a successful attempt to attract a steel marble with a magnet,

Int: OK but it's still being attracted to the magnet?

S30: Right. The only way to probably do it opposite would be to turn it the opposite way ...

At this point, the subject turned the magnet around and brought the other pole near the steel marble

S30: Nope, guess not. I thought maybe there would be a repelling force or something.

D. Conclusions from pre-instruction data

There are a number of significant conclusions that can be drawn from the data just presented. Perhaps the most important is that few introductory students begin their instruction on electricity and magnetism with a concept of a field. Of the 216 students who were asked what the term “electric field” means, only 12 (6%) could give an answer that would agree with the operational definition. Part of the problem is that the students lack the language necessary to express their understanding. The definition is not easy to put in words. Many of the 108 (50%) students who indicated that an electric field is an area may only have had difficulty phrasing their thoughts, and know that electric fields produce forces on electric charges that are brought into an area where the field exists. The oral interviews are a better method of finding how students really think about fields; the problem is that people talk in partial-sentences and use informal language in speech. It is through lengthy discussions, including sketches and gestures, that subjects demonstrated their understandings. Of the nine oral interview subjects, four were judged to have an adequate conception of a field. While that fraction is better than the 6% obtained from the written pretests, the sample size is too small to claim that nearly half of the students understand fields. This leads to the conclusion that students lack either the language or the mental construct to express an accurate conception of fields.

Without a conception for a field, it was not easy for students to describe the sources for electric fields and magnetic fields. All students seem to know that likes repel and opposites attract, and they can describe electric and magnetic interactions with that simple rule. What they do not seem to know is *like what*

repels *what*, and *opposite what* attracts *what*. The terms “positive” and “negative” are used frequently, but in reference to electric charges and magnetic poles alike. This may again be a problem of students lacking the language to make their understandings clearly known.

The representation used by physicists for electric and magnetic fields is not used by the students prior to instruction. Only five of the students used in this study drew sketches that resembled the vector representation used by physicists, and one of those students indicated that the field is the flow of charge. Students are much better at sketching magnetic fields than electric fields, but they sketch the patterns formed by iron filings, not field lines and field vectors.

With the problems students have with the field concept, as well as with the representation used for fields, the fraction of students with an understanding of superposition was not determined. From more than 250 pretests, only four students showed superposition of fields due to magnets. The results were not quantifiable since many students did not consider the net field at a point, rather considered the effect of one magnet on another.

Not only was the conception of a field a problem for many students, but the relationship between electric and magnetic fields was not clear. Given that few students actually seem to understand what a field *is*, it is not surprising that students cannot explain the similarities and differences between electric and magnetic fields. Many students thought they were the same thing. Others knew they were different, but still said that both fields were due to positive and negative charges, and have attractive and repulsive characteristics.

It was not clear from the pre-instruction data whether many students think gravity is similar to or different from electric fields or magnetic fields. Students did not clearly indicate a belief that gravitational fields are different from magnetic fields, or from electric fields.

The final conclusion from this pre-instruction data is that a majority of students do not understand how a magnet affects other objects – 75% of the students in this study thought that one end of a magnet attracts and the other end repels, despite everyday observations with magnets on refrigerator doors.

V: MULTIMEDIA LESSONS

The multimedia lessons were based on the Karplus Learning Cycle.

During the Exploration part of each lesson, the students were allowed to **explore** concepts in an open-ended environment. During the Invention phase, certain probing questions were used to guide the students to **invent** key ideas and perform important activities. Finally, as Application activities, the students were guided to **apply** the concepts to additional phenomena. This is similar to the methods used successfully by prior studies (McDermott and Shaffer, 1992, for example).

The topics for the lessons were chosen to correspond to the concepts of electricity and magnetism covered in a typical second-semester physics course. The labs were constructed to foster conceptual development, especially the concept of electric and magnetic fields. A brief discussion of the individual lessons follows:

A. Batteries and bulbs

The students at the beginning of the course were considered to have had no formal instruction on any of the topics in electricity and magnetism, hence the first lesson was selected to be useful for the course without the need for prior instruction. Simple circuits were selected as most practical.

This lesson was designed based on the research reported in the literature regarding simple circuits (Evans, 1978; Shipstone et al., 1988; Licht, 1991; and McDermott and Schaffer, 1992; for example), as well as laboratories done at the

University of Nebraska-Lincoln. Specific activities were designed to challenge the preconceptions known to be held by a large portion of the students. This lesson consists of five activities.

Activity One in this lesson began by asking the students to predict whether it is possible to light a bulb with only one wire and a single battery. This particular activity was designed around two known preconceptions: a complete circuit is not needed for current to flow, and that current is “used up” in a circuit. Either of these preconceptions would lead a student to connect one terminal of the battery to one terminal of the bulb, leaving the second terminals on both the battery and the bulb disconnected. If current is “used up” in circuits, then no path would be necessary for the current to return to the battery, thus the open circuit. Another typical prediction uses the wire to connect the battery terminals together (shorting the battery), with one terminal of the bulb touching the wire at any point. Early research in this study showed that each of these two predictions occur on about one-third of the predictions. The final third of the predictions show a complete circuit which would successfully light the bulb.

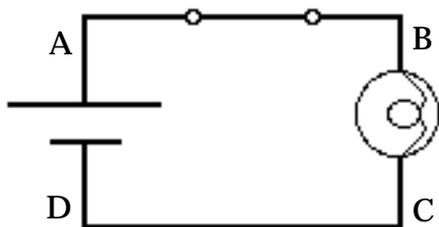
After the students explained their prediction, they committed themselves to their answers by showing the lab instructor. This was to force the students to consider their answer before trying to test it. It was hoped that this would prevent students from using a trial-and-error method without calling on their preconceptions. As discussed by Redish (1994), it is when predictions based on preconceptions are clearly demonstrated to be incorrect that the mental model is more likely to be replaced. To make their mental models more complete, the students must describe what conditions are necessary to make the bulb light.

Note that this is different from simply having the students verify that certain arrangements will make the bulb light; the student is an active participant in exploring what makes the bulb light.

Evans (1972) recommended that students should have the need for a concept before it is introduced. Since the labs were only three hours long, the concept of current may not occur to the students within a normal lab period; therefore, this first activity asked the students to consider the source of the energy given off by the bulb, and the manner in which that energy gets to the bulb.

Activity Two was a short exercise to demonstrate the relationship between a schematic diagram and a real circuit, as well as to introduce the common schematic symbols.

Activity Three was again based on the preconception that current is consumed by circuit elements. The first question for this activity (see below) was used in some of the pretests in this study and was borrowed from the *Real-Time Physics Electric Circuit Pre-Test* (Sokoloff, Thornton, & Laws, 1992) in which the currents at various points in a simple series circuit were compared.



- A. The current is largest at A.
- B. The current is largest at B.
- C. The current is largest at C.
- D. The current is largest at D.
- E. The current is the same everywhere.
- F. The current is the same in AB and smaller than in CD.
- G. The current is the same in AB and larger than in CD.

H. None of these is true.

(This question was adapted by David Sokoloff at the University of Oregon from an examination used at the University of Washington.) Conservation of current was then tested by using two bulbs in series. Since the bulbs were identical and were equally bright, the students should have concluded that the first bulb in the series did not consume all, or even a majority of, the current.

Activity Four explored parallel combinations of identical bulbs to demonstrate that physical nearness to the battery makes no difference in brightness. Activity Five, the final activity for this lab, compared batteries in series and parallel.

The students were asked to write a conclusion about what their experiments showed about circuits.

B. Electric charges, fields, and forces

This lesson consists of an Exploration activity, three Hands-on activities, and a Computer-assisted Laboratory Application.

Early results from this study indicated that students lacked language to explain interactions-at-a-distance. Since many students did not have a conception for fields prior to taking this course, it may be that most alternate conceptions for electric fields are to be generated during the time in which the student is taking the physics course. This lesson was written to introduce the idea of “action-at-a-distance,” following the SCIS work of Karplus (1974). Qualitatively exploring the interaction between electric charges should allow students to

observe action-at-a-distance prior to investigating the underlying concept of the electric field. That is, the students were shown the need for the concept before giving it a name.

The Exploration activity served as the introduction to the electric field by encouraging open-ended experimenting with static electricity. Suggested experiments used plastic rulers rubbed with wool to affect pieces of paper or foil. The students recorded both the material affected and the observed effect.

During the Invention, the lab instructor introduced the electric field concept as a means of explaining what was observed. This was to help students learn the language necessary to discuss electric fields, a language which this study concluded was lacking for introductory students. Electric charges were identified as the source of electric fields. The students then investigated the forces due to electric fields in the Hands-on and Computer-assisted Laboratory Applications.

In Hands-on Activity One the students explored how a charged ruler affects a neutral pith ball. The students predicted what would happen if the pith ball touched the charged ruler, and then compared this prediction with experiment. Students had real-life experience with static electricity and quickly recognized this as an example. They also were aware that electric charges may be positive and negative. The main goal outcomes for this activity were that students recognize that like charges repel and that charge can be transferred from one object to another.

In Activity Two the students investigated the attraction between opposite charges. In Activity Three, one charge was identified as negative (the charge on

the plastic ruler) and the students were asked to explain what the charge must have been for the other objects (a glass rod and the pith balls).

After these activities, the students explored and described the processes of charging by induction, conduction, and the analog to convection (charge being carried by a body from one place to another).

The Computer-assisted Laboratory Application was a quantitative investigation into electric fields via the electric force between two charged spheres. The experiment consisted of digitized pictures of one charged sphere repelling a second charged sphere hanging by a string. When the spheres were brought close together, the hanging sphere was repelled and the resulting displacement was measured. The displacement was proportional to the repulsive force. Thus students investigated how the electric force between two charged spheres depends on distance. All measurements were made using the computer, for several reasons. When this experiment was performed in a Hands-on fashion, taking the data often disturbed the system; when the experimenter approached a charged sphere, the sphere was attracted to the experimenter. Using video prevented this. The computer allowed the experiment to be repeated in a very short period of time. When the first sphere was brought near the hanging sphere, it took a few seconds for the hanging sphere to reach equilibrium. Drafts in the room made this worse. In the time required for the system to settle down, charges leaked off the spheres and the data was corrupted. If it was humid in the room (as it often is when there are many people in one room), charge leaked off even faster. By digitizing the

experiment once, in a calm, dry room, students could take measurements and do the analysis without the problems associated with the real equipment.

This computer application produced results that are in good agreement with Coulomb's Law. Rather than simply verifying that law, students were allowed to discover it.

C. Electric fields and potentials

This lesson consists of an Exploration, one Hands-on activity, and a Computer-assisted Laboratory Application. It was used to explore electric potentials, and used potentials to further explore electric fields.

The Exploration activity was a sample of the Hands-on Application; students were asked to find and plot equipotentials between electrodes. Resistive paper was used as the medium, and conductive ink was used to create the electrodes. A voltmeter was used to measure potential differences. Once the equipotentials were found, the electric field was calculated and the direction of the electric field was found. During the Invention, students were directed by the lab instructor to compare how a negative charge behaves due to the potentials with the behavior due to the electric field. This was to demonstrate how electric potentials and electric fields are related.

The Computer-assisted Laboratory Application used *EM Field*, software that allows one to place simulated electric charges in various configurations, and can display the electric field vectors, electric field lines, and electric potentials. The students predicted how the electric field at one location was affected by the addition or removal of electric charges to the configuration. Superposition of

field vectors was demonstrated by tracing field vectors on transparencies for two charges, separately and together. By overlaying the transparencies, vector addition was clearly displayed.

This activity was designed to help students learn the vector representation used for electric fields and to show superposition of fields, a concept that students did not appear to understand on the pretests administered during this study.

D. Magnetic fields and electric current

This lesson consists of an Exploration, two Hands-on activities, and a Computer-assisted Laboratory Application. This lesson allowed students to explore magnetic fields. Before this lesson was created, it was known that students often do not distinguish magnetic fields from electric fields. No comparison was made in this lesson between electric and magnetic effects, as students were to consider only magnetic effects. A direct comparison between electric and magnetic fields was made in a later lesson.

The goals of this lesson were to explore the vector representation, superposition, and production of magnetic fields. Permanent magnets and moving charges were used as sources for magnetic fields.

The Exploration asked the students to consider how a compass works. This study found that approximately 83% of the students had prior experience with compasses, and 84% understood that compasses measure some magnetic phenomenon. A demonstration was used to show that a compass was affected by magnets, but not by ordinary wire. When a current flowed in the same wire,

the compass was affected, leading to the idea that electric currents (moving charges) create magnetic fields.

These ideas were brought together in the Invention, when students discussed that compasses are affected by magnetic fields, and that magnetic fields are produced by moving electric charges.

Hands-on Activity One guided the students in discovering how compasses are affected by the magnetic field created by a bar magnet. Students mapped the magnetic field around a bar magnet using iron filings and the compass. The students were asked to think about how the compass is affected by the Earth's magnetic field, the bar magnet's field, and the combination (superposition).

Hands-on Activity Two used an electric current to create a magnetic field. After discovering a rule to describe the magnetic field due to a straight current-carrying wire, the students used that rule to predict the shape of the magnetic field created by a coil. Then they compared that field to the field created by a bar magnet.

The Computer-assisted Laboratory Application used *EM Field*, the same software that was used in the "Electric Fields and Potentials" lesson. For this lesson, *EM Field* was used to simulate magnetic fields. Again, superposition was explored, specifically with current-carrying wires simulated by the software. These simulated wires were then used to explore the field created by current-carrying coils.

This lesson was designed to help students learn how magnetic fields are produced, how magnetic fields are represented, and how magnetic fields add via superposition.

E. Electric and magnetic fields

This lesson consists of an Exploration, two Hands-on activities, and two Computer-assisted Laboratory Application activities. Students had explored electric fields and magnetic fields separately in other lessons. This lesson allowed them to explore both, to see the similarities and differences.

In the Exploration, students were first asked to summarize what they had discovered about electric and magnetic fields. Then a video clip was shown of an electron beam as it responds to an electrically charged rod and to a magnet. The students compared the direction of the force on the electron beam to the direction of an applied electric field and the direction of an applied magnetic field. In this case, the electric and magnetic fields were in the same direction, but the forces were not. Students concluded that electric fields and magnetic fields are not the same thing, since they have different effects on the electron beam.

In Hands-on Activity One, students were asked to predict the effect of one end of a magnet on a paper clip, then predict the effect of the other end of the magnet on the same paper clip. After recording their predictions, students tested their predictions. This activity was designed specifically to confront a conception that was discovered during the oral interviews: that if one end of a magnet attracts something, then the other end of the magnet will repel it. Students then compared the materials that could be visibly affected by electric fields, magnetic fields, both, or neither. Again, students compared the electric field to the magnetic field, and also compared electric charges to magnetic poles. This

activity was also designed to counter a common conception: that electric charges and magnetic poles are identical.

Hands-on Activity Two used moving magnets to create electric currents, as indicated by the deflection of a galvanometer needle. Activity One showed that electric and magnetic fields are different, and Activity Two showed that they are related.

The Computer-assisted Laboratory Application used a magnetic field sensor interfaced with a computer to investigate magnetic fields. First the students familiarized themselves with the sensor and found the direction of the Earth's magnetic field. Then they explored the strength and direction of the magnetic field produced by a bar magnet. The final activity was to use the field sensor to investigate the field produced by an electrically charged plastic rod. This showed again that electric fields are not the same as magnetic fields.

This lesson was designed to show how electric and magnetic fields are produced, how they are the same, and how they are different. These goals were chosen based on student difficulties in explaining the relationship between electric and magnetic fields, as shown in the pre-instruction research.

F. The ratio of electric charge-to-mass for electrons

This lesson consists of a single activity and was a modified version of a laboratory that had been used for many years at the University of Nebraska-Lincoln. The former lab used an electron gun to aim an electron beam into a region where a magnetic field alters the path of the beam. Based on several measurements, students could calculate the ratio of the electric charge to mass

for an electron. Comments made by students in this study, and by their instructors, suggested that students can do the calculations with some success, but that the students often do not understand the function of the equipment.

The former lab was modified to explicitly use the concepts explored in the earlier lessons. In “Electric Fields and Potentials “ the students learned how electric potential and electric fields can be used to accelerate electrons; this was then used in this lesson to create the electron beam. The lesson “Magnetic Fields and Electric Current” provided students with a knowledge of how to use electric current to create magnetic fields. The Exploration for “Electric and Magnetic Fields” allowed students to find the direction of the force on an electron beam due to a magnetic field. These elements were combined in this single lesson. Probing questions were used to make the students think about the concepts involved in each stage of the experiment.

VI: POST-INSTRUCTION PERFORMANCE

The effectiveness of any instructional strategy can be measured by its effect on student learning. In order to assess the effectiveness of these multimedia activities to increase student knowledge of electric and magnetic fields, written and oral examinations of the students were conducted. The post-instruction data gathered in this study were from four sources: oral interviews, and written hour exams, a final exam, and quizzes. The final exam was administered to 95 students after all instruction on electricity and magnetism had been completed. See Appendix A for a tabular summary of the data collection. A concise summary of the collection and analysis of a subset of these data appears in Appendix B.

All post-instruction quizzes were administered after the relevant lab was taken. Every three weeks, a quiz based on the three previous labs was given to the students. The post interviews were conducted at different times during the semester, so some interviews were post-instruction for electric fields, but pre-instruction for magnetic fields. There were 15 oral interviews conducted after the subjects had completed all multimedia electricity and magnetism lessons. The post-instruction oral interviews followed the same procedures as the pre-instruction semi-clinical oral interviews (except there was no electrophorus equipment for the post-instruction interviews). Plastic rulers, wool, a Ping-Pong ball, Styrofoam, a steel marble, pith balls, aluminum, magnets, etc. were used as before.

As a result of their multimedia activities, the students gave much improved responses (as compared to the pre-instruction responses) to both

written and oral questions. A summary of the written responses is given in the table below:

Question	Answer	Percent
What is an electric field, as used in this course?	Correct (Force per charge, caused by charge, etc.)	71%
	An area or volume	7%
	The flow of charge	4%
What is the fundamental source of electric fields?	Charges	65%
	Potential difference	14%
What is the fundamental source of magnetic fields?	moving charges	76%
	gave example only	12%
Sketch the electric field for an isolated charge.	correct vectors	83%
	wrong vectors	4%
Sketch the electric field for an isolated charge, and for two charges.	both correct	72%
Sketch the electric field for an isolated charged plate, and for two charged plates.	both correct	65%
Sketch the magnetic field around a bar magnet.	correct	98%
Sketch the magnetic field around a current-carrying wire.	correct	90%

It was found that student understandings of fields can be discussed in seven categories: i) existence of fields, ii) source of fields, iii) representation of fields, iv) superposition of fields, v) relationship between electric and magnetic fields, vi) relationship between gravitational and electric fields, and vii) relationship between gravitational and magnetic fields. An eighth category for

discussion is the behavior of magnets. The reasons for including this category were explained in Chapter 4, and include the possible confusion of magnetic poles with electric charge.

A. Post-instruction data

i) existence of fields

Physicists think of fields in a highly abstract manner, as discussed in Chapter 3. To see if college students in introductory physics courses use concepts similar to a physicist's field concept, most oral interviews began with a question, for example, "How can you affect this system without touching it?" Based on the initial response, the interviewer tried to deduce what mental construct the subject used to explain action-at-a-distance.

Of the 15 post-instruction interviews, 13 were judged to have an adequate conceptual understanding of the field concept, and only 2 did not seem to understand the concept.

During an interview, subject S1 suggested using a charged object as a means for affecting a pith ball from a distance. A ruler was charged by rubbing it with wool then brought near the pith ball. After the pith ball touched the ruler, the pith ball became charged and was repelled from the ruler. After observing that the pith ball continued to shift away from the ruler, the interviewer asked the subject to explain this interaction:

Int: How it can repel it from so far away?

S1: Create an electric field.

- Int: What produces that field?
- S1: The charges.
- Int: Is that field still here even though I'm not very close to the pith ball?
- S1: Yeah... The closer you are the stronger it is.
- Int: If we're very far away does it become zero or does it just get smaller?
- S1: It gets smaller. Infinitely smaller.
- Int: How far do we have to go before it becomes zero.
- S1: Forever.

Before using any of the interview equipment, subject S4 discussed how one can affect a system without contact, making references to laboratory activities in which charged objects affected other (charged and uncharged) objects. While describing the activity in detail, the subject suggested "use electric force":

- Int: You mentioned this electric force ... how does the ruler put a force on the pithball without actually touching?
- S4: The charges don't have to touch in order to have an effect. There's just an attraction that travels between here and here.
- Int: Once you charge the ruler, is it producing something that charges on the pithball feel?
- S4: Yes it is. It's producing a ... this has a charge and then it interacts with the pithball, so it is producing a field around this.
- Int: What kind of field would that be?
- S4: It would be an electric field.

Int: How can you describe an electric field?

S4: An electric field is kinda like an excess charge that is on something. It's usually in all directions around something. It can be positive or negative. Usually it depends where it's charged, what you're charging. But it doesn't have to touch something to have an affect. It's an invisible force.

Subject S15 was able to discuss a multimedia lesson in which charged rods were used to affect various objects. No equipment had been used during the interview before the subject used the word "fields":

Int: You used the word "fields," what do you mean by "fields"?

S15: Field is ... I'm not sure ... whenever you charge something, it has ... the force of the charge will come off of the object in a direction ... the pattern around the object to create the field and when we bring something into that field it will be affected by the charge of the object.

Int: Is there a field there even if we don't have something like another charge there to detect it?

S15: Yes.

After using a charged plastic ruler to affect a pith ball, and after identifying a field as the cause for the force, subject S6 discussed how the strength of the field depends on distance:

Int: What can you tell me about the strength of this field if I were close versus far away?

S6: The field's stronger when you are closer to it and weaker when you move away from it.

Int: And how far would I have to go before the field becomes zero?

S6: It will never become zero.

Int: So even if I were infinitely far away it would ...

S6: it would still have magnetic force, it would just be so weak that you couldn't see it.

Subject S26 suggested charges could affect objects from a distance at the beginning of the interview:

Int: How is it that charges can affect each other without touching?

S26: Because they have electric fields, the field that surrounds the charge.

The inability to explain one's thoughts was still a problem, but much improved. Subjects still needed discussion, sketches, and gestures to indicate their understandings, but these short excerpts from the post-instruction interviews show that students give improved responses and discussion of fields as compared to the pre-instruction subjects.

On the final exam, students were asked to "Describe what an electric field is, as used in this course. Sketch if you wish." This is a difficult question to answer, and most answers were not completely correct. Of the 90 answers to this question, 71% (64 of 90) were acceptable. However, there are some important incorrect concepts that were noteworthy. Many students simply drew sketches and included no words. Only 7% (6 of 90) said that an electric field was an area, a region, or a volume where something happens. 4% (4 of 90) answers indicated that an electric field is a flow of charge. Only 2 of 90 said that an electric field is a path where charges move, down significantly from the first hour exam (see "representation of electric fields," below).

ii) source of electric fields

Causality is a fundamental presupposition of physics. If students affirm the existence of a field, then it is logical to ask them about its cause. When asked on the final exam “What is the fundamental source for electric fields?”, 65% (62 of 95) of the students said “charges.” The next most common answer involved “potential difference,” and was used by 14% (13 of 95 students) of the students. Once the language of fields was suggested by the question, all of the students proposed a cause.

Subject S6, interviewed after completing all instruction on electricity and magnetism, suggested using static electricity and electrical forces to affect objects without touching them. No equipment had been used during the interview prior to the following discussion:

Int: How might we go about generating static electric forces?

S6: By rubbing a ruler with wool or silk to generate the charge on it.

When asked what is the source for electric fields, many subjects gave similar answers. Subject S33 had observed a charged ruler affecting a pith ball and suggested the field around the ruler as the cause for the attraction. When asked what created the field, the subject said the following:

S33: Electric charges ... charges induce the field.

Subject S38 had discussed observations from the multimedia lessons but had not used any equipment for the interview when the interviewer asked about the source for electric fields:

Int: What creates electric fields?

S38: Electric fields? Just current or charge.

Similarly, subject S15 had only discussed electric fields when asked what creates them:

S15: I think just a net charge of one type or the other.

Subject S42 discussed magnets and magnetic fields before electric fields. After the subject mentioned using a magnet to create an electric current in a multimedia lesson, electric fields were discussed. There were no static electric effects observed during the interview prior to this discussion on electric fields:

Int: What would you say produces the field?

S42: It's a charge on an object whatever it is.

When asked to describe or sketch an electric field, subject S26 drew two electric charges and the field surrounding them. When asked if two charges are needed to create an electric field, the subject replied "No, you only need one."

One of the five interviews that were completed after all instruction on electricity and magnetism (including lecture) had an answer that allowed for

potential difference. This excerpt is from a discussion in which subject S3 had observed a charged ruler attract a pith ball and identified the electric field as the cause for the action-at-a-distance:

Int: What's the source for this field?

S3: In general it's going to be a difference in electrical potential. I could think of applications like in lab where we'd have like a positive electrode and a negative electrode, I mean I know that's kind of a more specific example. But there would be a potential difference because ... I guess I don't know if I can be a lot more specific in general terms ... the fact that it's a difference in the electrical potential.

ii) source of magnetic fields

When asked "What is the fundamental source for magnetic fields?" on the final exam, 76% (72 of 95) of the responses mentioned currents or moving charges. 12% (11 of 95) of the students gave examples of magnetic objects, such as the Earth or magnets.

Again, these same answers were common in the oral interviews. Subject S8 had discussed electric charges, electric fields, and magnetic fields when the interviewer asked how one can create magnetic fields:

S8: Well you have to have current flowing through it for that to create a field. I mean if you just have ... let's say you create positive charges here and negative charges here. It's not going to do anything unless you do something to move current through this.

Int: So only moving charges will create magnetic fields?

S8: Well this one has moving charges but it has magnetic properties. To create a magnetic effect from an electric substance you have to move current through something. For example if you move current through a wire it's gonna create - this is the wire and it's going into the paper - you're going to create the field around it if there's moving charge.

After observing a magnet attract various objects during the interview, and discussing the field produced by magnets, subject S33 was asked to relate magnetic fields to activities from the multimedia lessons:

Int: How did you produce magnetic fields in lab?

S33: Just kinda having a magnet.

Int: Did you use anything else to produce magnetic fields?

S33: Oh, a current. Through a wire.

Int: Do you have to have a current through a wire or was it just a simple wire producing a magnetic field?

S33: Yes it had current going through it.

Int: Okay and can you tell me what current it is? Or what a model for current might be?

S33: Just a formula or the model?

Int: Just in words maybe, what is current?

S33: The flow of electric charges through a wire.

iiie) representation of electric fields

To gain the most from instruction, it is important that students understand the representation for electric and magnetic fields. When asked on the final exam to sketch the electric field for an isolated negative charge, 83% (79

of 95) of the students drew essentially correct diagrams. About 4% (4 of 95) drew arrows pointing in the wrong direction, and 2% (2 of 95) drew lines but no arrows.

A slightly different question was asked on a quiz during the course, after relevant instruction had been provided. Two versions of the quiz were used. On the first version, students were asked to sketch the electric field for an isolated charge, then asked to sketch the field due to two opposite charges. 72% (56 of 78) of the answers were essentially correct.

The second version of the quiz, taken by a different group from the first version, asked the students to sketch the electric field for an isolated charged plate, then asked them to sketch the field due to two oppositely charged plates. 65% (63 of 97) of the sketches were essentially correct.

The following True/False question was used on the first hour exam with 97 students:

“Electric field lines represent the flow of charge from an area of high charge density to an area of low charge density”

56% (54 of 97) of the students correctly chose the statement to be false. As indicated in the table and discussion above, understanding of the representation improved by the end of the course, when only 4% of the students thought that the electric field was a flow of charge.

iiim) representation of magnetic fields

After completing the instruction on magnetism, 176 students were given a quiz on magnetic fields. When asked to sketch the magnetic field surrounding a

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Nearly 70% (65 of 93) of the answers were essentially correct in showing superposition, with minor errors. Acceptable answers needed to show a field vector due to each of the given charges, and some attempt to add them vectorially.

Many of the oral interview subjects displayed an understanding of the superposition of forces. Since the interview questions were not planned in advance, it was not known if the interview subjects would introduce a given subject for discussion. None of the post-instruction interview subjects discussed how fields superpose, many did discuss the combination of forces acting on an object. A typical discussion, which took place immediately after a charged ruler was used to attract a pith ball, follows:

Int: What other objects would you expect this to affect?

S6: It should affect all of them just being the metal ones are heavier so its harder to see the attraction.

Int: Why would it be harder to see the attraction on a heavier object?

S6: Just because you have all that force and the force of the magnetic field isn't great enough to show the attraction or repelling on a heavy object. You have the mass times gravity which is the force exerting down on them. That force isn't as great as that one.

v) relationship between electric and magnetic fields

The following True/False question was used on the final exam with 93 students:

True or False: Positive electric charges are repelled by North magnetic poles.

This question was designed to test how many student confuse electric and magnetic phenomena. 62% (58 of 93) correctly said it was false.

Twelve interviews were conducted with subjects after they had completed the multimedia lessons on magnetism, but prior to magnetism being discussed in lecture. Eleven of these demonstrated a knowledge that electric fields are not the same as magnetic fields. Excerpts from some of these twelve interviews follow.

Subject S40 had discussed the multimedia activities involving electric fields and magnetic fields, and no equipment had been used during the interview when the subject compared electric fields to magnetic fields:

Int: What can you tell me about magnetic fields?

S40: They're similar to the electric fields but they're not the same because magnetic fields are ... the source is different so I don't know exactly how to explain it, but the source is moving ...

Int: They are different?

S40: Yeah, they're different. But they have a lot of similarities.

During a discussion about the multimedia activities, subject S38 mentioned both electric and magnetic fields. No apparatus from the interview had yet been used, and the interviewer asked for more information:

Int: How does the magnetic field compare to the electric field?

S38: Compared with electric fields, magnetic fields well they do have currents running in them as well as ... I just learned from the galvanometer in there that magnetic field can produce an electrical current.

After discussing magnetic fields and how they were used in the multimedia lessons, subject S42 was asked if there were any other kinds of fields and how they compare to magnetic fields:

Int: Are there any other kinds of fields that you're aware of?

S42: You mean like electrical.

Int: What similarities might there be between electric fields and magnetic fields?

S42: If you have a current running through a wire it will have a magnetic field. But they're similar but they're not the same. You can use a magnetic field to make an electric field or vice versa I can't remember which. We talked about it in lab on Friday.

Int: That was where you were using a magnet and a coil?

S42: Coil and magnet.

Int: And you caused a galvanometer to deflect.

S42: Ah huh (yes).

Int: When you compare the electric and the magnetic ... we have charges and you have poles on a magnet. How do you suppose those are related?

S42: They are related but I'm not sure how.

Int: Do you think they're the same thing?

S42: No.

No equipment had been used in the interview with subject S15 at the time magnetic fields were first discussed. Electric charges and electric fields had been discussed, with the subject referring to activities from the multimedia lessons.

When the interview turned to magnets and magnetic fields, the subject was able to continue the discussion without using any equipment. Only after the following excerpt did this subject use any of the items provided for the interview:

Int: Do you believe that magnetic fields and electric fields are different?

S15: In some respects, yes.

Int: What might be some similarities?

S15: They have the same sort of repulsion and attraction behaviors; likes repel, opposites attract type of deal. And the attraction can be used to attract other objects besides each other. It can be used to create a current, we did that in lab... not create but induce.

Int: Do you think there's some difference between these two kinds of fields?

S15: I don't think you can transfer magnetic fields or induce one. They affected things differently. I don't think you have a negative magnetic field. And in what we did in lab that we surmised or we thought that magnetic fields were ... the electron stream was affected differently. It wasn't direct ... the affect on the electric charges was perpendicular.

This subject was describing a video that was used in the Exploration of the multimedia lesson "Electric and magnetic fields," in which an electron beam was deflected first by a charged rod and then by a bar magnet, in order to show that when the field direction is the same, electric fields and magnetic fields have different effects on the same objects. This was one of the methods used to show that electric and magnetic fields are not identical.

Another subject who had completed multimedia lessons about magnetism prior to have any related lecture also showed an understanding that electric fields and magnetic fields are different. After discussing electric fields, but prior to using any equipment during the interview, subject S4 suggested magnets could affect objects from a distance:

Int: What can you tell me about magnets in general?

S4: Magnets always have two poles no matter how... I mean you could cut it here and it would still give you two poles. That's one thing that is kinda unique about magnets. Positive and negative charge on each end. And attractive and repelling forces.

Int: Okay is that the same kind of charge as what we were talking about on the charged ruler and on the pithball?

S4: No it's a different type of charge.

Int: Do you think they have anything in common with electric charges?

S4: Yeah they have some of the same types of facts, the repelling and attracting facts. But this is a constant field. It's always going to be there, it's always going to exist whereas electric charge you can fool around with it and change an electric charge. This field here is in the magnet.

When asked how one could affect objects without touching them, subject S34 suggested charged rods and magnets, including making references to activities from the multimedia lessons. After discussing electric charges and electric fields, and using the electrostatic equipment during the interview, the subject discussed magnets:

Int: We mentioned electric fields. Is there some similar thing associated with magnets?

S34: Magnetic fields are very much like electric fields in the fact that they have positive and negative poles or whatever and that the electric or the magnetic field lines are almost identical.

Int: You said that a magnet has poles?

S34: Mm hm (yes). Magnet has two poles but I guess they call one positive and negative.

Int: Can you sketch a field around this magnet with two poles?

S34: Mm hm (yes).

Int: You said one end is positive and one end is negative. In your picture, which would be which?

S34: I'm not sure if this is right but I would say this is positive and this is negative.

Int: How do those positives and negatives compare to the positive and negative electrical charge? Are they the same? Is a positive pole the same as a positive charge?

S34: It's not the same because it doesn't ... I don't think it attracts its own electrons or I don't think it attracts like a positive charged object or material. They indirectly have to deal with each other with electric potential or magnetic potential but its not directly a relationship to it.

Int: So positive and negative are more of a label and not really a defining thing?

S34: exactly.

Subjects who had experienced lecture in addition to the multimedia lessons also expressed the understanding that electric and magnetic fields are different. After observing and discussing magnets, magnetic fields, electric charges, and electric fields, subject S22 was asked to compare:

Int: How would you compare electric fields and magnetic fields?

S22: There are some similarities but they're similar in some ... both have attractive ones that attract and ones that don't ... the poles... I guess they are different.

Int: Do you have any idea how?

S22: An electric field around every electric charge and the charges are moving that it goes (inaudible) magnetic field and a magnetic field is created from the motion of the charges.

Int: Ok so every charge is producing an electric field but only moving charges would create a magnetic field?

S22: Yes.

After observing and discussing the effects of electric fields and gravity, and mentioning magnetic fields, subject S26 was asked to describe magnetic fields:

Int: We discussed gravity and electric fields?

S26: And magnetic fields.

Int: How would you describe a magnetic field?

S26: I think it's similar to an electric field in that it's multi-directional, I mean it's around a magnet but then you get with a magnet a north and south pole. Which I think is comparable to the plus and minus charge.

vi and vii) relationship between gravitational and electric or magnetic fields

During the interviews with subjects who had completed the multimedia lessons on magnetism but had no lecture on magnetism, many subjects compared gravitational fields with electric fields or magnetic fields. Subject S15 had discussed electric fields and magnetic fields, including the relationship

between electric and magnetic fields, and had used a magnet with some of the interview equipment before the topic of gravity was introduced:

Int: Would you say there's anything else acting on this pithball right now for example that's not touching it?

S15: Oh, there's gravitation force.

Int: Would that also be a field?

S15: I suppose you could consider it a field. I guess you probably would.

Int: How would you compare that to either electric or magnetic fields?

S15: Gravitational only has one direction, only it's always going to affect things in the same direction which is towards its center. I mean it's always an attraction, never repulsion with gravitation.

After discussing electric fields and magnetic fields, and using only a magnet to affect a steel marble, subject S4 indicated that gravity also affects objects without contact. A pith ball was hanging nearby for the following discussion:

Int: Can you think of anything else that might be affecting the pith ball or any of these others without touching?

S4: Gravity, I guess that's a field.

Int: How would you compare gravity to electric and magnetic fields?

S4: It's a different type of force. It really doesn't have to do with charge and polarity. It's more of a mass and a mass and how that force acts upon that and it really doesn't have to do with charge.

Subject S34 had discussed electric fields and magnetic fields, including using charged rulers and magnets to affect other objects, when gravity was discussed:

Int: We've discussed the electric and magnetic fields. Are there any other kinds of fields you are aware of?

S34: Well, gravity fields.

Int: How would you compare a gravitational field to an electric field?

S34: I think it's a pretty even comparison. I think the farther that you leave the object ... everything is always perpendicular to the surface of say the earth and I think the gravitational force decreases as you increase your distance from the earth, although I don't believe there is an actual repelling force in gravity while there would be if there was two positive charges, say.

Int: How would you compare gravitational fields to magnetic fields?

S34: The same way ... This always attracts all kinds of metals but if there's another magnet then they would have a repelling force, so I think the shape of it and the relationship to distance is the same or in relationship to gravitation is the same except that it doesn't have a repelling force.

Subjects who had finished the multimedia lessons and also had lecture on magnetism showed similar understanding of the differences between gravitational fields and electric or magnetic fields. Subject S26 had discussed electric fields, including observations of charged objects affecting a pith ball and other objects, before gravity was mentioned:

Int: What other ways can you think of that we might be able to affect some object hanging here?

S26: If you could change gravity.

Int: Would you say gravity is comparable to the static charges and the electric field that we've been talking about?

S26: Actually, that's similar. It's also a field, especially with similar properties, but it's always pushing down. I mean a charge on an object doesn't affect gravity.

Int: So gravity is a completely separate thing from what we've been seeing?

S26: Right.

Int: But you said it was a field ...

S26: Yeah, it's a gravity field, yeah.

Int: Okay. How might the field of gravity be different from the electric field?

S26: Well, because gravity is in our earth is always going toward the center of the earth, it's always pushing down. Whereas in an electric field, I don't know if this would be uni-direction I suppose, whereas electric fields are multi-directional. And it can affect things, you know wherever. So I put it near here and it's gonna push it up. If I put it here, if they're the same charge it pushes up, whereas gravity is always pushing down towards the center of the earth, no matter what.

viii) behavior of magnets

One conception of magnets that was encountered in this study was a belief (held by 75% of pre-instruction subjects) that one end of a magnet will attract a steel marble, and the other end of the same magnet will repel the same marble. This conception was found during the interviews, and was a subject for later written pretests and posttests. On a posttest with 27 subjects, only 11% (3 of 27) still held this misconception. It was also discussed during some of the post interviews.

Subject S8 had discussed electric fields and magnetic fields without using any equipment during the interview. When asked to predict how a magnet would affect a steel marble, the subject said the following:

S8: Steel? It should act.

Int: Okay and what should the effect be?

S8: The magnet will attract.

Int: Okay.

S8: Both poles should attract it.

Subject S22 was asked to predict how a magnet would affect a steel marble prior to using a magnet or discussing electric charges during the interview:

Int: It depends on the pole. Is that what you're saying?

S22: I guess so.

Int: What should one pole do and what should the other pole do?

S22: One should attract and one should repel.

After discussing electrical forces, but before using a magnet during the interview or learning about magnets in lecture, subject S6 predicted that both poles of a magnet will attract a steel marble:

Int: Will both poles attract or will one of them attract and the other do something different?

S6: I believe they'll both attract.

Int: Why do you suppose both ends of the magnet will attract the steel marble?

S6: This is funny but that doesn't have a pole or anything so either pole will attract it.

Int: So if the steel did have a pole how would you expect it to react?

S6: The north-south poles will attract and similar or like poles would repel.

Subject S33 has discussed electric fields and observed static electric phenomena when the interviewer asked how a magnet would affect some of the same objects:

Int: What would the effect be?

S33: Attractive at both poles.

Int: Both poles? So if I decided bring one close it should attract?

S33: Yeah it does.

Int: Okay and the other end should also attract?

S33: Yeah.

Int: Okay and it also does. Why should both ends attract?

S33: Cause the ball isn't producing a magnetic field.

The interview subjects that discussed this prior to lecture on magnetism also knew that both ends of a magnet will attract an unmagnetized steel marble. Subject S15 had not used any equipment during the interview prior to predicting how a magnet would affect a steel marble, although electric fields had been discussed:

Int: What do you think the effect of that magnet will be on the steel marble?

S15: An attraction.

Int: Should it always be attraction or something else?

S15: It will always be attraction.

Int: Did you have any reason to believe one end might repel?

S15: Well even if I know that the poles differ as far as charges but I know that from what we've done in lab that both ends will attract. I mean they could because of the different affect of each pole it could have a different effect on some materials.

B. General results from the post-instruction interviews

Students showed improved responses after multimedia instruction. Prior to instruction, few students could explain what a field was or how they are created, the vector representation used by physicists was not used by students,

superposition was not demonstrated by many students, and students were very confused over the relationship between electric and magnetic fields.

After instruction, 71% of the students could describe the concept of an electric field. 65% identified charge as the source for electric fields, and another 14% indicated that a difference in electric potential would create an electric field. Electric current (moving charges) was identified as the source for magnetic fields by 76% of the students, and another 12% gave an example of an object that creates a magnetic field (perhaps due to misreading the question).

The ability to sketch electric and magnetic fields improved dramatically when compared to pre-instruction answers. 83% of the students could sketch the electric field due to an isolated charge using the vector representation. 4% drew the correct picture, but had the vectors pointing in the wrong direction. 98% of the students could sketch an accurate representation for the magnetic field due to a bar magnet, and 90% could sketch the magnetic field due to a current-carrying wire.

Superposition was correctly demonstrated by 70% of the students on the final exam. This is difficult to compare to pre-instruction results, since students lacked the representation and concept for fields with which to demonstrate superposition.

A majority (62% of written responses) of the students distinguished between electric and magnetic phenomena on the final exam. 11 of the 12 interview subjects who had completed multimedia lessons but had no lecture on magnetism were able to distinguish electric fields from magnetic fields. Most

subjects also expressed the belief that gravitational fields were different from either electric field or magnetic fields.

Students know “likes repel and opposites attract.” They apply this for both electric charges and magnetic poles. Students also know that field (or force) strength decreases with distance. There was some confusion over how far one must go before the field strength is zero - some thought it might be a few feet, others thought infinite distance.

The number of students believing that one end of a magnet repels what the other end attracts dropped from 75% of pre-instruction subjects to 11% of post-instruction subjects.

C. Multimedia lessons with lecture

When looking at the data just presented, the effects of the multimedia lessons are commingled with the effects of the lecture and recitation activities. The problem is to assess the effect of lecture and recitation and subtract it from the data. One method is the use of a control group so that one group taught with “traditional” methods can be measured against another group taught with “new” methods. For this study, there was no chance to have a control group. Various considerations required that all students enrolled in Physics 142 in any one semester must take identical laboratories. Additionally, all laboratories were to be changed from traditional to multimedia at the same time, and there was no chance to use the traditional lessons again.

One solution would have been to test the Physics 142 students during semesters prior to modifying the laboratories. There are problems associated

with that method. From one semester to the next, the class professor changes, and the text might also. Historical events may have an unmeasurable effect on the data. Another factor precluding this solution is that this study evolved over time; the variables under study during post-instruction data collection were not identical to the variables under study during the pre-instruction data collection. An example was that the conception held by many students that one end of a magnet will repel what the other end attracts; this was not known prior to writing the first multimedia lessons, and an activity was designed to correct that conception.

There is one method that were used to attempt to measure the effectiveness of the multimedia lessons with as little dependence on lecture or recitation as possible: some of the oral interviews were conducted prior to certain topics being discussed in lecture. These interviews can be used to measure the effect of the multimedia lessons separate from lecture.

There were fourteen oral interviews conducted prior to the first multimedia lesson on magnetism. Of these fourteen, only two expressed a clear belief that electric and magnetic phenomena were different. Given that those fourteen subjects had no formal education on magnetism yet, they were not able to discuss magnetism in detail.

There were twelve subjects interviewed after taking at least one multimedia lesson on magnetism and before having any lecture on magnetism. Of these twelve, eleven expressed a clear belief that electric and magnetic phenomena are different. Many of these subjects were quoted in the section of this chapter that discussed the relationship between electric and magnetic fields.

This study began with the hypothesis that effective instructional materials can be created through the use of research into students' understandings. These results lead to the conclusion that the multimedia activities in addition to traditional lecture and recitation produced effective student understanding of the concepts of electricity and magnetism at the end of one semester of formal instruction in algebra-based general physics.

VII: SUMMARY AND SUGGESTIONS

College physics students begin a course on electricity and magnetism with preconceptions about how the world works. While these preconceptions often work well for the students in their lives, these preconceptions often do not match the formal concepts used in physics instruction. The first part of the study found that students lacked both the concept of a field and the language to discuss it. It was also found that beginning students did not understand the sources for electric and magnetic fields, nor did they understand the vector representation used for these fields. Confusion of electric and magnetic phenomena was common. Many students also did not understand that there is a difference between gravitational fields and electric or magnetic fields.

This study explored how college physics students think and talk about electric and magnetic fields prior to instruction in electricity and magnetism. Little prior research had been done on this topic, and this study expands the database of research in students' understandings. Such research is valuable for creating effective instructional materials.

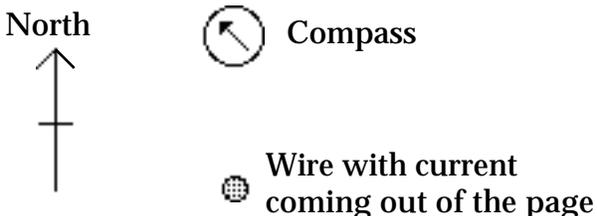
Multimedia lessons were developed based on the collection and analysis of data on students' understandings. These lessons were effective in overcoming many of the preconceptions and misconceptions found to be held by a majority of the students. As a result of this instruction, students could discuss electric and magnetic fields, identify the sources for these fields, use the vector representations, demonstrate superposition, and distinguish electric fields from magnetic fields, as well as explain some similarities and differences between

gravitational field and electric or magnetic fields. The table on page 101 gives a summary of the effectiveness of the instruction.

It was also shown in this study that multimedia lessons can be effective apart from lecture: prior to the multimedia lessons, only 2 of 14 interview subjects could discuss the relationship of magnetic fields with electric fields; after the multimedia lessons, 11 of 12 interview subjects could successfully do so, with all 26 of these interviews conducted before any lecture on magnetism.

A preconception was found in this study that many students (75%) believe that magnets attract objects with one end, and repel objects with the other end. Part of this preconception was due to the belief that magnets have opposite charges at each end, and misuse of the rule “opposites attract and likes repel” for interactions with neutral objects. Only 11% of the post-instruction students still held that conception.

This research project began with only a small understanding of how college physics students think about electric and magnetic fields. By talking with students and analyzing quizzes, it was found that there were several areas in which students had difficulty learning about electric and magnetic fields. Through a series of revisions, pretests were developed to probe preconceptions. Early versions of the pretests showed potential student difficulties, but analyses of some questions were inconclusive as to exactly what difficulties were responsible for incorrect responses from the students. For example, the following question was given to many students as a pretest:



Consider the picture above. There is a compass placed 2 cm north of a current-carrying wire. The current is coming out of the page. This causes the compass needle to point 45 degrees west of north.

- 1) What direction will the needle point when the compass is placed 2 cm south of the wire? Explain.
- 2) What direction will the needle point when the compass is placed 2 cm east of the wire? Explain.
- 3) What direction will the needle point when the compass is placed 2 cm west of the wire? Explain.
- 4) What direction will the needle point when the compass is placed 4 cm north of the wire? Explain.

Only after many students were unable to correctly answer these questions was it found that there were many complicating factors: (1) students may not understand that the current creates a magnetic field, (2) students may not understand that compasses measure the direction of the net magnetic field, (3) students may not know how to find the direction of the magnetic field at the location of the compass due to the electric current, (4) students may have trouble calculating the new angles for the compass (many suggested that if the field strength doubles, the angle will double), and (5) students may not understand that the Earth's magnetic field needs to be accounted for, and that is why the compass initially points at a 45-degree angle. In order to find the real difficulties students have, these problems need to be addressed one at a time, or it may be

difficult to ascertain which difficulty is causing students to answer incorrectly. A large part of this study was the important investigation of finding out what questions to ask.

This study has provided a broad but crucial foundation to an area that has had little prior research. Now that some of the student difficulties are known, the instruction needs to be revised to further improve understanding. As stated in Chapter 2, the process can be described by these 7 steps (Grayson, 1996):

1. Select topic (content area) and target group;
2. Identify student conceptual difficulties;
3. Write preliminary version of the instruction;
4. Try it out with students - observe what they do and how they interact with the program, test what they learn, and solicit students' comments and suggestions.

This thesis reports on these four stages. Future work will use the next three steps:

5. Modify on the basis of step 4;
6. Try it out with students again;
7. Repeat steps 5 and 6 until the instruction is reasonably robust and fairly stable.

The instruction used in this study was designed with some students' understandings partially understood. These results may not be typical or generalizable, even at similar universities. More data need to be collected to determine if the understandings discussed here are pervasive and persistent.

Due to the subjective nature of the interpretation of the written responses, there is an innate uncertainty in the data reported here. Additional data can help quantify such uncertainty.

This study has shown that research in students' understandings can be used to develop effective multimedia lessons to help students learn concepts in electricity and magnetism. This is an area that needs more research. The multimedia lessons were used in conjunction with lecture and recitation. Each of the eight categories of student understandings used in this study (existence of fields, source of fields, representation of fields, superposition of fields, relationship between electric and magnetic fields, relationship between gravitational and electric or magnetic fields, and the behavior of magnets) can be explored separately. Superposition is an especially powerful unifying approach to explaining physical systems (Fuller, Fuller, & Fuller, 1978). This concept seems to call for special attention.

VIII: PERSONAL POSTSCRIPT

During my undergraduate experience, I thought I was going to be an electrical engineer. It was during the summer preceding my senior year in college that I realized I was more interested in *how* my world worked than in only applying the laws of physics. I went to graduate school as a physicist, but I had barely begun graduate work when I realized that I was not only interested in how my world worked, but I enjoyed helping others to understand their world. To me, that was a bigger challenge than simply learning for myself.

I conducted my early research work in High Energy Physics. I had been working on the main detector for a major research project that was canceled. That gave me a choice: find other research in a physics lab to get my degree, or do something I found both more challenging and rewarding. I chose the latter, and joined the Research in Physics Education Group at the University of Nebraska-Lincoln. This type of research was exactly what I had hoped for. I was able to use all of the quantitative analytical tools I learned earlier in my physics career, but I needed more. I needed to be able to figure out what percent of my students answered correctly, but I was also interested in *why* some students answered incorrectly. None of my early training prepared me to do that. Only qualitative research would be effective for finding the data I needed, so I learned how to conduct a study in which I needed not only numbers, but words to describe how students understood concepts.

As I looked back at my early interests, I decided that studying student understanding of electricity would be personally challenging and rewarding. It was quickly apparent that other physicists had the same idea, but earlier than I,

and student understandings of simple electric circuits were already well-researched. A little more reflection on my own interests suggested a broader view than only electricity – electricity and magnetism! That would be the perfect area for me, since it was an area I had some interest and knowledge about. More than that, electricity and magnetism was a subject that caused me great frustration in graduate school. Part of that frustration grew out of not getting a complete understanding as an undergraduate. The final piece to my personal research puzzle was that many other topics in physics had been researched previously, and electricity and magnetism was wide open.

In addition, I was fortunate to have been part of the modification of laboratories for the first semester of introductory physics. It was apparent that the traditional methods used for teaching physics worked for some people, especially people who wished to be physicists. But for people who wished to be something other than a scientist, it did not appear that traditional physics teaching methods helped as much as they could. There was one instructional tool that was under-used – multimedia – especially for teaching abstract concepts in electricity and magnetism. Things that students could not easily experience or visualize could be brought to them via computers and video. For example, students taking class during the humid summers had trouble quantitatively investigating how static electrical charges interact. They could read about it in books, and hear about it in lecture and recitation, but the humidity made hands-on investigation difficult. To complicate matters, it seemed that students lacked a conceptual understanding of the interaction. Some students could do very nice calculations, but had trouble expressing their understanding in words.

As I began my research, I found that the task was much larger than I had imagined. There are *many* topics in electricity and magnetism with which students have difficulties. I had to limit myself and my research to a manageable task. Consideration and consultation with my adviser, Dr. Fuller, led to the decision to study students' understandings of the field concept. Fields are incredibly useful tools for physicists, and I knew that I would have been better off if I had gone to graduate school with a more thorough and fundamental understanding of fields. Although my research had been started more than a year before this narrowing in focus, I already had very useful information to guide the rest of my research.

By combining my early physics training with my educational interests, I was able to modify the methods used by physicists before me, and create multimedia lessons that were effective in helping students learn the field concept in electricity and magnetism. In my opinion, this research has only just begun. I have created a foundation for future research, which I can continue in my teaching. I have accepted a teaching position at a small college where I will have great freedom to gather more information and try new teaching strategies. I can investigate superposition, a topic that was studied in this thesis research, but still is not completely understood by students. In this manner, I hope to enable students to better understand and appreciate the world they live in.

As my father said (or made me think he said) many times as I was growing up, "I don't see how people can live in a world they don't understand." Of course, this was from a man who can (and does) identify plants growing in ditches over three-fourths of the United States and Mexico while traveling at 50

miles per hour, and has trouble understanding why everybody does not do the same. Perhaps I feel the same about physics.

APPENDIX B

A TYPICAL PRE-INSTRUCTION INTERVIEW

Int: The apparatus is fairly simple. We have a string suspended from the ceiling so it has a lot of room to swing. And I have a selection of 6 objects here, they all happen to be spheres, but that's not by design. And all they are is just an ordinary ping pong ball, a styrofoam ball, this is a pith ball so it's made up of stuff from inside plants.

S5: Oh, okay.

Int: And this is another styrofoam ball, this one's coated with graphite. This is a steel marble, so, solid steel. This is another pith ball, this one's coated with aluminum. And this is just a hollow aluminum sphere, it's rather light. Okay. And the idea here is that I can hang them from the string and I would like to ask you, can you think of a way that we can influence or affect one of these if we hang it from there without touching it or blowing on it or hitting the string?

S5: Without touching it, blowing on it, or hitting the string?

Int: Yeah.

S5: Could affect it. Mmm, you mean affect the motion of it going back and forth?

Int: Yeah, to make it go back and forth or something like

S5: Not that I'm aware of without blowing on it.

I: Okay, is there anything affecting, if I were to hang this ping pong ball,

S5: Mmm hmm. Just the air current in the room.

Int: Okay, so there would be air blowing on it. Is there anything else that affects this?

S5: Gravity.

Int: Okay, gravity is affecting it. How would you say gravity is affecting it?

S5: It's pulling it down.

Int: Okay. But nothing's touching it, right?

S5: Except for the string.

Int: But nothing is, is touching it related to the gravity right? I mean there's nothing reaching up and pulling it.

S5: No.

Int: So how do you suppose gravity can pull on that without anything touching it?

S5: It's, I'm not sure. It's just the force that pulls it down.

Int: Okay.

S5: The force that pulls you down.

Int: What's the source for that? Where does gravity come from?

S5: In the earth.

Int: Okay, so the earth is causing gravity, right?

S5: Sure, yeah.

Int: Okay. But the earth isn't touching this.

S5: No.

Int: How do you suppose that the earth can affect this without touching it?

S5: Does it have something to do with the earth's movement?

Int: Well, do you think it does?

S5: Sure.

Int: Okay.

S5: Is it, well, I would, I would think so. That would have to have something to do with it.

Int: Alright. Okay. But, do you have any idea maybe what the movement could have to do with it?

S5: Let's see. Well like, when it spins around, you're kind of st..., like in the, those rides where you spin around and you're stuck to the wall, the force is pushing you down. Well with the earth's movement the force is kind of like I say, holding you down.

Int: Okay.

S5: To the earth, is that, it probably causes the gravitational pull.

Int: Okay. Ah, so, so it is clear that the earth can affect this without touching it, right?

S5: Right.

Int: Can you think of anything else that might affect this without touching it. Something that you do, again not blowing on it or touching it. Something we can do to this that will make it move?

S5: You mean like the air?

Int: Okay, without blowing the air on it. No fans or anything like that.

S5: Mmm, no.

Int: Okay, well what if I asked you, say, could a magnet maybe do it.

S5: If that other magnet pulled to it it could. But with the magnet.

Int: Okay, would a magnet affect any of these.

S5: The metal.

Int: Okay.

S5: The metal plated or the metal coated.

Int: Okay, so why do you think a magnet would affect those and not the ones that are not metal coated?

S5: Because magnets are, they're metal and they attract one another, they have attraction or repel each other.

Int: Okay.

S5: Then with plastic or styrofoam there's no ...

Int: Okay, so here are two

S5: They can pull towards each other or push away. It depends on what you do with them.

Int: Alright, magnets. You say they can pull towards each other or push

away?

S5: Mmm hmm. Depending upon the direction of the ...

Int: Okay, ah, how do you suppose they do that?

S5: I have no idea. Probably something to do with the metal conducting.

Int: Okay. Do you have any idea what causes that force?

S5: Metal.

Int: Okay. Now you did say that those could attract, right. And so they can also repel?

S5: Correct.

Int: How can you get them to do that. What's the difference?

S5: The direction of the metal. If it pulls magnet one way it's positive and one way it's negative.

Int: Okay.

S5: Like, you have two negatives or two positives, they're gonna pull each other. Then you have a positive and a negative, they attract each other.

Int: Okay, could you do me a favor and maybe you draw, write out on this little paper how those orientations are if they both, the positives and the negatives.

S5: Like draw a picture?

Int: Yeah.

S5: Is it repel?

Int: Yes.

S5: I've really got myself confused. Okay. Those would attract.

Int: Feel free to describe anything you want while you're drawing.

S5: Okay.

Int: Ah, think out loud if you like.

S5: See here are the two forces. Actually the two forces would be going

towards each other, to repel against each other.

Int: Okay, well it's almost a choice on how you draw it. Because you're saying they repel so they are pushing against each other.

S5: Right.

Int: So this one feels a force due to this one, right?

S5: Right.

Int: And which direction would that force be?

S5: Well, the force would be pushing on it in that way, and this force would be pushing this way. They'd be repelling each other.

Int: Okay.

S5: They wouldn't be attracting each other.

Int: Have you drawn the free body diagrams in class yet? Okay, so what would be the forces on that magnet?

S5: Well you'd have a force going this way towards that one. And then you'd have the normal force from this one going to that one.

Int: Okay. Then you've labeled one end on each plus. Was there anything else that could be labeled in there?

S5: Well I guess, you could say this line could be a line down the center, (inaudible) towards each other and the other opposite side would be a line

Int: Okay.

S5: This force would be pulling that way. The force acting on this one would be pushing on that one... pushing back, that they attract each other because then the force is pushing that one over there they attract each other.

Int: Okay. How would you describe that force, ... the strength of that force as the magnets get farther apart?

S5: The force, well as they repel each other it would get weaker as they, it's the distance.

Int: Okay.

S5: As the distance becomes farther the force gets weaker.

Int: Okay. And as it gets closer?

S5: As they attract each other the force becomes stronger.

Int: Okay. Mmm, and do you have any idea how this force is created or how they can do this without touching? You know, while they're repelling they're not touching, but they can still push on each other. Any idea how they can do that?

S5: No idea.

Int: Okay. Now you had said that the magnet should affect these that have metal on them, right?

S5: Mmm hmm.

Int: Okay. (inaudible) is a little, this is a little bit coated and this is steel. So it should affect all of them?

S5: The steel. I don't think it would affect the other.

Int: Okay, why don't you think it would affect the other one?

S5: The composition of the metal.

Int: Okay, and you think it would affect steel because?

S5: It has a different composition.

Int: Well, let's find out if that's true. Okay, so here's the steel marble. Go ahead and see if the magnet will affect it. Now before you do, let me ask, what do you think the effect will be?

S5: Well, depending upon which way the magnet is, the plus or minus charge, the plus would probably repel it, they are two, both charges, both the same charges repel. But it has an opposite charge of what the magnet was so they would attract.

Int: Okay.

S5: So the ball would be pulled towards if it was attracted or pushed away if it was ...

Int: So it should attract on one end and repel on the other.

S5: It should.

Int: Okay. So let's see if that happens. Okay, it's attracted there. And did you

switch ends?

S5: Mmm hmm.

Int: Okay. Alright it's attracted there.

S5: Right. It's still attracted.

Int: Okay. Now, you were able to get those to push against each other. Those are two magnets, but both ends of the magnet will attract this.

S5: Mmm.

Int: Okay, does that make any sense to you?

S5: No, it doesn't.

Int: Okay. You expect it to repel.

S5: Yeah.

Int: Can you think of any time where you have used a magnet on some steel and had it repel?

S5: Not to my knowledge. Not that I can remember anyway.

Int: Is it always attracted?

S5: What I remember yeah.

Int: When do you normally use magnets?

S5: I don't use them a whole lot, but mmm, I use like refrigerator magnets.

Int: And you usually want those to stick to a refrigerator, right?

S5: Yeah. Other than that I don't believe magnets that I bought were ah,

Int: Okay. Well it attracted the steel in both cases. Ah, do you think it should attract the other one then, or nothing? Before you were saying you think it maybe wouldn't do anything.

S5: I don't think it would do anything.

Int: Okay. Then,

S5: But then, I've never tried magnets on aluminum before.

Int: Okay, well, see if there's anything.

S5: (inaudible)

Int: Okay, and that is what you predicted.

S5: Mmm hmm.

Int: Okay. Now these nonmetallic objects, you didn't think it would affect those either. Why do you think it wouldn't?

S5: Because they're not metals.

Int: Okay. And from your experience you've not seen magnets interact with metals, or with nonmetals, sorry.

S5: No, I haven't.

Int: Okay. Well, would you describe this as a metal?

S5: It doesn't feel like metal.

Int: Okay. It's a little flexible, feels almost like hard rubber maybe.

S5: Mmm hmm.

Int: Okay, do you think a magnet would affect that?

S5: I wouldn't think so.

Int: Okay, go ahead and check.

S5: It doesn't seem to be. (inaudible)

Int: Okay, well here's another one, it's just a slightly different shape. Do you think those should affect each other?

S5: Well, if they weren't made of metal then no, they wouldn't affect each other. This little (inaudible) a refrigerator magnet.

Int: Yes.

S5: Ah, (inaudible) a true metal and ah, (inaudible) metal.

Int: Well those two are magnets. They're not as strong as the ones I gave you earlier.

S5: Right.

Int: So you notice there might be a small attraction here, for example you can do that, but they are fairly weak and so they don't react very well. But these are metal and so they don't really match what you're talking about with those.

S5: Right, right.

Int: Do you think it's the same thing, or you think it's actually something different. I mean is it, is this magnet the same kind of, the same kind of phenomenon as that magnet? Or would you say they're different?

S5: Well they seem to be.

Int: Okay.

S5: The other kind made of different materials.

Int: Okay, so a magnet could be made of metal but it could be made of other things. Is that ...

S5: That, well, the only magnets I've ever known were, have been made of metal.

Int: Okay. Ah, just to verify, see you could, can feel any effect between this and one of the others in your hand. It might be weak but ah, see if there seems to be any affect.

S5: Yeah, there's a small, there, there is.

Int: Okay, does it seem to be an attraction or is there a repulsion?

S5: This is an attraction.

Int: Okay. Is there any where other that, that they will repel?

S5: Oh, that one.

Int: (laughs) Yap.

S5: No, it seems to attract it. No matter what we put the magnet.

Int: Okay. Would you agree that these are magnets? Are maybe they're something else.

S5: Well I think that they're magnets.

Int: Can you think of a way we can test them? Like what, what is something

that magnets do that you expect maybe only magnets to do?

S5: Be attracted to other metal.

Int: Okay, and you did see that those magnets were attracted (inaudible) to the steel, right so. So if that's attracted that at least might indicate something.

S5: Yeah, there's (inaudible) attraction there.

Int: Okay. And if it does not attract the aluminum that would be consist with the magnet, right?

S5: Right. It doesn't seem to be.

Int: Okay. So it seems that this is in every way the same kind of magnet except,

S5: Right.

Int: you couldn't really get it to repel.

S5: Right.

Int: It's not really easy to see but there are positions in here where these, they would what?

S5: Right, they repel each other.

Int: Yeah, that's just, yeah, it's it's hard to get.

S5: Mmm hmm.

Int: Sometimes it'll attract and sometimes it'll repel. Okay, so those are actually magnets in the same way that these are.

S5: Mmm hmm.

Int: Is there anything else that you can think of that might influence any of these things? Have you ever seen objects that attract or repel that are not magnets?

S5: A vacuum.

Int: (inaudible) okay that's moving air again.

S5: Moving air. No. That attract each other other than magnets.

Int: Yeah, attract or repel.

S5: Not that I've seen.

Int: Okay, mmm, how bout when you, like on a cold winter day and you comb your hair, your hair stands up.

S5: Static electricity.

Int: Okay. You think static can attract and repel things? Without touching them.

S5: It seems to be, it seems to.

Int: Okay.

S5: Like with, let's see, when you rub your hair on your comb your hair is attracted to the comb.

Int: Okay.

S5: (inaudible)

Int: Okay. And does it have to be touching for that to happen?

S5: Hun un.

Int: Okay, so that's something that could, static electricity could affect something without touching it, right.

S5: Mmm hmm.

Int: Well, can you think of, would you think static electricity would affect any of these?

S5: I'm not sure.

Int: Okay, can you think of any convenient way that we could maybe generate some static electricity.

S5: Mmm, rubbing a comb through your hair.

Int: Okay.

S5: But that has to be, needs to be kind of on a dry day though.

Int: And today is far from dry.

S5: Yes.

Int: Okay, well what if we

S5: Or rubbing your metal

Int: replace the comb with a plastic ruler and replaced the hair with wool?

S5: Okay.

Int: Does that seem like it should work.

S5: I would think so.

Int: Okay, so if we were to rub that a little bit there could be some static in there. Can you think of a way we can test it?

S5: Mmm, try it on one of the balls, see if anything is attracted or repelled.

Int: Okay. Which one or ones do you think might work?

S5: Oh, ah, ping pong ball might work.

Int: Okay.

S5: Otherwise I'd say the (inaudible) balloons though.

Int: What have you seen with balloons?

S5: When people roll them on their heads and then they like stick to walls

Int: Okay, so

S5: Stuff like that.

Int: So, maybe this'll do the same kind of thing? Okay, let me just rub this really good. Okay, tell me if you see any effect.

S5: It seems to move towards it. It's attracted to it.

Int: It's attracted to it. Does it seem, does that seem to be the only reac, ah interaction that you see. It's kind of, it's hard to tell

S5: Kind of repels it there it looks like. There's a small amount.

Int: Okay, so

S5: It does, it looked like it moved back. There it moved, oh.

Int: Yeah, it's hard to tell if you see the (inaudible) swinging (inaudible). So, but there was that initial attraction. That we definitely saw. Ah, okay, how do you think this attracted the ball?

S5: The electrical charges

Int: Okay.

S5: are not from the wool.

Int: And what do you know about these charges?

S5: Not much (laughs).

Int: Can you describe them or tell me anything about the way they operate?

S5: Mmm, no really I can't.

Int: Okay.

S5: Maybe, well, maybe they just flow around the ruler.

Int: Okay, ah, how do you think they compare to, yeah, we saw attraction here, how do you suppose that compares to the magnets?

S5: Same principal. I don't think that attraction between that is as strong as it is between magnets.

Int: Okay. So do you think that a magnet would attract the ping pong ball the same way this did?

S5: I don't think so.

Int: Okay, so it's the same principle but you think it's a different effect.

S5: Right.

Int: Okay, want to test that?

S5: Sure.

Int: Okay.

S5: That doesn't seem to be anything.

Int: Okay, do you think the magnet would interact with this ruler?

S5: Mmm, plastic ruler?

Int: Mmm hmm, yes.

S5: I wouldn't think so.

Int: Okay, well let's check it out.

S5: There doesn't seem to be anything.

Int: Okay, so here were two things that attracted each other, same principle as a magnet, but it doesn't interact with the magnet. So would you say it's the same or a different phenomenon?

S5: In, in a sense it's different because you have different materials and a different type of magnetism.

Int: Okay.

S5: But the same in the sense that there isn't attraction between the two, there isn't force flowing between the two that is causing them to attract. same way with that one.

Int: Okay. Do you think that this ruler would then affect some of these other things.

S5: I don't think it would affect the metal.

Int: Okay. Well let's try that first.

S5: I don't know if it will affect that styrofoam or not.

Int: Okay, well let's just start with this one since it's on the end. And the magnet did not affect this, correct?

S5: Right.

Int: Okay. Let me charge this up again. Let me know if you see an effect.

S5: There it was attracted. And there it's repelled. (inaudible) Yeah, it's repelled.

Int: Okay, so it was attracted

S5: Mmm hmm.

Int: And now it's repelled. Why do you suppose it was attracted initially but now would be repelled?

S5: I don't know.

Int: Okay, well you saw an initial attraction with the ping pong ball.

S5: Right.

Int: And, if there was repelling after that it was really weak, it didn't seem to do anything.

S5: Right. Right.

Int: But in this case it's pretty obvious, right.

S5: Mmm hmm.

Int: And yet

S5: It's attracted, then repelled.

Int: Right.

S5: It was like the current changed directions.

Int: Okay, and what do you mean by current?

S5: The electric, well the charge, the electrical current charge must have shifted over time which at first it was attracted to the aluminum and then it repelled it.

Int: Okay, what do you suppose might have caused that current to shift?

S5: I have no idea.

Int: Okay. Mmm, well we now have this aluminum coated pith ball, do you think it will have a reaction to the ruler?

S5: That aluminum, I would think so.

Int: Okay. Do you think it will be basically the same, or do you think it will be different?

S5: I would think it would be the same.

Int: Okay. And do you think it would be the same for the same reasons or for different reasons?

S5: I'd say same reasons. The material on the outside's the same as that material.

Int: Okay.

S5: So I don't know, aluminum is aluminum.

Int: Okay, well, again let me know if you see an effect.

S5: There it's attracted. Mmm, it's repelled there.

Int: Okay. So it's the same effect right?

S5: Un hun.

Int: Okay, and you said for the same reasons. You still believe it's for the same reasons?

S5: Mmm hmm.

Int: Okay. And how do you think this steel marble will react?

S5: That I don't think it will have an effect on.

Int: Why not?

S5: Just because the magnet didn't have any effect on the ruler. And the magnet did affect the ball. I don't think there's gonna be a strong enough. It doesn't seem to be affecting it.

Int: Okay. And so, ah, it sounded like you were saying that whatever this will affect the magnet won't, and whatever the magnet affects this won't.

S5: Mmm hmm.

Int: Do you think that's in general true?

S5: Well I would say so.

Int: Okay, so

S5: For what seems to be going on, yeah.

Int: Okay, so, can you think of ah, can you think of anything that maybe they'll both affect.

S5: Mmm, no.

Int: Okay. Can you think of things that maybe neither will affect.

S5: Mmm, I'd say the styrofoam. Well maybe it would. I this, this, I would

say, the one made of the, did you say plant material?

Int: Yeah, it's a pith ball, but without the aluminum coating. So you think that maybe neither one will affect this.

S5: Yeah.

Int: Okay, well

S5: I think.

Int: Well, go ahead and check this with a magnet if you would.

S5: It doesn't seem to be affecting it at all. Nope.

Int: Okay. And you didn't think this would affect it.

S5: I wouldn't think so. Look, it does. It repels it.

Int: Okay. Now you notice it's stuck to the ruler for a little bit before it was repelled. Any idea why it might stick for a little while and then repel?

S5: Mmm mmm. No.

Int: Okay. So here again was something that one affected, the ruler did, but the magnet did not affect.

S5: Right.

Int: Okay. Mmm, let's see, I guess the things we really haven't tried yet are the graphite coated styrofoam and the normal styrofoam.

S5: Mmm.

Int: How do you think they will react? To both the magnet and the, the ruler.

S5: Mmm, the styrofoam the magnet will not affect that.

Int: Either one of them?

S5: The graphite

Int: Okay.

S5: It might affect the graphite.

Int: Okay, well let's check that out.

S5: I never really, I don't think I've ever tried graphite near a magnet.
(inaudible)

Int: Okay, let's see if the magnet does anything.

S5: No, it doesn't seem to have an effect on it.

Int: Okay. So do you think this will?

S5: Mmm. With what we're studyin, it should in the sense that if what we said, what the magnet doesn't affect, the ruler should.

Int: Okay, so, so if that's correct

S5: If that's correct then that should be attracted to it.

Int: And do you think it will only be attracted or do you think it will attract

S5: It will attract and repel.

Int: Okay. Definitely attracted, and

S5: And it looked like it repelled there.

Int: Okay, there

S5: (inaudible) small (inaudible)

Int: It's just weak. Okay, so so far it seems to be doing the same thing. And what do you think about the plain styrofoam?

S5: The magnet should not have an effect on it.

Int: Okay. Ah, that makes sense because if magnets affected styrofoam it should have affected this other one.

S5: Right. Right.

Int: Well, go ahead and check that if you would.

S5: Nope.

Int: Okay. Now what do you think, will this affect it?

S5: If what we're following is true, then yes it should attract it then repel it. There doesn't seem to be an attraction (inaudible). It looks like there's maybe a small attraction there.

Int: There seems to be kind of a weak attraction maybe.

S5: Yeah, and then it pushes away.

Int: Can you tell if it's repelling or if it's just bouncing off?

S5: (inaudible)

Int: So if there's an effect it's pretty weak.

S5: Right.

Int: Okay.

S5: A small effect on it (inaudible).

Int: Okay, so ah, so far then what we have seen was that the things that the magnets affect, ah this charged ruler seems not to affect. The static electricity. And the things that static electricity effects, the magnet seems not to.

S5: Right.

Int: Okay. Ah, and some effects were obviously stronger than others. Okay, can you think of any other way, you know things we might be able to use to influence this.

S5: No.

Int: Okay, well let me try something here. Take, oh let's take this again. The hollow ruler is here. Now, what I have here, this is also aluminum, this nice aluminum disk. Do you think this should have any effect on that aluminum sphere?

S5: I wouldn't think so.

Int: Okay, and why not?

S5: Because there's no charge between them.

Int: Okay. See anything?

S5: No. Well there, there was ah pull, looks like they were pulling each other, where the balls were (inaudible).

Int: Okay. There appears to be repelling. But you say there was only repelling or did something else happen first? They, they did touch

S5: Yeah, they did touch. Maybe there was a small attraction and then

Int: Okay

S5: they repelled.

Int: Can you think of any reasons that might have happened?

S5: No.

Int: Okay, do you think it's possible that maybe I charged this up when you weren't looking? That this has static electricity.

S5: That could be.

Int: Or could this be a magnet?

S5: Could be.

Int: Okay. Did a magnet affect that before?

S5: No, it's have to, well cause, no the static electricity did.

Int: Okay, so

S5: An electrical current of some kind?

Int: Okay, nothing attached to it right?

S5: Right.

Int: It's definitely repelling.

S5: Right.

Int: Okay, well, do you think, can you think of anything I can do to this to make it attract that?

S5: Mmm, just the opposite charge.

Int: Opposite charge.

S5: (laughs) Well actually no.

Int: Well, what if I were to put this back here?

S5: (inaudible) some attraction.

Int: Okay now, do you expect it will stay attracting? Is there anything I

can do now, like what if I let them touch? What should happen?

S5: They would probably repel.

Int: And why do you think they would repel?

S5: It would be the opposite of what it did the first time. I would think.

Int: Okay, so what do you, what do you suppose will happen when they touch? You think they'll stick for a little while, or you think they'll repel immediately?

S5: I'd say repel immediately.

Int: Okay, and what

S5: As I recall that's what it did the last time.

Int: Okay. What do you suppose happens when they touch that causes them to repel?

S5: The inner changes. I don't know. Unless there's just like this, something to do with the charges.

Int: Okay, well let's see what happens.

S5: They just seem to be repelling that instant.

Int: Okay.

S5: Like the impact adjusted, adjusts, adjusts the charge or flow.

Int: Okay, now there is an effect, it's rather weak you know, but I have to admit that it's difficult to see. But they're repelling very weakly there. And you mention that ah, maybe the charge is doing something.

S5: Mmm hmm.

Int: Do you have any idea what that might be, if the charge is doing anything?

S5: You mean what's causing it, or

Int: Mmm, what, how is the charge causing ah repelling or attracting?

S5: Well the charge must have been opposite between the two, which is causing them to attract. And that instant of impact must have altered it, that caused them to go both the same

Int: Okay, so you're saying

S5: so they repelled.

Int: So you had opposite charges at first. Then they touched, something happens, and they become the same charge.

S5: Mmm hmm.

Int: Do you have any idea what that something might be that happens?

S5: No, I don't.

Int: Okay, ah. Okay, ah, have you ever heard of a magnetic field or an electric field?

S5: Yeah, I've heard of them.

Int: Okay, do they mean anything to you? Any idea what they might be?

S5: No, just the field around the object.

Int: Okay.

S5: But as far as, but, like the flow of magnetic field around the object. That's all I can think of.

Int: Okay, do you have any idea what the shape might be? What it looks like, if you could see it?

S5: Mmm, probably be the same shape as the object.

Int: Okay.

S5: Like if that's a sphere it would be a sphere around it.

Int: Okay. Would you say that a magnet has a magnetic field around it?

S5: Yeah.

Int: Okay, so the magnet's in your hand. What do you suppose the magnet field around one of those looks like?

S5: Probably just almost circular.

Int: Okay, could you maybe draw a quick sketch of what that might be?

S5: Poor sketches (inaudible).

Int: No, that's, no, they're actually quite good.

S5: Just something around the object.

Int: Okay.

S5: I wouldn't say they're like square in shape and have corners, they're more probably rounded.

Int: Okay, ah why do you think they'd be rounded rather than having sharp corners.

S5: Mmm, I don't know, it just, it makes more sense to have them rounded.

Int: Okay. Okay, well thank you very much. That finishes the questions that I wanted to ask.

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APPENDIX A

Table of Research Data Collected

TABLE A1: Chronological account of data collected as part of this research. Only data that contributed directly to the analyses is reported here.

Instrument	Pre- or post-instruction	When	Number of subjects
written test	pre	summer '96	66
oral interview	pre	summer '96	9
written test	pre	summer '96	39
oral interview	during*	summer '96	20*
oral interview	post	summer and fall '96	16
written test	pre	fall '96	80
written test	post	fall '96	78
written test	pre	spring '97	177
written test	post	spring '97	176
written test	post	spring '97	95

* 16 of these 20 were post-electric fields, but pre-magnetic fields.

APPENDIX C

A qualitative investigation of college students' conceptions of electric fields

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This paper describes a qualitative investigation of introductory college physics students' understandings of the electric field prior to and following instruction. Four aspects of electric fields are examined: existence/definition (or mental construct), source, vector representation, and superposition. Results are discussed as a means for improving the development of the physics curriculum.

I. INTRODUCTION

The Research in Physics Education Group at the University of Nebraska-Lincoln has been interested in using research in student understanding to develop effective instructional materials. The first step in creating these materials is to investigate student understanding of the relevant concepts. This paper discusses such an investigation into college physics students' understandings of the electric field concept. Investigation of students' preconceptions helps design instructional materials that may be effective in overcoming students' difficulties. Investigation of students' misconceptions after instruction provides insight for making additional changes to the instruction.

It has been suggested that students who can successfully solve quantitative physics problems may not qualitatively grasp the underlying concepts.¹ This investigation examines how college physics students understand electric fields before and after instruction, and the student difficulties that need to be addressed by formal physics instruction in order to improve qualitative comprehension.

II. DESCRIPTION OF THE RESEARCH

A. Reasons for the study

After formal physics instruction, many students who can successfully perform mathematical algorithms to arrive at numerically correct answers seem to lack a conceptual understanding.² To overcome this failure to understand, instruction must address the specific difficulties students have with the relevant concepts.³ An appropriate qualitative research study can explore these student difficulties.

The concept of a field is fundamental to the study of physics. It is through the field concept that action-at-a-distance is described.⁴ Fields are used in the study of gravity and electricity and magnetism, topics studied in virtually all

introductory college physics courses. While there have been several studies on conceptual understanding of simple circuits,⁵ other topics in electricity and magnetism have not received similar attention.⁶ By investigating how college physics students think about electric fields, a foundation for future studies and a guide to physics curriculum development can be prepared.

B. The field concept

The concept of a field has been very powerful for modern physicists. The field construct has led to the development of such useful entities as photons and gluons. Even with his work on gravity, however, Isaac Newton was not comfortable with the idea of action-at-a-distance.⁷ Despite the observation of electric and magnetic phenomena by the ancient Greeks, the concept of a *field* to explain action-at-a-distance was not introduced until the early 1800s by Michael Faraday. The pinnacle of classical field theory was reached upon publication of Maxwell's equations for electromagnetic fields in 1873. Although Maxwell's equations summarize and describe all classical electromagnetic phenomena, students in introductory physics courses may not use such advanced methods. Their experiences with and perceptions of electric fields may not have provided them with the understanding or language to offer an adequate description of an electric field. We attempted to determine their understandings of various aspects of electric fields by using oral interviews and written examinations.

C. Methods of investigation

For instruction to address specific student difficulties, it is necessary to understand student conceptions. Such knowledge was obtained in this study using written tests and individual oral interviews, similar to the interviews developed by Piaget.⁸ Careful analysis of the interviews and written answers provided some understanding of student difficulties. This study focused on a fundamental concept in electricity and magnetism, the concept of the electric field. Table I shows an account of the Test Instruments (TI) used in data collection.

TABLE I. Test Instruments (TI) used in data collection.

TI #	Instrument	Pre- or post-instruction	Date	Number of subjects
1	oral interview	pre	summer '96	8
2	written test	pre	fall '96	39
3	written test	post	fall '96	78
4	written test	pre	spring '97	177
5	written test	post	spring '97	176
6	written test	post	spring '97	93
7	oral interview	post	summer and fall '96	32

Many of the subjects were both pre- and post-tested; however, the pretests and posttests had different forms, and it is not believed that the pretests had a

measurable effect on the posttest responses. For example, Test Instruments 3 and 5 asked subjects to sketch electric fields for various charge distributions. On pretests (Test Instruments 2 and 4), the same subjects were not presented with charges, but were asked only to sketch their idea of an electric field.

1. *The oral interviews*

Individual oral interviews were conducted with common laboratory objects for electrostatics experiments, such as pith balls, plastic rulers, and wool, which could be used by the subject or the interviewer. Subjects were encouraged to use the provided objects to explore electrostatic phenomena. They were asked to predict what would happen and explain their reasoning. Paper and pen were provided for sketching. The interviews were designed to encourage the subjects to discuss electrostatic interactions. The subjects were free to discuss any aspect of their observations of electrostatic phenomena. Guidance was provided from the interviewer through probing questions. Words such as “fields” were not used unless used by the subject. The format for the interview was constant throughout the investigation. The interviews were videotaped and professionally transcribed for later analysis. The transcripts were compared to the original videotapes for accuracy by the author. Every interview subject in this study was asked to explain an example of electrostatic attraction or repulsion. If the subject did not suggest using electric charges to cause action-at-a-distance, the interviewer would demonstrate the effect of a charged ruler on a pith ball and ask the subject to explain the interaction. A typical interview began as follows (the letter “I” represents the interviewer and the letter “S” the subject):

- I: The system in question consists of a string suspended from the ceiling, from which we can hang any of several objects, including a pith ball, a Styrofoam sphere, a steel marble, and a hollow aluminum sphere. The first question I would like to ask you is this: can you think of a way we can affect this system without touching it?
- S: Yes, you can induce a charge on [the pith ball] and with that charge you could move it in just about any direction depending on how much charge you used.
- I: How would you go about inducing a charge on this?
- S: What we did in lab was use the plastic ruler which was, I believe, a negative charge and held it underneath the pith ball to make the positive charge on the lower half of the ball and the negative charge on the top half of the ball. We touched the top of the ball to remove the negative charge and left positive charge on the ball.
- I: You used something just like this [plastic ruler]?
- S: Right.
- I: If you were just to charge this up and bring it close what would happen first?
- S: ... I would say that it would attract.
- I: Why do you think it would attract? Draw pictures if you want.
- S: Because of what I said ... that [ruler] is charged where this [pith ball] isn't.

- I: Ok let's see what it does.
 S: They attract.
 I: Now that you know it attracts, can you explain why it attracts?
 S: ... back to the old saying that opposites attract

After this subject also observed electrostatic repulsion, the interviewer asked why they now repelled.

- S: I don't know why they repel each other, other than 'like charges' ... I guess I don't know how to put it in words.

It was important that the interviewer used the same vocabulary as the subject. For example, once the subject used the word "field," the interviewer would ask for clarification, and thereafter use the word in the same manner as the subject. When possible, the subjects were asked to provide sketches.

2. *The written tests*

The written tests used in this study consisted of open-ended questions. Students were asked to answer the questions and to provide an explanation of their reasoning, including sketches when possible. This was an evolving process in which knowledge obtained from the early written tests and the oral interviews guided the development of the later written tests. The written answers were evaluated by two independent professionals, the author and another physicist.

With the exception of some sketches, explanations were required for all answers, written and oral. The oral interviews gave a more thorough understanding of students' difficulties, while the written answers provided an indication of the prevalence of the difficulties.

D. Student population and instruction

All student subjects used in this study were enrolled in the algebra-based introductory physics course at a typical midwestern university. This was a two-semester, five credit-hour course, with three fifty-minute lectures, a single fifty-minute recitation, and one two-hour-and-fifty-minute laboratory per week. The recitations and laboratories were led by graduate teaching assistants who were not part of this research study. The laboratories included multimedia lessons designed in parallel with this study as part of an ongoing process of curriculum development, described elsewhere.⁹

Approximately 50% of the students indicated taking a high school physics course. Approximately 44% of the students used in this study were female, and 56% male. The written test instruments were administered to the entire class, therefore the entire range of grades and abilities was represented. The oral interview subjects represented approximately 90% of their class, and none of the interview subjects received a grade lower than C.

III. SPECIFIC STUDENT DIFFICULTIES BEFORE INSTRUCTION

From analyses of the test instruments, the student difficulties with electric fields were grouped into four categories which are explained below: existence/definition, source, vector representation, and superposition. These categories are not mutually exclusive – difficulty with the vector representation may cause difficulty in demonstrating an understanding of superposition, for example – and may not be exhaustive. In addition, there may be uncertainty in categorizing an individual student’s difficulties because of the imprecise use of language on the part of the subject, the researcher, or both.

A. Difficulties with existence/definition of the electric field

Of the pre-instruction oral interviews considered in this study, one-fourth (2 of 8) were judged to have an adequate mental construct for an electric field. For this study, an “adequate” mental construct allowed for action-at-a-distance requiring no physical contact, having a direction, and depending on distance, without being described as outlined below. The 6 oral interview subjects who did not meet the criteria for an adequate mental construct used one or more of the five misconceptions of an electric field discussed below.

The written pretests for this category were analyzed independently by two investigators as described above. The analyses were compared, and differences discussed between the investigators. Cases of simple misinterpretation of students’ answers were resolved. The prevalence of the various conceptions are summarized in Table II.

1. Description of an electric field as an area

When asked to explain their idea of an electric field, some students indicated that a field is an area where something exists or occurs. For example, “a corn field is an area with corn.” Below is a typical statement from an oral interview that expresses this.

I: ...What could you tell me about a field?

S: ...I thought an electric field was just the area around this charge or something ... just area around it [in which] the force could be exerted.

The same description was also use on written pretests. (The letter “Q” designates the question and the letter “S” the response.)

Q: What does the term “electric field” mean to you? Please be as specific as you can.

S: The area around a charged object.

Approximately 20% of the 216 students who were asked this question on written pretests responded in a similar manner. When analyzing these responses, we were careful to make certain that the response emphasized the *area* and not what was in that area. What was important for this study was what the students *said*, since we cannot probe any further than the words they used in their written answers.

2. Description of electric fields as charges

Many students think of an electric field as a collection of charges. This often was equated with a group of ions or electrons. Below is a typical statement of such belief from the oral interviews.

- I: How do you suppose this [ruler] is affecting that [aluminum sphere] without even touching it?
 S: There's a flow of electrons around the ruler and a flow of electrons around this aluminum ball, so when you get them close enough to one another then they exchange electrons and that probably causes them to stick to one another but if you get really far away then their clouds are not close enough to exchange their electrons.

Approximately 17% of the students in this study described an electric field as a collection of charges, ions or electrons, as in this answer from the written pretests:

- Q: What does the term "electric field" mean to you? Please be as specific as you can.
 S: Electric charge surrounding a (sic) object.

2.5. Description of electric fields as areas of charge

About 30% of the written student responses were not clearly area or charge, but seemed to emphasize both the area and the charge. For example,

- Q: What does the term "electric field" mean to you? Please be as specific as you can.
 S: An electric field is an area of charge surrounding an object.

This description did not appear in the oral interviews. Answers such as "An electric field is the area around the nucleus of an atom that contains electrons," or "The cloud of electrons around a nucleus," were difficult to categorize as area, charge, or both, contributing to uncertainty in some categories.

3. Description of an electric field as a force

This category is used for students who can only talk about forces, not fields. This was often the case for students who only understand "likes repel and opposites attract." This category is also used for students who have heard of "force fields" in science fiction movies. This description was often combined with an area, as below:

- S: Force fields.
 I: Where have you heard of those?
 S: Scientific TV shows, SciFi movies.
 I: How would you describe the force field?
 S: The area around the object in which the force is present.

Note that if force is discussed with charge, and the discussion is close to the formal definition of the electric field ($E = \frac{F}{q}$), the description is accepted in this study as correct.

Only about 2% of the written responses on the pretests were limited to describing fields by “likes repel and opposites attract.” When students offered more information, we classified their answer elsewhere.

4. Description of electric fields as energy

Some students provided very clear descriptions of their conception of an electric field:

S: A field is energy. You can't create energy so you cannot create a field.

This student also indicated that all objects must come with their own fields, and all we can do it make them larger or smaller, since we cannot create them.

Only about 2% of the students described electric fields as energy on the written pretests, perhaps indicating that this is also not a significant preconception.

TABLE II. Prevalence of misconceptions about the existence or definition of an electric field prior to instruction

TI #	Number of subjects	Correct	Misconceptions					
			Area	Area of charge	Charge	Force	Energy	Blank/no info.
2	39 100%	0 0%	8 21%	9 23%	10 26%	3 8%	0 0%	9 23%
4	177 100%	12 7%	36 20%	56 31%	27 15%	1 1%	4 2%	42 24%
total	216 100%	12 6%	44 20%	64 30%	37 17%	4 2%	4 2%	51 24%

B. Difficulties with source of the electric field

If students affirm the existence of a field, then it is logical to ask them about its source. It was not expected at this introductory level that students would suggest that changing magnetic fields give rise to electric fields; our expectations were correct, and no student in this study made such a suggestion. Many students in this study did state that electric charges create electric fields.

Confusion between electric and magnetic phenomena was evident from some interviews. The terms "positive" and "negative" were used to discuss electric charges and magnetic poles. This made it difficult to ascertain whether some subjects understood that electric charges produce electric fields.

With few students (6%) demonstrating a mental model for an electric field prior to instruction, it was difficult to measure student understanding of the source. It was clear from the oral interviews as well as written tests that students knew "likes repel," but it was not clear if they knew *what* repels. Confusion of electric with magnetic phenomena was evident, but not quantifiable given the imprecise use of language.

C. Difficulty with representation of the electric field

The improper use of the vector representation for electric fields has been suggested as a possible source of confusion,¹⁰ and we included it in our investigation. Of the 8 pre-instruction interview subjects, seven could not attempt a sketch of an electric field. The single interview subject that did sketch a field did not use vectors.

On the 216 written pretests, only five students drew sketches that resemble a vector representation of an electric field. All five students had taken a high school physics course. Of these five, one drew a circle around the vector arrows and said the field is “the area where an electric charge can be measured,” a second drew field vectors but called them “the flow of electrons,” and the third drew lines but no vectors. The fourth sketch had only three vectors, but they were well-drawn. The fifth sketch contained an accurate representation, and it included the following caption: “The electric field of an object is an area around a charged object where electric force is ‘felt.’ The force decreases w/ increasing distance.” Despite the indication that an electric field is an area, this student understood that the field is the vehicle for action-at-a-distance, and that the force decreases with distance. This fifth student demonstrated that the language needed to describe the concept may be as problematic as the concept itself. If a student cannot accurately describe a concept, it may be impossible to accurately assess that student’s understanding.

D. Difficulty with superposition of the electric field

Superposition of electric fields was not discussed in the oral interviews. These oral interviews were part of a larger investigation,¹¹ in which superposition of magnetic fields was found to be a problem for students. It has been suggested in the literature¹² that students do not understand superposition of electric fields. Superposition is used throughout physics; we frequently linearize systems so we can simply add. Given the importance of the concept, we created this category for investigation.

Attempts to measure students’ understandings of superposition of electric fields in written pretests were inconclusive. To demonstrate an understanding of superposition in this study, it was necessary for students to know that electric charges create electric fields and be able to sketch the fields thus produced. As discussed above, only 6% of the students used in this study demonstrated an understanding of the field concept. With such small numbers, it was not possible to reach a conclusion about the pre-instruction level of understanding of superposition.

IV. INSTRUCTION

All student subjects used in this study were enrolled in the algebra-based introductory physics course at a typical midwestern university. This was a two-semester, five credit-hour course, with three fifty-minute lectures, a single fifty-minute recitation, and one two-hour-and-fifty-minute laboratory per week. The written test instruments were administered during the second semester of this course, the semester in which electricity and magnetism were introduced. The textbook was a popular text¹³ that covers topics in a traditional manner. Mechanics, thermodynamics, and waves are covered in the first fourteen chapters. The second semester of this course began with electric forces and electric fields, followed by energy and capacitance, electric current and resistance, direct current circuits, magnetism, inductance, alternating current and electromagnetic waves, then optics and modern physics.

Hour exams were offered approximately once per month and were at least 80% quantitative. Some of the instructors used multiple choice for as much as 40% of each exam and rarely used short-answer or essay questions.

The recitations and laboratories were led by graduate teaching assistants who were not part of this research study. Recitations were used primarily for practice at solving quantitative homework problems. The laboratories included multimedia lessons, including the following: Batteries and bulbs; Analyzing circuits with graphs; Electric charges, fields, and forces; Electric fields and potentials; Magnetic fields and electric current; Magnetic fields due to coils; Electric and magnetic fields; and Ratio of electric charge-to-mass for electrons. These multimedia lessons¹⁴ were designed based on Karplus' Learning Cycle.¹⁵ Specific activities were developed to address student difficulties found in the early parts of this study, so the effects of the instruction may not be typical.

V. PREVALENCE OF SPECIFIC STUDENT CONCEPTIONS AFTER INSTRUCTION

This study investigates the impact of instruction on students' understandings of electric fields. Individual oral interviews and written pretests gave a measure of students' preconceptions of the electric field. Using written posttests, we investigated the persistence of these preconceptions after instruction. The posttest questions used in this study were not identical to the pretests, having been modified by the pretest results. The posttests also used the appropriate vocabulary, which was not always possible on the pretests.

A. Difficulty with existence/definition of the electric field

Analysis of the written posttests was performed in the same manner as with the written pretests. Results from Test Instrument 6 are shown in Table III. Ten students provided only a specific example of an electric field, usually a sketch of the electric field between charged parallel plates.

Accurate descriptions of electric fields were much improved, with 62% of these students providing essentially correct definitions. No students described electric fields as areas of charge on the posttest.

TABLE III. Prevalence of misconceptions about the existence or definition of an electric field after to instruction.

TI #	Number of subjects	Correct	Misconceptions					
			Area	Area of charge	Charge	Force	Energy	Blank/no info.
6	93 100%	58 62%	7 8%	0 0%	6 6%	0 0%	1 1%	11 12%

B. Difficulties with source of the electric field

When asked after instruction “What is the fundamental source for electric fields?”, 65% (60 of 93) of the students said “charges.” Five of these answers were “moving charges,” which is correct, but may indicate a confusion with magnetic fields.

The next most common answer involved potential difference, and was used by 14% (13 of 93 students) of the students. This misconception was not present in the pre-instruction difficulties and was added by the instruction process. Students may believe that terms on the left-hand side of a formula are caused by the terms on the right-hand side; this is called *cause in the formula*.¹⁶ This may have been responsible for some students claiming that electric potential difference is the source for electric fields and may have come from the equation $E_x = -\frac{V}{x}$. Students expressing this belief often said that a single, isolated electric charge could not produce an electric field.

C. Difficulty with representation of the electric field

The post-instruction written tests showed that a majority of students could sketch the vector representation for the electric fields for simple arrangements of charged objects. These results are summarized in Table IV. More than 60% of the students drew proper vector representations, while some students drew vectors pointing in the wrong direction, sketched equipotentials rather than field lines or field vectors, or sketched a cloud of charges near the charged objects.

TABLE IV. Sketches of the electric fields for various configurations of charges or charged objects.

TI #	Number of subjects	correct	Alternate representations			No information
			opposite vectors	equipotentials	cloud of charges	
3	78	49 63%	3 4%	6 8%	0 0%	20 26%
5	176	114 65%	5 3%	28 16%	10 6%	19 11%
6	93	77 83%	4 4%	3 3%	1 1%	8 9%

Test Instruments 3 and 5 were similar; both posttests asked questions such as the sample in Fig. 1, taken from Test Instrument 3:

FIG. 1. A sample question of the type used in Test Instruments 3 and 5.

a) Sketch the electric field in the region surrounding an isolated positive charge.	⊕
b) Sketch the electric field in the region surrounding an isolated negative charge.	○
c) Sketch the electric field in the region surrounding these two charges:	<div style="display: flex; justify-content: space-around; align-items: center;"> <div style="text-align: center;">+</div> <div style="text-align: center;">-</div> </div> <div style="display: flex; justify-content: space-around; align-items: center;"> <div style="text-align: center;">○</div> <div style="text-align: center;">○</div> </div>

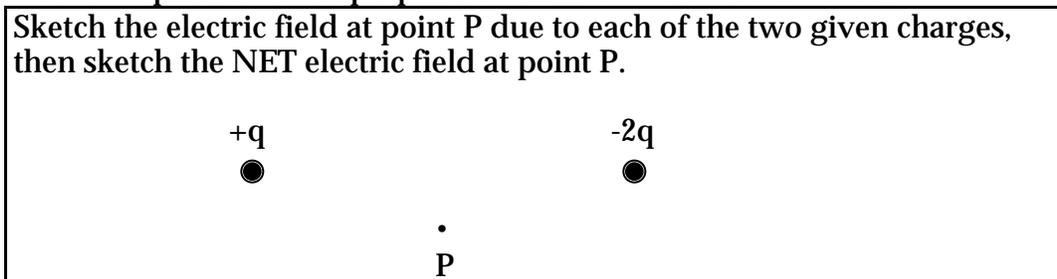
Test Instrument 5 used macroscopic objects instead of charges

Test Instrument 6 asked for a sketch of the electric field due to an isolated negative charge. Eighty-three percent (77 of 93) of the students drew essentially correct diagrams. About 4% (4 of 93) drew arrows pointing in the wrong direction, and 3% (3 of 93) drew equipotentials. Only one student drew a cloud of charges surrounding the isolated charge. The remaining sketches were unclear and were not classifiable. The higher success rate on this posttest is most likely due to the relative ease of the task; rather than requiring a sketch for two separated charges, this test only ask for the field due to a single charge.

D. Difficulty with superposition of the electric field

The question in Fig. 2 was asked on Test Instrument 6. Nearly 70% (65 of 93) of the answers were essentially correct in showing superposition, with minor errors. Acceptable answers showed field vectors due to each of the given charges, and an attempt to add them vectorially. The sketches that were not correct contained a wide variety of errors, including treating point P like a charge, and drawing only a net electric field due to the charges.

FIG. 2. A question on superposition used on Test Instrument 6.



VI. CONCLUSIONS

This study shows for the first time how students' descriptions of four aspects of electric fields studied here improved with instruction. Pretests showed that only about 6% of the students entering our algebra-based introductory college physics courses could describe electric fields in a manner that we found acceptable. This increased to more than 60% after instruction, 65% of the students named charge as the source for electric fields, more than 60% could sketch a vector representation of the electric fields produced by simple charge configurations, and nearly 70% of these students could demonstrate superposition. On pretests, only five out of more than 200 students could sketch an electric field, and all five had taken high school physics. While five is not a large number, *none* of the students who did not take high school physics were able to sketch anything resembling a vector representation for electric fields. Our present modes of instruction enable two-thirds of our students to demonstrate an understanding of an electric field. For the other one-third of the students, some specific misconceptions persisted.

A. Persistent misconceptions about existence/definition of electric fields

The description of an electric field as an area remained after instruction. Knowing this, we can design instructional materials that address this specific problem. Also persistent was the description of electric fields as charges or clouds of charge. To do away with such persistent misconceptions, instruction must address them directly. Further study is needed to discover why 12% of these students could not provide a useful description of electric fields on posttests.

None of the post-instruction oral interview subjects who received an A for this class lacked the mental construct for an electric field. The presence of an adequate mental construct did not guarantee a good grade; the students who had the mental construct spanned the entire grade spectrum from the highest grade in the class to the lowest. The average grade for those with the mental construct was 2.95 (on a 4.0-point scale), while the average grade for those without the mental construct was 2.69. No final grade information was obtained for the written posttest students.

B. Instruction-induced misconception about source of electric fields

No pretest students believed that a potential difference is the source for electric fields, but 14% of the posttest students did. A post-instruction interview subject (who earned an A in the class) was convinced that charges do not create electric fields:

I: ... What's the source for this [electric] field?

S: ... In general it's going to be a difference in electrical potential.

I: Would you say that a charge creates a field?

S: I know it senses fields. I guess no, an individual charge could not create a field, because there's no [potential] difference. It's just this one charge and it's positive or a negative. And so I think that it's influenced by fields or electrical forces. But I don't believe it generates electrical fields.

One other post-instruction interview subject shared this misconception, earning a C for the course.

C. Persistent difficulty with representation of electric fields

More than 80% of these students could sketch the electric fields due to single charges, but one-third of the students could not sketch the electric fields for multiple charges. The most frequent identifiable error was to sketch the equipotentials, and as many as one-fourth of the students drew sketches that did not resemble vector fields, potentials, or any other representation used in their physics class. Additional research may find one or more specific student difficulties that prevented such a large portion of the students from producing clear sketches.

As the instruction in this study was based partially on pretest results, these results may not be typical. Similar studies should be done to obtain results that may be more widely generalizable.

While only a few persistent difficulties were identified in this study, we feel that similar studies need to be conducted with other important concepts in physics. For instruction to produce substantive improvement in students' understandings, curriculum development must take into account the specific student difficulties and devise strategies to overcome them. The strategies should directly confront and challenge these difficulties. Only when students directly observe that their understandings do not explain their observations will

they begin to alter those understandings. Instruction that ignores the results of such research may not successfully overcome some of the persistent difficulties students have in learning the concepts of physics.

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