How Does the Computer Facilitate the Development of Physics Knowledge by Prospective Elementary Teachers?

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SYSTEMIC REFORM INITIATIVES CALL FOR INCREASED USE OF COMPUTERS IN K–12 science classrooms. It therefore becomes increasingly important to understand how particular types of computer software and pedagogical structures can support interactions that lead to meaningful learning by students. The role that the computer plays in students' learning in a collaborative environment depends not only on the ways that students use the computer and software but also on how they interact with each other as they use the computer. In this paper, we present some research results of studies that were conducted in collaborative guided-inquiry physical science courses for prospective elementary teachers. In these courses, each group of three students had access to its own computer. We first describe how the computer can be used as a representational tool to support meaning-mak-

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ing conversations in small student groups. Second, we discuss how special computer simulators make it easier for groups of students to construct robust conceptual models. It does so by providing the opportunity for students to make model-like observations that can help them bridge the phenomenological and conceptual domains. Finally, we discuss the design of this pedagogy, how the computer is embedded within classroom activities, and how these activities are based on prior research in science learning.

Introduction

Contemporary researchers in physics education have determined that innovative pedagogical strategies that make use of inquiry and collaborative techniques can be very successful (Hake, 1998). They have done this by computing learning gains from measurements of pre- and post-test scores using commonly available assessment instruments and comparing these gains to learning gains computed for traditional lecture style classrooms. In depth studies on student learning in collaborative environments can generally look at *what* students learn and/or *how* students learn. To understand more about *what* students have learned we can take an *individual cognition* perspective focusing on students' ideas and changes in those ideas. We can also examine students' inquiry skills and beliefs, and changes in those skills and beliefs. However, if we wish to look at *how* students have learned, many other factors become relevant. For example, the learning environment in a collaborative guided inquiry physical science classroom often consists of small groups of students, laboratory apparatus, and pedagogical materials. Computers can also play a role. We consider the small group, computer, laboratory apparatus, and pedagogical materials to be a *cognitive system*. We seek to understand learning in this complex system by looking for things that transform, or change the nature of interactions within, this system. We therefore look not only at how ideas evolve within a group, but also at the roles that various components of the system play in mediating discussion and sense-making activity and how members of a group share in the group's construction of ideas.

Our research has revealed that the computer, as it is used in a specific collaborative guided inquiry classroom, can play a significant role in the learning that takes place in this environment and can have positive effects on knowledge construction. Some of our research conclusions are described in this paper. In Part I we describe our theoretical background, the research setting, and methodology for our research. In Part II, we focus on how students use computer documents as shared spaces for representation and how this facilitates collaboration and the articulation of ideas. In Part III, we discuss how students use simulator results as a special type of evidence and how this seems to assist in the formulation and development of explanatory models. Finally, in Part IV, we describe how physics education research is incorporated into the development of the pedagogy and design of the computer software, and illustrate how the computer simulators are embedded in the pedagogical structure.

Part I: Theoretical and Experimental Background

Theoretical Perspective Learning often involves gradual development of ideas including making new connections, comparing with what is already known, and creating and trying out new ways of talking (Lemke, 1990). To understand these social and cultural processes, we follow a social constructivist perspective established by Vygotsky (1986) and developed by others (Cole, 1996; Cobb & Bowers, 1999). In his work, Vygotsky focused on learning in interactions between an authoritative superior such as a teacher, and a student. We believe, however, that social interactions between peers such as those in a collaborative group can also result in gradual construction of knowledge. Such gradual peer-based learning relies on the social and cultural milieu of the setting, in this case, the guided inquiry classroom.

We also follow a systems cognition perspective where the student, the student in interaction with other students, and the student in interaction with others and with tools (such as the computer, activities, and the pedagogy) are considered a cognitive system (Hutchins, 1995). This perspective focuses on influences of environmental structures on students' sense-making processes. Environmental features such as classroom layout and how the computer is used in the pedagogy contribute to the ways that people organize their cognitive activity. In other words, learners may often solve problems by "piggy-backing" on reliable environmental features. According to Hutchins, the 'opportunistic' use of, and interaction with, these sorts of features is a fundamental aspect of cognition that is often overlooked. To elucidate this notion, we provide an analogy given by cognitive scientist Andy Clark in his book *Being There: Putting The Brain, Body, and World Together Again.*

> The simple sponge, which feeds by filtering water, exploits the structure of its natural physical environment to reduce the amount of actual pumping it must perform: it orients itself so as to make use of ambient currents to aid its feeding. The trick is an obvious one, yet not until quite recently did biologists recognize it. The reason for this is revealing: Biologists have tended to focus solely on the individual organism as the locus of adaptive structure. They have treated the organism as if it could be understood independent of its physical world. In this respect, biologists have resembled those cognitive scientists who have sought only inner-cause explanations of cognitive phenomena (Clark, 1996).

In the same way, we believe that humans use physical, social, and cultural features of their environment to their advantage. The process of cognition, like the analogous process of feeding, becomes a system consisting of interactions between individuals and their surroundings. Like the biologists in the analogy above, if we look only at the individual student's minds, we may miss some crucial aspects of the cognitive process. As researchers of learning, we feel that we must seek explanations for cognitive phenomena that include structures that are external, as well as internal, to individuals. Our research in the science classroom suggests that two particular classroom features, computer documents and computer simulators, are relevant factors of the cognitive system and, therefore, in students' learning. In the pages that follow, we provide descriptions and examples of the special roles that the computer can play in the learning process.

Setting and Research Methodology This article draws on research conducted in a physical science course for prospective elementary teachers at San Diego State University. The course is taught using a collaborative inquiry pedagogy that focuses on the building of conceptual models and makes heavy use of computers in the classroom (Goldberg, 1997). The course design was part of a five-year NSF funded project entitled Constructing Physics Understanding in a Computer Supported Learning Environment (CPU Project).[1] In a CPU course, students are in control of inventing science ideas. Through carefully guided and sequenced activities, students are expected to construct physics ideas that are very closely aligned with the main ideas found in physics textbooks. For example, in the CPU classroom students are expected to establish for themselves that force is proportional to acceleration and ultimately to establish the relation between force, acceleration, and mass (or Newton's Second Law). There is no textbook for the course, instead, students construct their own "textbook" from print-outs of the computer activities they engage in in a majority of class time. The main role of the CPU instructor is to guide whole class discussions that either bring out students' initial ideas or lead a class to consensus on a small set of powerful ideas that can explain a majority of the experimental observations students have made. The instructor provides very little direct information involving the content of physics but sometimes asks questions that lead to rich discussions in the whole class or in small groups.

Most of the students who enroll in this course are college juniors and seniors who plan to become elementary school teachers. These students have little science background and many of them express fear and anxiety about science when they first enter the classroom. They come from a mix of socioeconomic and ethnic backgrounds within the range of lower to upper middle class. Typically about 90 percent of the students are women, and approximately one third are Hispanic. Possibly because of their junior and senior class standing, some students have habits of thoughtful reflection. However, comparisons with science courses for prospective elementary teachers at universities around the nation indicate that our students' academic abilities and preparation are similar to preservice teachers at other universities.

Our research data were taken in a regularly scheduled CPU classroom. Students were videotaped during large class discussions, while they worked in groups of three with activity sheets and white boards at their desk, and while they worked in groups of three performing hands-on experiments and "computer experiments" using the computer simulator. Students recorded their group's predictions, observations, and explanations in documents on the computer. Videotapes of the groups' discussions were transcribed and analyzed in several different ways. Hypotheses about each student's evolving understanding were developed and explored. We also interviewed students outside of class and asked them to explain some interactions they had or some comments they made in the videotaped data. Hypotheses about how students used the computer screen, the computer documents, and the computer simulator were formulated and triangulated using additional data from videos, interviews, and other sources.

The CPU Pedagogical Structure Each unit in a CPU course focuses on the conceptual aspects of a specific subject area in physics, such as current electricity, static electricity and magnetism, motion and forces, the small particle model, waves and sound, and light and color. A unit consists of several cycles and each cycle begins with an Elicitation Phase, which is designed to elicit students' initial ideas about a particular concept through predictions, demonstrations, and discussions. This is followed by a Development phase where groups of three students engage in a set of carefully sequenced activities presented to them on the computer screen. The group uses these activities as a workbook by editing diagrams and pictures, constructing new diagrams and pictures, and adding text to the documents. The activities are based on physics education research and are designed to target a particular concept. The goal of the Development phase is for students to construct explanatory models of phenomena they observe. Many of the activities ask students to predict the results of an experiment and then to test their prediction by performing a hands-on experiment and/or a "computer experiment" using the computer simulator. In each case, students are expected to explain their reasoning and then to compare the results of their experiments with their predictions. Because students are expected to construct conceptual models of observed phenomena, the hands-on laboratory experiments are conducted in the space beside the computer. The structure of the activities requires that students move back and forth between the laboratory apparatus, the computer simulator, and the activity documents. When a group of students comes to a consensus on a prediction or explanation, they enter it into the computer document either as text or as a picture. A whole class consensus discussion immediately follows the Development phase, during which the whole class can participate in establishing several powerful ideas that can explain a majority of the observations made during the Development phase. This is then followed by an Application phase, where students apply their consensus ideas by using them to solve challenging problems and to design experiments.

The CPU simulator software includes both phenomenological and conceptual representations. That is, the simulator shows what would happen in a hands-on experiment and overlays representations of a corresponding conceptual model. This property of dual representation helps students to make connections between their hands-on experiments and their evolving conceptual models of observed phenomena (Goldberg and Bendall, 1995). There are two types of model-like representations built into the simulators. The first is the type that is typically seen in textbooks. For example, the CPU light and color simulators show light ray diagrams that can be used to explain the formation of images and shadows. This type of information provides students with the opportunity to make model-like predictions by drawing their own light ray diagrams and compare them with those that they construct using the simulator. A second type of representation is of the form of a simple model that is general enough to be consistent with several different conceptions or certain concepts. For example, the CPU static electricity simulators color the surface of objects red or blue rather than using positive and negative symbols to represent charge. This allows students at different stages of conceptual development to communicate with each other and to begin to build models of static electricity.[2] The red and blue coloring scheme also can serve as a conceptual bridge between students' initial ideas and the scientific model that would be the target of instruction.

We expect that students begin to build conceptual models based on their prior understanding of fundamental concepts and phenomena. The CPU pedagogical structure provides a forum for students to work with each other in efforts of modifying and developing their models through experimentation, collaboration, and consensus. In the sections that follow, we discuss how specific environmental features played a role in the development of the students' conceptual models.

Part II: The Computer Document as a Shared Representational Space

Researchers have found that the pictures, equations and other types of representations available to students in sense-making situations can substantially impact their discussions and their thinking (Kelly & Crawford, 1996; Cobb & Bowers, 1999). Particular representations such as tables or diagrams can spark new ideas or enable evaluations of current ideas (Meira, 1995). We have found in our research that the way students are asked to represent their ideas can have a crucial effect on the discussions they have.

In a CPU classroom, the three students in each group look at documents on their computer screen and they construct responses within these documents. The individuals in each group usually share this task even though there is only one typist at any given time. The documents contain text and pictures (representations) and students add text and pictures to them. We say that each document on the computer screen is a "shared representational space" used by the group. Computer documents have several qualities of being shared. First, all students can look at and refer to the same part of the same document. Second, there is one document per group. Third, the responses typed and drawn by students are considered to be the work of the group rather than of one individual student. As such, the computer document is similar to other types of representational media such as a whiteboard, a sheet of paper, or a chalkboard to which all members of a group have access.

One important thing to consider about the computer monitor as a shared representational space, is that the text typed into the keyboard and the drawings done using the mouse and keyboard are physically separated from the hands and personal space of the individual who is constructing the diagram or text. When a student writes something or draws a diagram on a sheet of paper, his hand is directly on the paper and often covers part, or all, of the representation being constructed. Thus, other members of the group have visual access to the diagram only *after* it has been created. On the computer, all members of the group have equal visual access to all parts of the computer monitor. Therefore, each student in a group can see the text, picture, or diagram *as it is being created.* This separation of text and diagrams from the hands of the person constructing it presents an opportunity for all students to simultaneously consider, respond to, and gesture at representations *as they emerge* on the computer screen. Thus, the computer provides a shared representational space that could serve as an effective communication tool between individuals in a group. (Figure 1) It allows all students in a group to participate in the construction of representations simultaneously. Two ways in which the CPU computer documents, as shared representational spaces, support meaningful discussions about physics are discussed in the remainder of this section. First, they promote the construction of concrete statements using language that is agreed

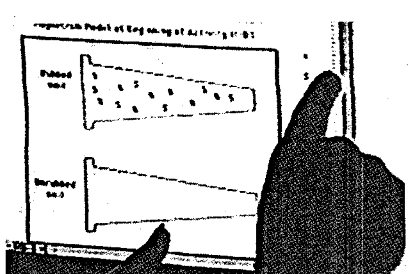


Figure 1. Two different students pointing to their diagram as it is being constructed on the computer screen.

upon within the group. Second, they provide contexts within which groups can modify and enhance their explanatory models.

A shared representational space supports collaboration As students work on a computer document in their groups, they are expected to have discussions about their ideas and are encouraged to type a single response to each question. We have found that each group member often contributes to a common group response. To illustrate this process we provide an example taken from an analysis of the interactions within a particular group that was working on the CPU Unit on Static Electricity and Magnetism.

Early in the unit, three students who we refer to as Donna, Anne, and Marge were asked, in the computer document, to predict the electrical effects of a plastic straw before it was rubbed with wool. The group predicted that the unrubbed plastic straw would not attract any other objects. The activity asked for an explanation to support the group's prediction. Donna, the group's typist that day, asked for help in writing this explanation. All of the students in the group suggested ideas and Donna typed words on the screen. Each student contributed to the explanation that gradually appeared on the computer screen. Their contributions were influenced both by words *as they were appearing* on the computer screen and by statements that were being made by other members of the group. The students' interactions with each other and the students' interactions with the computer screen can be seen as a cognitive system where each component influenced the other; the emerging statement on the screen influenced discussion and the discussion influenced what was typed into the keyboard and seen on the screen. In the transcript shown on page 62, note the ways in which the statements made by each student often concluded or continued the statements made by other students. Also notice the way statements were sparked by the text being typed into the computer. The second column in the transcript is what the students said and the third column is what Donna typed on the screen at that time.

The group's final statement is given below.

> We decided that there would be no reaction with an unrubbed straw to all of the [test objects]. The reason why, is because there were no reactions in our previous trials [in the previous] experiment.

Donna began the discussion above by saying, "We decided there would be no reaction" to suggest how the group's statement might begin.

Student	Spoken	Typed by Donna
Donna	We decided there would be no reaction	
Marge	to an un	
Anne	with an unrubbed straw	
Marge	unrubbed straw would have no reaction.	
Anne	Because of our observations in [the previous activity] that its because of our previous observation	We predicted that there would be no reaction with (pauses)
Donna	With, with	
Anne	an unrubbed straw	
Marge	an unrubbed straw	
Anne	and any of the [objects]?	an unrubbed straw to all of the victims.[3] The reason why is because (pauses)
Donna	. . . there were no reactions in any of our previous?	
Anne	observations	
Donna	[mutters]	there were no reactions in our previous (pauses)
Marge	Previous trials?	
Donna	um—to the [previous activity] experiment?	trials
Anne	yeah, yeah	to the [previous activity] experiment.
Donna	Okay	

The group then began to construct a shared way of talking about their prediction. As each student contributed a few words, a concrete statement gradually appeared on the computer screen. Each student's spoken statements only made sense in the context of the words that were being typed into the computer and the words that were being said by other individuals. Thus, the statement that was gradually emerging on the computer screen provided the thread that held the conversation together. This kind of close interaction of the group members in concert with their text or drawing happened frequently. These discussions all seemed to have two important features. One feature was that each member of the group contributed to the construction of statements that were meaningful to them. These statements can therefore be considered to be group products over which no one student could claim ownership. A second common feature of this kind of discussion was the group members' development and maintenance of shared language for their evolving understandings.

We believe that to learn science well students must articulate ideas, examine them, and make informed changes in their thinking. We have illustrated how a shared representational space can support collaborative articulation of ideas. Another important feature of the computer as a shared representational space is ease of typing and modifying statements and pictures. The computer can therefore provide a manageable and efficient way for students to flexibly construct, evaluate, and modify a large number of responses, diagrams, and pictures that support their thinking.

A shared representational space supports the evaluation and modification of ideas. The CPU computer documents, as shared representational spaces, can facilitate joint construction of pictorial representations of explanatory models. For example, in the Static Electricity and Magnetism Unit, each group is expected to develop a model of magnetic materials that can explain magnetic phenomena such as attraction and repulsion. Students performed experiments with magnets and nails and constructed explanatory models, in the form of pictures, of what might be going on inside a nail when it is magnetized. Drawing in the computer documents provided a setting for students to extend their thinking and modify their explanatory models. To illustrate this, we describe a particular case involving Donna, Anne, and Marge.

During the Elicitation activity, each group in the class was asked to formulate their model of magnetized and unmagnetized nails. Donna, Anne, and Marge's model depicted an unmagnetized nail containing a random mixture of two types of "charges," which the group members called north (N) and south (S) charges. They explained that rubbing the nail with a magnet moved the N charges to one end and the S charges to the other end of the nail (see Figure 2).[4]

In the Development activity that immediately followed, each group was asked to draw its best pictures of unmagnetized and magnetized nails in the computer document. Donna was watching the screen as Anne was putting N and S letters representing north and south charges at opposite ends of the picture of a nail. The model Anne was attempting to draw on the computer screen showed N and S charges only at the ends of the

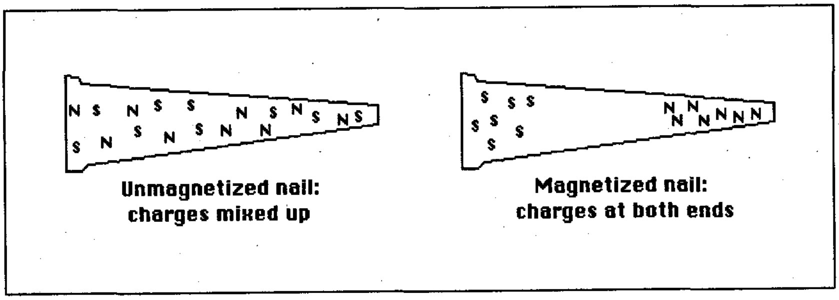


Figure 2. The group's initial model diagrams for an unmagnetized and magnetized nail.

magnetized nail, with nothing in the middle (Figure 2). As Donna watched the model being constructed on the computer screen, she asked where Anne would stop placing Ns and where she would start placing Ss. The group had not previously discussed where the Ns ended and the Ss began. In the following transcript Donna brings up the question about what is going on in the middle of the nail.

The process of drawing the diagram on the computer screen in a shared representational space seemed to have an influence on the group's thinking. Donna asked the question about the gap between N and S while Anne was placing those symbols on a diagram of a magnetized nail. Donna saw alternate possibilities in the drawing (see Figure 3). The construction of the picture on the computer screen prompted the evaluation of the current model and led to the consideration of an alternate model. A possible reason for this is that Donna was able to see the entire diagram *as it was being constructed.* This presented a clear choice about an issue that had not previously been considered by the group. The construction of diagrams sometimes requires different kinds of details than students tend to give in verbal or textual descriptions. About the same model, students could write

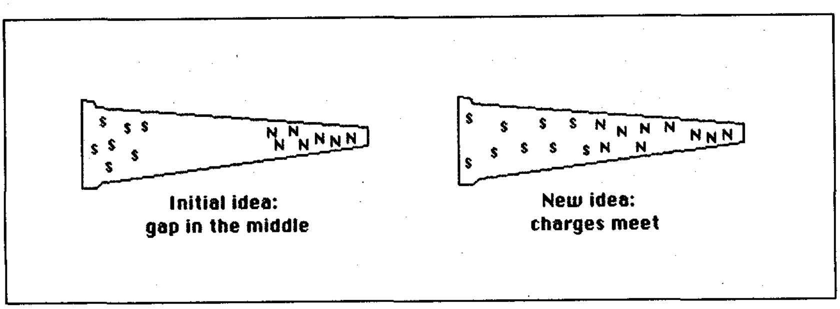


Figure 3. Two models of what might be inside a magnetized nail. The group's original model is represented on the left, with N and S charges separated. Donna's alternate conception is represented on the right.

that "the N and S charges separate to opposite ends of the nail," without explicitly indicating what happened in the middle. This is what Donna, Anne, and Marge had done in the Elicitation activity. Watching their diagram being created in their shared representational space on the computer screen seemed to help the students pay attention to the diagram from a conceptual standpoint. These students began to consider what might be happening in the middle of a magnetized object instead of just considering what was happening at the ends.

By evaluating their model in this way, the group made progress in developing it, but it was not their final step. In the discussion below, the group constructed a model that would not be accepted by scientists. According to the scientifically accepted model of magnetism, randomly oriented "magnetic domains" (or, for simplicity, tiny magnets) are inside unmagnetized materials. When a material is magnetized the tiny magnets align so that their "south" ends all face more or less the same direction. This accounts for the bipolar behavior of a magnetized material and its

Donna	—think there's a space in the middle of the nail?
Anne	I dunno
Donna	Do you think like the south—they just butt up.
Anne	Just meet at each other.
Donna	You know what I'm saying?
Anne	Yeah
Marge	We didn't test anything for the middle of it, I don't know what happens
Donna	I mean just based on our model, do you think, because we're drawing a picture of what we think is happening, do you think that Ss come right up to the Ns? . . . or do you think there's a space in the middle of it?
Marge	I don't know. It'd be interesting to take a magnet and
Donna	Put it in the middle
Marge	yeah, and go up and see when it changes. See if you can keep attraction, attraction, attraction all the way up through the center.

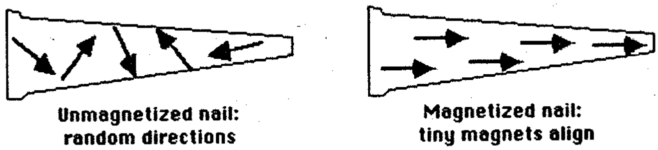


Figure 4. A formal model of magnetism. Arrows represent microscopic magnetic domains within the nail.

tendency to align itself in the presence of a magnetic field such as that of the Earth (see Figure 4).

The group's model did eventually evolve into a magnetic alignment model that is very similar to the accepted "magnetic domains" model. The evolution and development of this group's model resulted from an extensive series of predictions, experiments, and sense-making discussions. These features of the pedagogy were supported by the shared representational space of the computer screen as well as by other features of the classroom environment (see Part IV for a more detailed discussion that highlights ways in which the computer is used within the pedagogical structure). The group in the examples given in this section is representative of all of the other groups we have studied. In the following section we describe how special features of the simulator software transformed the process of model building in a shared representational space.

Part III: The Computer Simulator Facilitates the Process of Model Building

In the science classroom, students often have difficulty distinguishing between observation and inference. When asked to form an explanation or explanatory model that can account for an experimental result, many students end up either repeating the experimental procedures or simply describing the result (Kuhn, 1993). Furthermore, many students in a science class have the tendency to perceive information given by the instructor, the textbook, or the classroom materials as dictums of authority rather than as information that can aid their model building process (Hammer, 1994). This can serve as a barrier to learning because constructing conceptual models is often the goal of an inquiry-based science course. The problem is particularly acute for prospective elementary teachers because they typically have little science or mathematical experience.

Our research in the CPU classroom during the unit on static electricity and magnetism has revealed that the computer plays an important role in students' development of sophisticated explanatory models. Specifically for this topic, two factors seemed to play a special role: (1) A red and blue coloring scheme that is introduced by the activity documents and (2) model-like evidence that is made available through the computer simulator. We have found that these two things together facilitate the process of model building.

The red and blue coloring scheme in the CPU static electricity simulators represents electric charge as a continuous distribution or fluid. Two electrical conditions (positively charged and negatively charged) are represented by red and blue lines of varied thickness. The red and blue coloring scheme does not impose a specific physical description of charge. Instead, students are expected to develop such concepts on their own. We therefore use the term "electrical conditions" to refer to surface charge on an object since students may or may not have developed a clear concept of charge in the early stages of the cycle when the red and blue coloring scheme is introduced. The simulator's model-like representation does not depict charge as discrete units and does not use the convention of positive and negative in the visual representations. These simulator results are governed by electrostatic theory but the interface between the theory and the students is a representation of red and blue lines.

The simulators offer both phenomenological and conceptual results. Phenomenological simulator results are representations of what one actually would observe in a hands-on experiment such as an object attracting or repelling another. Conceptual results are model-like representations using the coloring scheme; for example, a red-colored pendulum is attracted to a blue-colored insulator and repelled from a red-colored insulator (see Table 1). From this, one can infer that objects with similar electrical conditions attract and objects with dissimilar electrical conditions repel. The conceptual results offered by the simulator allow students to make "observations" that they could not make with laboratory apparatus. These model-like observations can help students make inferences more easily. The static electricity simulators provide a variety of tools and setups which allow students to make observations that are relevant to concepts in static electricity such as charge transfer by touching, charge polarization, and charging by induction. Selected examples of the simula-

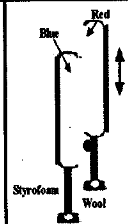
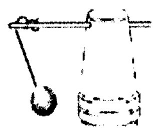
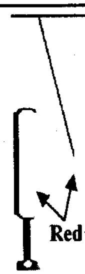
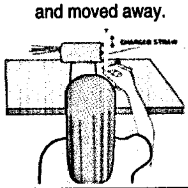
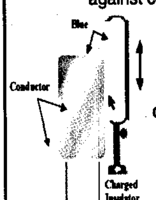
Phenomenological Observations Made With Laboratory Apparatus	Phenomenological Observations + Conceptual Observation Within the CPU Simulator	Formal Inference With Scientific (Expert-like Explanation)
A straw is rubbed with wool. Once rubbed, the straw and wool exhibit electrical effects such as attraction and repulsion. 	 Insulator surfaces, when rubbed together, become colored red or blue with lines of equal thickness.	**Charging:** When two objects are rubbed together, negative charges are transferred from one object to the other leaving one with an excess of negatives and the other with a lack of negatives (or excess of positives.)
A wool-rubbed styrofoam plate repels a hanging wool-rubbed stryofoam pith ball. 	Red-charged ball is repelled from red-charged insulator. 	**Repulsion:** Similarly charged objects repel each other.
Conducting tinsel sticks out away from a soda-can when charged object is rubbed against soda-can and moved away. 	Blue line on insulator gets thinner as insulator is rubbed against conductor. A blue line appears on conductor. 	**Charge Transfer:** The conductor is initially electrically neutral. After rubbing, negative charge is transferred from the insulator to the conductor. Since the tinsel is also a conductor it acquires the same charge and repels from the end of the conductor.

Table 1. Conceptual tools provided by CPU Static Electricity Simulators. Formal inferences (column 3) can be made from model-like representations (column 2) of the phenomena (column 1).

tor's phenomenological and conceptual components and how they are associated with formal inferences are shown in Table 1.

With the red and blue coloring scheme, students can *predict* how an object should be colored to explain particular observations that they make in hands-on experiments. They can then perform a *computer experiment* and obtain *model-like evidence* to check against their coloring prediction to help them make sense of their hands-on observation. We therefore consider the prediction of how to color an object to be a *concept prediction* and the simulator results to be model-like or *concept evidence* for that prediction.

The computer is not necessary for the introduction and use of this type of analogical model in the classroom. Students can make concept predictions using white boards, chalkboards, or paper and pencil. The difference is that with the computer simulator, relevant formal information is not "in the back of the book" and is not revealed as the "right answer." Instead, it is revealed in the form of model-like evidence from a computer experiment that the students perform themselves. Our data analysis suggests that students used this concept evidence (simulator results) in a way that is very similar to the way they used phenomenological evidence (what they actually observe with apparatus). Students did not seem to differentiate between the two forms of evidence even though from our perspective, they are somewhat different (see Table 1). This suggests that students were not viewing a simulator result as a dictum from authority to be memorized and forgotten after the test. Instead, they were using this model-based information as evidence that they needed to make sense of in order to further develop their understandings of the phenomena.

To illustrate this, we provide an example from an activity in the unit on static electricity and magnetism called the "Soda Can Electroscope." A soda can electroscope is an aluminum soda can, turned on its side and taped to an inverted styrofoam cup, as shown in Figure 5 (Morse, 1992). Several pieces of aluminized tinsel are taped to one end of the soda can. When a charged insulator is brought near, but not touching the soda can, the tinsel moves out away from the end of the conducting soda can.

A simple explanation, in terms of the scientifically accepted model of static electricity, is as follows. The aluminum soda can initially contains an

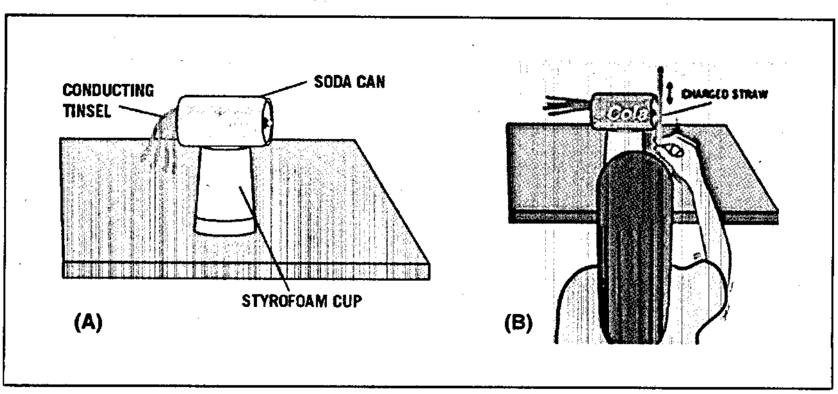


Figure 5. Soda Can Electroscope: (A) realistic view of the electroscope and (B) the conducting tinsel sticks out when a charged object (such as a wool-rubbed straw) is brought near.

equal number of evenly distributed positive and negative charges. When the negatively (blue) charged insulator is brought near the soda can, the freely moving, negative charges within the conducting can are repelled as far away from the negatively charged straw as possible, since like charges repel each other. As these charges move away from the end of the soda can nearest the straw, positive charges (which are not mobile) remain in place. Therefore this end of the soda can is left with a deficit of negative charge (or excess of positive charge) and is thus, positively charged. The far end of the soda can (the end with the tinsel) now contains an excess of negative charge and is therefore negatively charged. Since the tinsel is also a conductor, negative charges move through it also. Since the tinsel and the end of the soda can are now both negatively charged, the tinsel, which is very light and semi-mobile, moves out away from the soda can. This separation of charge in the conducting soda can is a phenomenon known as charge polarization.

The CPU simulator result associated with this phenomenon is shown in Figure 6. This model-like representation depicts a soda can that is colored red on the end nearest the blue-charged straw and blue on the end to which the tinsel is attached. The tinsel is also shown colored blue.

The process of charge polarization is not fully explained by the representation offered by the simulator. The simulator depicts charge polarization in terms of a bipolar representation (red on one end and blue on the other). Although this can assist students in the framing of an explanatory model, it certainly does not explain why the tinsel moves out away from the soda can. The simulator result still requires interpretation by the students.

For the remainder of this section, we provide a specific example of how students interpret and use the concept evidence provided by the

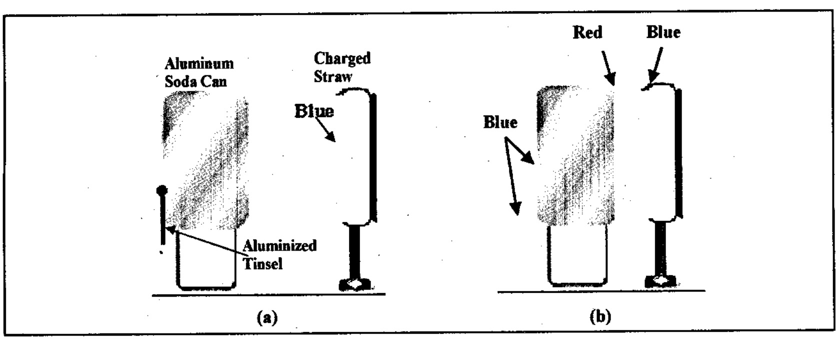


Figure 6. The simulator results. (a) Before the charged insulator is moved close to the soda can. (b) After the charged insulator is brought near, but not touching the soda can. The red and blue coloring scheme represents a bipolar distribution of charge in the conductor, a phenomenon known as charge polarization.

simulator. This example is representative of all of the groups that we studied. In this example, a group of three students, Janet, Abby, and Max were working on the Soda Can Electroscope activity at their computer. During the first part of the activity the students brought a wool-rubbed straw (charged straw) near the end of the conducting soda can. The first question of the activity asked them to describe their observations and to construct an explanation in words and enter it into computer document. The students answered with little discussion and no apparent disagreements. A reproduction of a portion of their computer document is shown in Figure 7. Students' answers are shown in bold.

Despite the apparent agreement that the group members had while formulating these statements, our analyses of preceding and successive activities, homework, journals, and interviews suggested that the group's answers meant something very different to each of the three students. As described in detail below, each student seemed to assume a different basic causal mechanism for the repulsion of the tinsel. However, because each student understood the typed sentence according to his or her own *implicit* assumptions, they were not even aware of the disagreement, at least not at first.

It was not until the group began to address the next question in the activity document that the individual students' different underlying assumptions became explicit. This question asked them to color pictures of the objects (soda can and straw) in the computer documents using the red and blue coloring scheme. While framing their coloring prediction, there was an interesting disagreement among the group members and a long discussion. They immediately discovered that they did not agree on how to color the soda can, even though they seemed to be aware of no disagreement when they had entered the answer to a very similar question in the previous step.

1. Describe what happens to the tinsel.

We saw that the tinsel repels from the soda can.

2. Why do you think the tinsel behaves the way it does?

Because the can is conducting (or transferring) like charges towards the tinsel.

Figure 7. Actual activity questions and the group's response to those questions (shown in bold).

The analysis of students' homework, interviews, and video data suggests that part of the problem was that each student's prediction of how to color the soda can was based on different fundamental assumptions of how or why the tinsel moved out away from the end of the soda can. We concluded that Janet assumed that the tinsel was repelling directly from the blue-charged straw. Since the straw was assumed to be charged blue, she thought that the tinsel must also be blue since like-charged objects repel. Max ascribed no electrical properties to the tinsel at all. He viewed the tinsel solely as an indicator of the electrical interactions of the soda can. Therefore, he reasoned that if the tinsel was sticking up, the soda can must be repelling from the blue-charged straw, therefore the soda can must be blue since like-charged objects repel. Abby, on the other hand, believed that the straw was charged blue *because* many of its red charges had transferred over to the soda can, thereby charging the soda can red and leaving the straw with mostly blue charges. According to her model, the red charges then moved through the soda can and into the tinsel. The soda can and the tinsel were both now red and so the red-charged tinsel was repelling from the red-charged left end of the soda can. Throughout their discussion, these students seemed to be inhibited from making progress toward a resolution because they did not make their assumptions explicit to each other, and perhaps to themselves.

The analysis of students' homework, interviews, and video data suggests that because of the very different ways that the group members seemed to be thinking about the phenomenon, they could not come to a consensus on how to color the soda can. The discussion ended when Max suggested to Abby that they go to the simulator to "help clear [her] up." This is significant because it illustrates the group's expectation that some sort of "evidence" to help them evaluate their coloring prediction would follow. After running the computer simulator, the group was faced with the task of interpreting the simulator results. This led to a collaborative construction of a sophisticated, model-based, explanation of why the tinsel moved out when a charged object was brought near, but not touching the soda can.

The Computer Simulator Supports The Development of Explanatory Models. When the students first saw the simulator results (see Figure 6b) they were all very surprised. None of the students had predicted that the soda can would have two colors. Abby had previously argued for a coloring scheme that assigned red to the soda can and tinsel and blue to the straw.

Janet had argued for a coloring scheme that assigned blue to the tinsel and straw. Max had argued for a coloring scheme that assigned blue to the soda can and straw. The students were faced with the problem of accounting for the red *and* blue that appeared on either end of the soda can on the computer screen. The discussion that followed led to the convergence of the three students' ideas and to the development of a group explanatory model that helped them make sense of the phenomenological results.

The three students began to work together to make sense of the simulator results as soon as the results appeared on the computer screen. In the face of this new evidence, the students shifted from tenaciously adhering to their initial ideas and began to consider alternative points of view. The model-like simulator results provided a context for the members of the group to evaluate their own ideas as well as the concept evidence in a shared representational space. By simultaneously interpreting these results and applying their ideas, each student was able to contribute sense-making insights that led to the group construction of a model. For example, Max noticed that the end of the soda can that was closest to the straw was colored red and the straw was colored blue. He then suggested that the soda can and the straw were attracting each other since opposite "forces" attract. Abby then continued to say that the blue charges in the soda can must therefore be repelling from the straw and moving to the other end of the soda can, making it (and the tinsel) blue charged (see Figure 8a). After this, the group members began to support the ideas of one another, finish each other's statements, and converge on a conceptual model of charge polarization that was supported by a discrete model of charge.

Immediately following the construction of their explanation, Max suggested that they repeat their explanation using the actual apparatus. At this time, Abby picked up the straw, pointed toward the soda can and began to reiterate the group's model. An excerpt from this dialogue is given on following page.

In the following dialogue, Abby and Janet were jointly explaining the explanatory model that the group established after interpreting the simulator results.

The final model with which the group ended this segment of the activity provided a mechanism by which the soda can obtained a different charge on both ends. This explanatory model made use of their agreed upon prior knowledge that opposite electrical conditions attract and like electrical conditions repel. Until this point in the activity, only one member of the group had articulated a conception of charges as entities. Their

Janet	So we're making blue charges
Abby	We're making blue charges [by rubbing the straw with wool].
Max	OK. this is blue just like the straw.
Abby	And this is red charges. And when we're doing this, all the red charges are coming up this way (see Figure 8b).
Abby	They [the red charges in the soda can] are coming to get this [the charged straw], because it's attracting the opposite.
Janet	Cause it's attracting the opposite
Abby	So all of those reds are coming here towards the blue— In turn making this [pointing at the end of the soda can with tinsel attached] blue.
Janet	cause there is no red ones left down there [on the end of the soda can near the straw] or whatever
Abby	And the tinsel is blue so it's (Pause) It's repelling from it.

model also made use of the group's prior knowledge that conductors differ from insulators because electricity can move freely through a conductor. New knowledge was also constructed in the process of forming the explanation. The three students developed the notion that, to begin with, the conductor contained equal amounts of both kinds of charges. By the end of this activity, three very different individual models had converged and evolved into a group model that was closer to the model held by the scientific community. Although this group did not construct the scientific model of charge polarization in this activity, they did do so by the end of the unit.

The Coloring Scheme and Simulator Transformed the Task of Model Building. The computer simulator together with the coloring model seemed to play a significant role in the process of knowledge construction. The inclusion of a concept prediction, a computer experiment, and concept evidence transformed the task of constructing an explanatory model. This process is outlined in Table 2. In traditional inquiry courses, students make predictions, perform experiments, and make observations to obtain evidence. They are then expected to jump directly into the task of constructing an explanatory model (see column 2 in table). In the situation

Domain	Traditional Inquiry Approach	Approach That Uses Conceptual Tools
Phenomeno-logical	• Make Prediction • Perform Experiment • Make Observation & Obtain Evidence	• Make Prediction • Perform Experiment • Make Observation & Obtain Evidence
Conceptual	↓	• Make "Concept Prediction" • Perform Computer Experiment • Obtain "Concept Evidence"
Both	• Construct Explanatory Model	• Construct Explanatory Model

Table 2. CPU simulators transform the model building task by providing conceptual tools as well as phenomenological tools.

described above, students still made predictions, performed experiments and made observations in the phenomenological domain. However, instead of having to jump straight into the task of constructing an explanatory model, they made use of conceptual tools which allowed them to make a concept prediction, perform a computer experiment, and obtain concept evidence (see column 3 of table). As they evaluated concept evidence, these students seemed to move easily from the phenomenological to the conceptual domain and then were able to relate their resulting model back to the phenomenon (see Figure 8). This process can be particularly helpful for prospective elementary teachers and other students who have little science background.

We have discussed how computers can influence learning by supporting group collaboration and by making it possible for students to perform computer experiments and obtain concept evidence. Clearly, the influence that the computer has on the learning process is dependent on

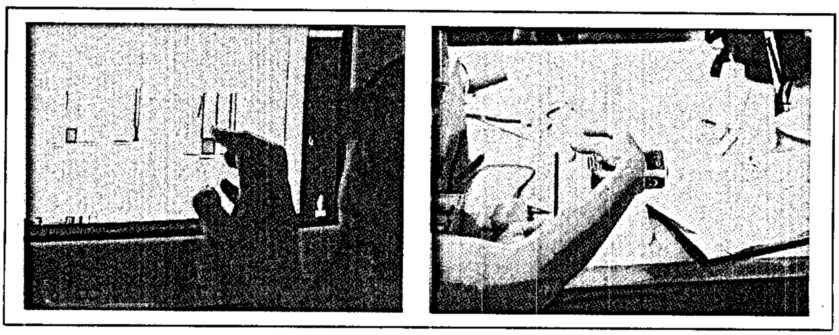


Figure 8. The coloring model helps students move from the phenomenological to the conceptual domains. Students use concept evidence (a) to help them make sense of the phenomenon (b). The picture on the computer screen in (a) is similar to the computer results shown in 6b.

the ways that the computer is used in the classroom. Thus far, we have only alluded to how simulators were embedded in the pedagogical design. In the section that follows we provide a more detailed outline of the CPU course design and its dependence on research in physics education.

Part IV: The CPU Computer Simulator is Embedded in the Computer Documents

All of the CPU simulators include a phenomenological and a conceptual component. Some simulators, however, do not make use of an analogical model such as the one found in the static electricity simulator. Instead, the subject matter often lends itself to particular formal representations. For example, the Light and Color simulators use formal light ray diagrams to represent some of the conceptual aspects of the behavior of light. Using these diagrams in the simulator also helps students link the phenomenological and conceptual domains.

When embedded in the CPU Light and Color curriculum unit, the simulators are used to complement and extend the students' hands-on experimental activities. This coupling of the laboratory apparatus and the computer simulator, along with a carefully designed sequence of activities, helps students build on and modify their own ideas. The decisions about how to design both the activities and the computer simulators were guided by research on student learning of geometrical optics. In this section we provide a specific example of how the curriculum was designed to promote the development of ideas involving the formation of images. Image formation is one of the most important topics in geometrical optics.

Figure 9 shows a typical experimental set-up used to study image formation by a converging lens. Previous research has shown that students beginning their study of light often conceptualize the image formation process *holistically* (Galili et. al, 1993; Bendall et. al, 1993; Goldberg and Bendall, 1995). They imagine that a *potential image* travels from the source, turns upside down inside the lens, and is then projected onto the screen. This conceptualization is represented in Figure 10. The lines that are drawn connecting the source, lens, and screen, seem to serve as guides for the projection of the potential image. The screen seems to serve the role of capturing the image, allowing it to be seen.

Someone very knowledgeable in the domain has a very different way of thinking about and representing the image formation process. Figure 11 shows a typical formal light ray diagram found in physics textbooks.

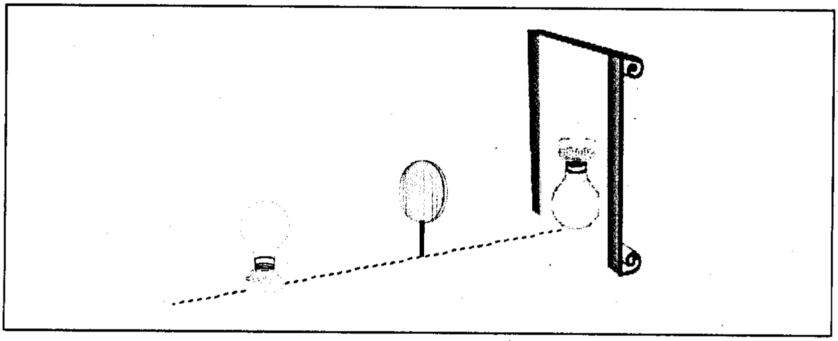


Figure 9. A set-up consisting of an extended light source, converging lens and screen. A sharp upside-down image of the source can be seen on the screen.

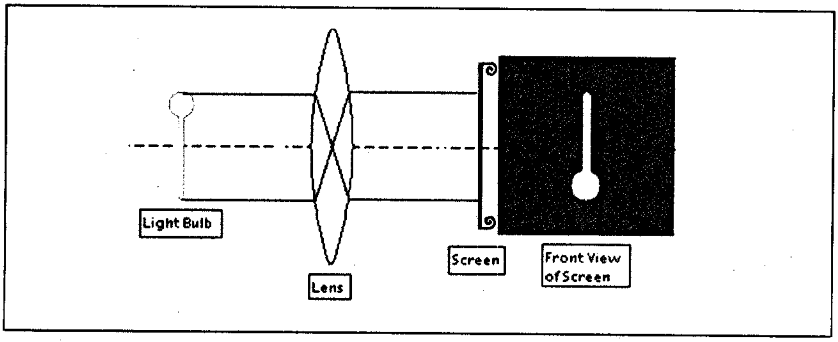


Figure 10. Common way that students think about image formation prior to formal instruction.

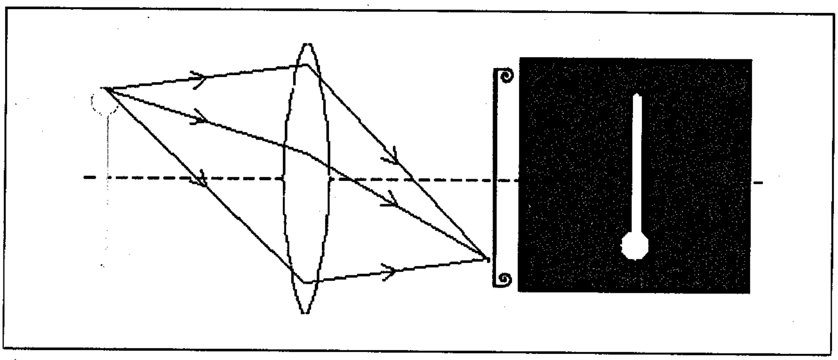


Figure 11. Formal light ray diagram that explains how a lens forms an inverted image of an extended light source such as a light bulb.

We wish to emphasize three important features of this diagram. First, the formal diagram has several light rays spreading out from different points on the source. This represents the idea that light travels outward from each source point in all directions, not just in one direction as suggested in the diagram in Figure 10. Second, the formal diagram uses two different points on the source (top and bottom) and is trying to represent what happens to the light that leaves each of these points. Any number of points on the source could have been chosen. Typically, two points are chosen both for convenience and to show how the image is formed upside-down. Implicit in this choice is the assumption that the entire source could be considered as a large number of closely spaced source points. Thinking of a source as composed of source points is quite different from thinking of the source as a single holistic entity. Finally, the diagram suggests that each image point is formed when light spreading out from each source point passes through the lens and is made to come together again at a different point. The entire image is made up of image points in the same way that the light source is made up of source points. The image formation process is seen as a one-to-one correspondence between each image point and its corresponding source point. In summary, in the formal diagram the following three ideas about image formation are applied:

- From each point source light travels outward in all directions (point source idea).
- An extended light source can be considered as a sequence of source points (extended source idea).
- In the image formation process light spreading out from each point on the source passes through the converging lens and comes together at a unique point called the image point (image idea).

The unit on Light and Color was specifically designed to help students develop the three major ideas listed above (in addition to other ideas not discussed here). The hands-on apparatus consists of both point sources and extended sources. Students use MiniMaglites® for point sources and standard light bulbs in sockets for extended sources. The computer simulators provide representations of each of these sources.

To help students develop the *point source idea*, the activity document instructs students to hold the maglite point source in front of a screen and to note that the screen is fully illuminated. This suggests that light from the source must have traveled outwards in many directions. To help students think of this, we designed a special tool to represent this idea explicitly. It is called the spray of light rays tool. Students click on this tool from a simulator palette and then click on a light source and drag out a light spray. Figure 12 shows a light ray spray in the process of being dragged out from a point source (a) and from a point on an extended source (b). As the cursor

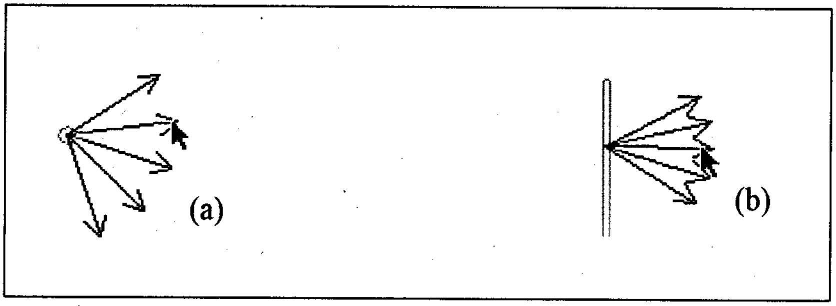


Figure 12. Screen snap shots from one of the light and color simulators. In (a) a light spray is being dragged out from a point source. In (b) a light spray is being dragged out from a point on an extended source.

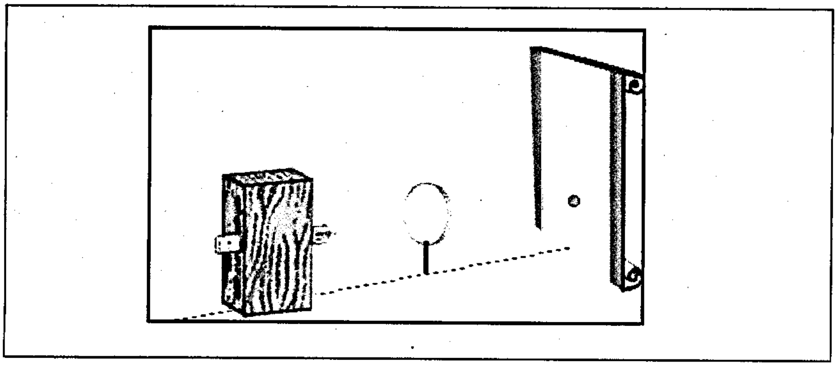


Figure 13. Set-up to study image formation with a point source (maglite tip), converging lens and screen.

is dragged out away from the source, several light rays are formed. The resulting spray of light rays extends out to the radius of the cursor.

There is a mix of two kinds of representation in these diagrams. Rays represent model-like information, while the sources represent physical light bulbs.

To help students develop the image idea, the activity document instructs the students to first perform an experiment with a point source, a lens, and a screen (Figure 13). Following this, they are asked to draw a ray diagram to show how they think light is behaving to form the image on the screen. They then compare their diagrams to the formal light ray diagrams that they construct using the simulator. The simulator not only provides a side view ray diagram, but also provides a view of what would be seen on the front of the screen (Figure 14)

The convergence of the rays onto a single point on the screen is intended to help students develop the idea that rays originating from a single source point create a single image point.

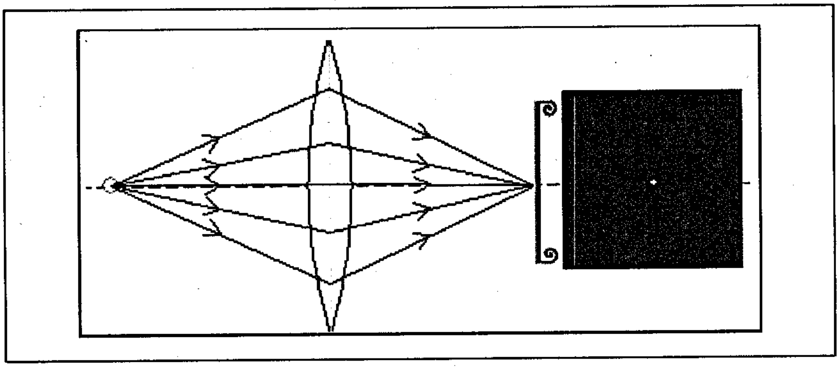


Figure 14. Ray diagram constructed by computer simulator to represent how light spreading out from a point source passes through lens and comes together at an image point on the screen.

To help students develop the *extended source* idea, the activity document instructs students to mount several maglites in a special holder and investigate the image formed with the converging lens (see Figure 15).

Then they work with the computer simulator, varying the number of point sources placed in front of the lens and using the simulator to construct ray diagrams. For example, with nine point sources, the simulator picture looks like Figure 16.

We expect that students could then imagine that as the number of point sources increases even more, the individual sources would approach a continuous extended source, and the image would approach a continuous extended image. To help students make that connection, the activity documents ask students to consider a set-up with an extended light source, similar to the one shown in Figure 9. Students draw a ray diagram and then compare it with one constructed by the computer simulator (Figure

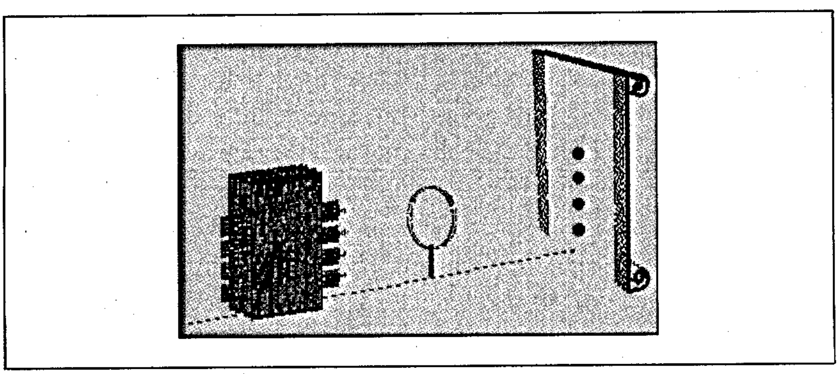


Figure 15. Set-up with four maglite point sources mounted vertically above one another, a converging lens and a screen. The four point images correspond to the four point sources.

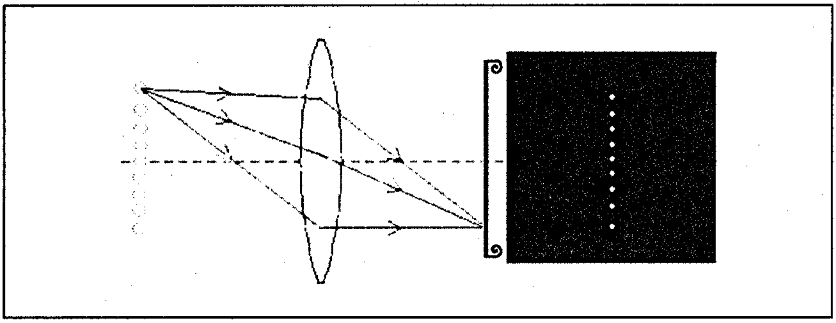


Figure 16. Snap shot picture from computer simulator, showing ray diagram corresponding to nine point sources placed in front of a converging lens. The screen view shows the position of nine point images on the screen.

11 above). Finally, to help students see explicitly that each image point on the upside-down image corresponds to one point on the source, the simulator allows the student to click and drag the origin of the light spray from one end of the source to the other end. As this happens, the student can see the corresponding image points being mapped out (see Figure 17).

To assess the extent to which students could apply the three main ideas discussed above in a new context, we developed the following question that was included in the exam that the students took at the end of the Light and Color Unit.

> A set-up consists of a light bulb, concave mirror and screen. A sharp upside-down image of the bulb can be seen on the screen. What, if anything, would change if a card was used to cover the lower half of the concave mirror?

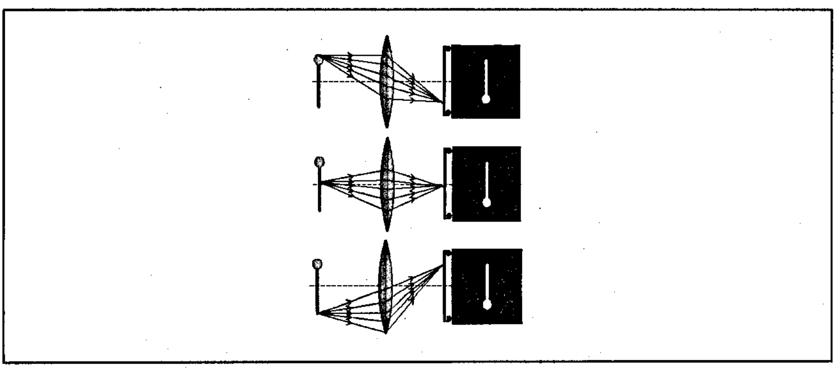


Figure 17. Three screen shots from the lens simulator, showing a spray of light rays leaving three different points on the source. As the spray is dragged downward along the source, the corresponding image point moves upwards on the screen.

This question dealt with image formation by a concave mirror, rather than with a converging lens. The relevant ideas, however, are similar to those mentioned above for lenses, except that in describing the *image idea* with curved mirrors one thinks of light reflecting from the mirror rather than passing through the lens. If one actually performed the experiment mentioned in the problem, one would find that the entire image remains but it would be dimmer than before. Figure 18 shows an appropriate ray diagram. Light spreading out from each point on the source can still reflect from the upper half of the curved mirror and then come together at the corresponding image point on the screen. However, because the card is blocking about half of the total light coming from the source from reaching the mirror, less light reflects from the mirror to form the image, and hence it is dimmer. To make the appropriate prediction, and to draw an appropriate ray diagram, one has to make use of the point source idea, the extended source idea, and the image idea (for curved mirrors).

There were 91 students from three sections taught by three different instructors who took the exam in the Spring 1999 semester. The results were as follows:

- 46 percent gave the correct prediction and supported it with a complete explanation and a complete diagram similar to that shown in Figure 18.
- 24 percent gave the correct prediction, and provided either a partial explanation or a partial diagram (e.g., wrong placement or size of image on screen, but diagram had most of the expected features).
- 30 percent gave an incorrect prediction.

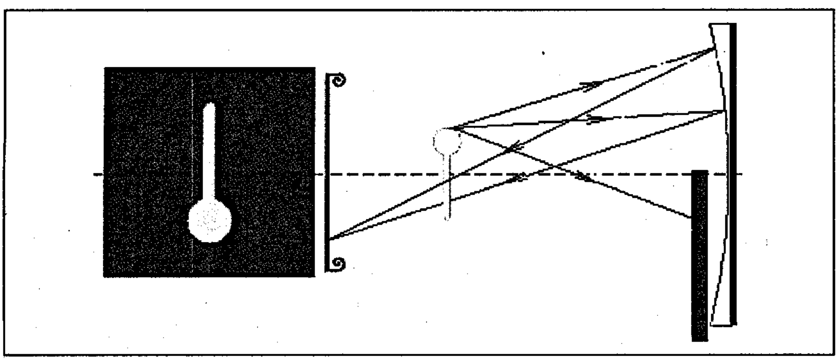


Figure 18. Ray diagram to show that even with half of a concave mirror covered with a card, an entire upside down image of an extended source is formed on the screen. It is only dimmer than it would be if the entire mirror were available.

Previous research has shown that students who study optics in a conventional course typically have a great deal of difficulty with questions similar to the one posed above (Goldberg & McDermott, 1986; Goldberg & McDermott, 1987). The fact that 70 percent of the prospective elementary teachers were reasonably successful in answering this question suggests that the CPU activities and software played a significant role in helping these students develop the appropriate ideas.

Discussion and Summary

In this paper we have suggested several different roles that the computer can play to facilitate knowledge construction in a collaborative environment. First, students can use the computer screen and computer documents as a shared representational space that provides a setting for fruitful collaboration. Within a shared representational space, students are able to share in the construction, evaluation, and extension of their ideas as a group. The computer has other logistical advantages such as its provision of an easily edited public space. Computer documents can easily and cleanly provide a large series of scenarios and spaces for responses. These responses are efficiently recorded both electronically and in hard copies. Using other forms of representational media such as white boards, chalkboards, or paper for collaborative efforts would be less practical, especially for large numbers of entries and records over long periods of time.

A second way that the computer can facilitate knowledge construction is for students to use the computer simulator results as concept evidence to assist in the formulation and development of their own explanatory models. Students tend to treat this type of information more like phenomenological evidence than like "the right answer" or dictums from authority because they actually perform computer experiments in order to obtain it. They therefore use concept evidence to *develop* their conceptual models rather than to *replace* them. The process of making a concept prediction, performing a computer experiment, and obtaining concept evidence can transform the task of model building by providing conceptual tools as well as phenomenological tools. In addition to computer simulations, there may be other forms of representations used in science instruction that can be thought of as concept evidence. We would like to continue to investigate how certain types of representations are perceived by students and what aspects of representations themselves, or the ways in which representations are used, contribute to students' sense-making activity.

A third way the computer plays a role in fostering knowledge construction depends on the computer-based instructional design. Using the unit on light and color as an example, we have shown how computer simulators can be used within a pedagogical structure to accomplish specific content goals such as students' development of the concept of image formation. In our discussion involving the unit on static electricity and magnetism we have shown how these science content goals can be accomplished in a broader framework of a learning community focused on model development. Understanding the nature of science as a process and community of practice is an equally valuable learning objective as the learning of specific content. We believe that pedagogical strategies should take advantage of tools, both phenomenological and conceptual, that can help students learn important *concepts* in science as well as the *process* of scientific investigation.

The Physics Education Research Group at San Diego State University continues to study the *process* of knowledge construction in collaborative learning environments. Future teachers will ultimately find computers in their own classrooms. We feel that it is important to provide these teachers with experience using the computer and an understanding of ways in which the computer can influence the pedagogy. Additionally, more and more K–12 inservice teachers are incorporating collaborative learning methods in addition to computers into their classroom structure. It is important to understand what features of these environments are playing a role in the actual learning that goes on in the classroom. We continue to look closely at the influences that the computer and other classroom structures have on the process of learning so that we can better understand and extend the usefulness of computers and pedagogical structures in the science classroom.

Authors' Note

The work described in this paper was supported in part by the National Science Foundation grant #ESI-9454341.

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Endnotes

1. For more information about the CPU Project and software distribution please see *http://cpuproject.sdsu.edu/CPU/.*
2. When students begin the unit, some are comfortable with terms such as "electron" while others have reported that they are intimidated by such terms. We have found that when students are forced to use terms with which they are not comfortable, they are often inhibited from making conceptual progress.
3. The term "victims" is used in the Static Electricity and Magnetism Unit to refer to objects that were placed in the test stand and tested by bringing other objects, "agents," nearby to test for attraction or repulsion.
4. The group's current model, depicted in figure 2, was motivated by observations that the magnetized nail was "two ended," that is, its two ends behaved differently when another magnetized object was brought near; one end was attracted and the other was repelled.