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ABSTRACT

This paper describes a curriculum unit developed in the domain of geometrical optics which has been incorporated into an activity-based physics course for prospective elementary teachers. The instructional goal was to help students develop a set of powerful ideas that could be applied both verbally and diagrammatically to account for optical phenomena encountered in daily experience. Students engage in extensive talking, writing, and thinking about the phenomena. Two separate sections summarize research on student understanding of geometrical optics and briefly describe the view of the learner that guided the curriculum development. Following this, a section describes the set of powerful ideas that comprises the conceptual model for geometrical optics developed during the unit and how an interactive multimedia program is used. Finally, an evaluation of the effectiveness of the unit is discussed. Contains 28 references. (MKR)

Intermediate States and Powerful Ideas: Learning about Image Formation

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Intermediate States and Powerful Ideas: Learning about Image Formation

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Introduction

During the past fifteen years there has been significant research documenting the difficulties secondary and tertiary physics students have learning geometrical optics.[1-7] In addition there has emerged from research a view of learning that suggests new approaches to helping students develop a robust conceptual understanding of science.[8-11] In this paper we will describe a curriculum unit that we have developed in the domain of geometrical optics that builds on this research base. The unit has been incorporated into an activity-based physics course for prospective elementary teachers. Our instructional goal was to help *students develop* a set of powerful ideas that they could easily apply both verbally and diagramatically to account for optical phenomena encountered in daily experience. To achieve this goal we engaged students in extensive talking, writing and thinking about the phenomena. The challenge was to have students participate in the practice of science and build conceptual knowledge about geometrical optics in a way that would make sense to them. Although we did not focus on the quantitative aspects of geometrical optics in our unit, we believe that the qualitative ideas developed by the students would provide a strong base for enhancing later quantitative understanding.

In the following sections we will summarize the research on student understanding of geometrical optics and briefly describe the view of the learner that guided our curriculum development. Then we will describe a set of powerful ideas that comprises the conceptual model for geometrical optics that we develop during the unit, and how we use an interactive multimedia program that we designed to help promote student learning of those ideas. In that discussion we will also mention how we make use of *intermediate states* of learning to help students develop some of the powerful ideas that research suggests are problematic. Finally, we will briefly discuss how we have evaluated the effectiveness of the unit itself.

Research on student learning of geometrical optics

As a prelude to developing the optics unit, we collected extensive information about students' understanding of geometrical optics both prior to and following "traditional" instruction. In particular, we focused on students' understanding of the image formation process, since this lies at the heart of geometrical optics phenomena. The students included those enrolled in traditional calculus-based and algebra-based introductory physics courses[1,2] as well as those enrolled in courses designed for prospective elementary teachers.[5,6] All of the students in the studies were interviewed individually using simple optical apparatus. Students' verbal and diagrammatic responses to the posed questions enabled the researchers to infer common ways that they seemed to conceptualize the image formation process. Although many of the students successfully solved conventional quantitative problems in geometrical optics (as reflected in exam scores and course grades), many seemed to lack a robust conceptual model of the domain that could guide their thinking about qualitative questions.

Figure 1 presents an overview of some of the results of this research.[12] Figure 1(a) provides a summary of main ideas that seem to characterize the thinking of pre-instruction students and post-instruction students in the study. Also included is a summary of pertinent formal knowledge of an expert. Figure 1(b) shows representative diagrams from each of these three groups. We found that we could describe much of the post-instruction students' knowledge as a hybrid combination of the common knowledge of both the pre-instruction student and the expert. For example, pre-instruction students tended to conceptualize the image formation process *holistically*; that is, they seemed to think of the situation as if a "potential image" travels in its entirety from the object, to the optical apparatus and to the place of observation. Furthermore, they always associated the place of observation with a surface. An expert, on the other hand, conceptualizes the image formation process as a special kind of point-to-point mapping: a flux of light diverging from each object point is mapped to a corresponding image point, which may or may not be located at a surface. Many of the post-instruction students who experienced difficulties during the research interviews seemed to have a hybrid conceptualization of image formation. A main feature of this hybridization is that students who might recognize that a flux of light diverges from an object point still seem to consider light traveling in only one particular *relevant* direction as necessary to form the corresponding image point. These students, then, typically draw just a single light ray going from an object point to its corresponding image point. In other words, their understanding of image formation includes the idea of the one-to-one mapping of object point and image point, but does not include the additional idea that this mapping occurs by diverging and converging fluxes of light. (The diverging-converging flux mapping holds for *real* images; in the case of *virtual* images, the mapping is from one diverging flux to another diverging flux of light.) Below, we describe how we take this partial knowledge explicitly into effect in our curriculum design. In another paper we provide a more detailed discussion about the comparative knowledge of pre-instruction and post-instruction students and experts.[5]

The optics unit

Recent research on student learning of science emphasizes the importance of creating a science learning environment where students can develop robust ideas that make sense to them through experimentation, discussion and reasoning, rather than have all the ideas put forth by the instructor, text or some other authority. This type of environment recognizes that students come to new learning situations with their own ideas or prior knowledge, and that these ideas will influence how and what students learn. The process of learning requires students to modify old ideas, develop new ones, and organize all of them in a coherent and useful way. Interactive strategies play a key role in this process, including both personal experience with phenomena and social interaction.[8] In this section we first describe the ideas that we aim for students to develop during the unit, and then describe some of the active learning and instructional strategies that facilitate the process.

Powerful Ideas

To promote the development of a qualitative understanding of image formation, we divided the content of the unit into a set of eight main ideas that we referred to as *powerful ideas*. They are listed in Figure 2. Collectively, these ideas, along with a set of diagram construction and interpretation rules, comprise a conceptual model that students could use to guide their thinking about optical phenomena. The scope and content of these specific ideas emerged from our analysis of both students' and experts' understanding of geometrical optics phenomena (summarized in Figure 1).

Some of the ideas in the list were part of the common knowledge of both our post-instruction students and experts. We assumed these ideas would be more easily developed by students during instruction than ideas that are part of the expert's knowledge but are often lacking in the post-instruction students' knowledge. Our instructional strategy would then aim at helping students build on these "easily developed" ideas as a pathway to their developing the more "problematic" ideas. For example, the *reproduction of a source* idea in Figure 2 is a specific formulation of the one-to-one mapping of object point and image point idea that seems to represent an intuitive belief of students (perhaps related to their pre-instruction holistic ideas). The *real image* idea, as formulated in Figure 2, emphasizes the diverging and converging aspects of the behavior of the light *in addition to* the one-to-one mapping idea. In our current instructional sequence, we first have students develop and consider the consequences of the *reproduction of a source* idea, and then explicitly have them consider the differences between that idea and the *real image* idea. This instructional decision recognizes that in leading students to a formal understanding of certain (complex) ideas it might be fruitful to guide them first through intuitively-supported *intermediate states* of knowledge. In the case described here, the *reproduction of a source* idea was seen as a useful intermediate state of knowledge along the way to developing the more complex *real image* idea. Others have used a similar approach to help students develop an understanding of some difficult ideas in mechanics [13-15]

The complete list of ideas in Figure 2 was intended to be robust and valid; that is, students would be able to apply these ideas to account for a wide range of optical phenomena and to make qualitative but reasonably accurate predictions about the behavior of simple optical systems. We also had some criteria in mind in deciding the specific formulation of these powerful ideas. First, we wanted each idea to be represented both verbally and diagramatically. Diagrams are powerful tools for guiding understanding and we wanted students to be able to switch easily between the verbal and diagrammatic representations. Second, we intended for students to construct in their own words an equivalent formulation of each idea through classroom activities. The sequence of ideas listed in Figure 2 corresponds to the sequence in which they were developed in class. Third, we chose a formulation of these ideas which would not only make sense to students in terms of language, but would also be relatively easy to apply in practice. Thus, most of the ideas are stated in a qualitative (and in some cases, approximate) form. A fuller discussion of each of the powerful ideas listed in Figure 2 is provided elsewhere.[16]

The *Learning about Light* Multimedia Programs

In our class we have developed a careful sequence of activities that provides the opportunity for students to both develop and apply the powerful ideas. The ideas are developed with the help of specially designed computer programs, guided laboratory experiences and instructor-led demonstrations and discussions. To help students apply the ideas we engage them in open-ended design-type laboratory experiences and extensive assignments in which they write comprehensive explanations of novel phenomena and carry out collaborative peer evaluations of those explanations. Below we discuss the computer programs in detail. The other components of the course are described elsewhere.[17]

The entire optics unit lasts for seven periods, each two hours and twenty minutes in duration. Each section of the class meets twice weekly and has a maximum enrollment of 30 students. We conduct the course in two adjacent rooms with a connecting door. One room is a wet lab where whole class discussions and many of the lab experiments take place. The connecting room is our computer facility, where students work in groups of two or three at each workstation using our special computer programs. They also perform simple experiments on the tables along side the computers.

Learning about Light, is a set of seven multimedia programs.[18] The titles of the programs are: ***Light and Illumination, Shadows, Pinholes, Reflection and Refraction, Converging Lenses, Looking Into Plane Mirrors,***

and *Looking Through Transparent Materials.* Table I briefly summarizes the content of each of the seven programs. The cornerstone of each program is a set of task questions specifically designed to elicit and challenge students' initial ideas. On the computer monitor students see pictures of optics apparatus and phenomena, and use a mouse-controlled cursor to construct the appropriate ray diagram directly on top of the pictures of the apparatus.

Each program begins with a menu screen that lists the sections of the program. Figure 3 shows the Menu screen for the *Pinholes* program. Most section names are in the form of questions, and these represent the initial Ponder questions asked students when working through that section. Sections with declarative titles usually contain both explanatory segments containing animation and audio as well as Ponder questions. Ponder questions prompt learners to consider certain key issues. Generally, when responding to a Ponder question students start with their own ideas and construct their own diagrams to guide their thinking and to support their reasoning, then discussion among the students working together ensues. Many of these questions were the same ones that were used in our previous research to investigate students' conceptual difficulties in understanding geometrical optics.[1,2,5,6] Figure 4 is a graphic representation of the Ponder question that students are asked to consider when working through the first section of the *Pinholes* program, before there is class discussion of this phenomenon.

Many of the Ponder questions ask students to make a prediction about some change in the optical set-up (like the one shown in Figure 4). After they discuss their own ideas and draw a diagram they are shown the actual task outcome on the computer screen. The outcome of some of the Ponder questions are a surprise to the students. (Indeed, many of the tasks were chosen so this would be likely.) In trying to make sense of what they observe they begin modifying their ideas. Sometimes, the student group comes up with a new idea that is closely aligned to a powerful idea.

To give an example of students modifying their ideas we present the transcript of a conversation between two students who are pondering the first pinhole task illustrated in Figure 4. This discussion took place on the third day of the unit on geomtrical optics. Prior to this the students had perfomed experiments involving the observation of light bulbs illuminating a screen and the formation of simple and complex shadows. The powerful ideas *Light Emission from a Source* and *Traveling in Straight Lines* had already been developed in class. In the transcript below we refer to the students as L and R, and their comments are printed in standard text. We have included descriptive information *in italics* to help the reader understand what is happening, and we have also added some interpretive commentary, which appears as indented text.

At the beginning of the task the narrator shows a bulb and a translucent screen, both mounted on a track. In the upper right is a view of what can be seen on the screen (full illumination). He then pokes a hole in a sheet of foil, producing a pinhole. He then poses the question: if the pinhole was placed between the bulb and screen, what would be seen on the screen? The following Ponder appears on the screen.

PONDER

What will be seen on the screen if the pinhole is placed between the bulb and screen? Consider the powerful ideas: *"Light Emission from a Source"*, and *"Traveling in Straight Lines"*.

R: "A pin hole of light? ..... O.K.*(reading the Ponder question from the screen)* What will be seen on the screen if the pinhole is placed between the bulb and the screen? In thinking about this situation consider the powerful ideas, Light Emission from a Source, and Traveling in Straight Lines. Hmmmm..."

L: "I think, that the light is going to be blocked from everywhere but this hole, right?" *(Points to hole.)*

R: "Right."

L: "and it is going to continue through the hole in a straight line. However, it's not just going to be coming from one point. Light is going to be hitting that hole from all over the place." *(She moves her finger from several different points on the bulb toward the hole.)*

> Here L is suggesting that light is going to travel towards the hole from all points on the bulb.

R: "Oh, Yeah."

L: "Do you know what I mean?"

R: "Umhmm."

L: "and going into that hole, and going through that hole. Now, will that hole act as a filter *(points toward hole)*, and then from that one point in the hole will light go in all the directions *(moves finger from hole to the right , first upwards and then downwards)* do you think?"

R: "I think so.."

L: "Or do you think it will go in one little tiny hole? *(Moves finger from the hole toward the right, horizontally.)*

R: "I think it'll..."

L: "I think it'll go in all directions (unintelligible)"

R: Illuminate not quite as.....wide as that. *(L uses finger to outline a circle of light on the upper right screen, a little less as wide as the present illumination on the translucent screen.)* Maybe just small illumination in the center? *(R points towards the center of the translucent screen in the upper right.)*

> At this point R seems to have considered two possiblities: a moderately large circle of light on the screen, or a small spot of light in the center of the screen. It is not clear whether L actually heard R's second idea about the small spot of illumination because she immediately restates her idea of the larger circle.

L: "I think so cause it goes,"

R: "O.K."

L: "uhh, I think it'll go in all directions still." *(She again moves her finger from the hole upward and downward to the right.)*

R: "O.K., draw a diagram"

(L now grabs the mouse which is located to the right of the keyboard.)

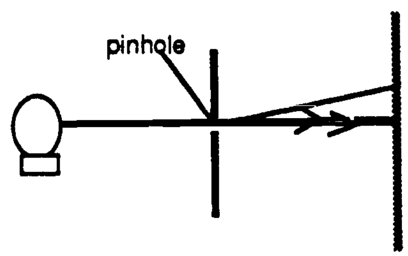
L: "So are we supposed to draw it from here to here *(pointing with finger from middle of bulb to pinhole)*, then from here to here *(pointing from pinhole to upper part of screen, then moving finger down somewhat to lower part of screen)* and then to the screen?"

R: "From the light bulb through the pinhole to the screen." *(Points from middle of bulb to pinhole, then to middle of screen.)*

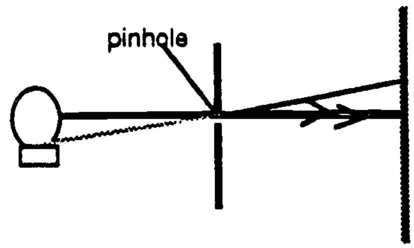
L: "We know one will go like this, for sure, right? *(Draws first ray horizontally from middle of bulb through pinhole to screen.)*

R: "Uh huh, straight."

L: *(laughs)* "Lightening bolts." *(She is referring to the line which is drawn almost horizontal ly, and therefore has some steps in it. Both laugh.)* And then *(she draws a second light ray essentially right on top of the first)*. Now do we think the line is going to go like this?" *(She draws light ray going from pinhole upward and to the right, striking the screen, as shown below)*



R: " Yeah, (but) you have to originate from the light source though." *(She moves her finger from the pinhole to the left and down, back to the bottom of the bulb., along the dashed line in the following figure.)*



L: "You can't cause it only goes in straight lines. See what I'm saying?"

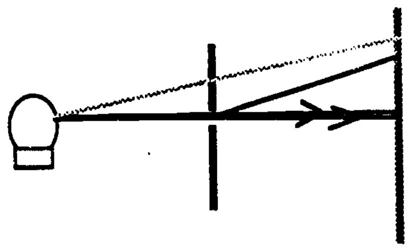
L may be interpreting the *Traveling in Straight Lines* idea as suggesting that light travels in the horizontal direction only.

R: "If it starts .... *(pointing to bottom of bulb)*"

L: "You can't. You can't draw it. If I draw it ..."

R: "Ohhh..."

L: " ... through the pinhole, I can't go up, or it goes out of the pinhole." *(She uses mouse and extends ray from middle of bulb, above pinhole, to the screen. This is illustrated in with the dashed line in the following figure. However, she then returns the cursor to the bulb without actually drawing this ray.)*



R: "Oh, Oh Oh Oh Oh."

L: "See what I am saying? See what I am saying?"

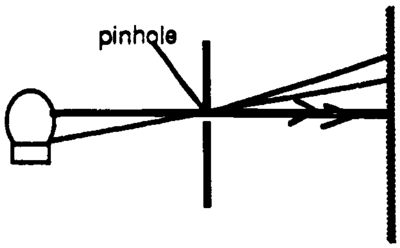
R: "Yeah."

L: "So, do we think it is going to go like that?"

R: "I don't know, let me try. What if I came from down here?" *(R takes over mouse and moves cursor to the bottom of the bulb. She starts to draw ray from bottom of bulb up toward the pinhole.)*

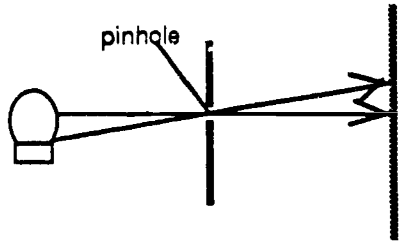
L: "Well it's still going to hit this hole. *(She points to pinhole. R continues drawing the light ray through the pinhole and to the upper part of the screen.)* Hey, you're right!" *(L then faces R, aims a finger at her, smiles, and then says:)* Good!

L seems to be indicating that she realizes that R is right.



(R begins to draw another ray.) Erase mine. Wait, we can start all over. *(L takes mouse from R.)* Erase all. *(She moves the mouse cursor up to the menu bar at the top of the screen and chooses the "Erase all" option, which clears the screen of the rays previously drawn.)*

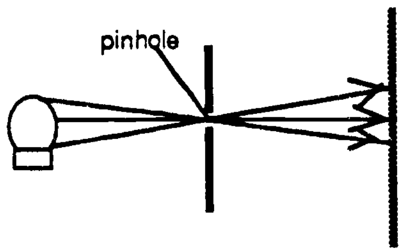
R: O.K. so we'll do one straight.....straight through...*(she draws one ray from middle of bulb, horizontally through pinhole and then to screen)* and then one from here *(she draws a second ray from bottom of the bulb upward through pinhole to top of screen)*."



L: *(R moves cursor to top of bulb, about to draw a third ray.)* "So it will be limited, but it will be more than just one hole. Like a bigger hole.

> L seems to be using the diagram to guide her prediction for what she thinks will appear on the screen. She suggests it will be a circle of light, bigger than the pinhole, but smaller than the illumination on the screen now ("it will be limited.").

(R then completes her drawing of the third ray.)



R: "O.K., you agree?"

L: "Yep, I agree."

(R clicks on the Continue button. The narrator now shows what happens: with the pinhole between the bulb and screen you can see on the screen an upside down reproduction of the bulb.)

R: "Oh, my God."

L: "Can you believe it?"

R: "No." *(She reads the new Ponder on the screen.)*

PONDER

Why does the screen show a reproduction of the bulb? You may want to erase your previous diagram and radraw it to account for what is actually observed on the screen.

"Why does the screen show a reproduction of the bulb? You may want to erase your previous diagram and redraw it to account for what is ...."

L: "Ah! I know why."

R: " ..... *(continues to read Ponder)* actually observed on the screen."

L: "I think I know why."

R: "Why?"

L: "We did, O.K., look here, we did it from here and here, right?" *(She uses her left forefinger and points to the top of the bulb and uses her right forefinger and points to the bottom of the bulb. Then she slides both fingers along the monitor screen so they cross at the pinhole and then continues to the side view of the translucent screen. She is tracing over the two light rays previously drawn by R.)*

> At this point L uses a significant amount of gesturing to explain her thinking about what is happening.

R: "Yeah.."

L: "Like in the angle..It's essentially ... we didn't do it from the sides (of the bulb), it's essentially redefining, shaping the bulb *(she now uses her two fingers and traces out the shape of the upside down bulb on the upper right view),* don't you think? Like we took (light) from here *(pointing toward bottom of actual bulb)* and this from here is that light from right here *(pointing to the corresponding part of the reproduction of the bulb on the screen in the upper right).* And then this....do you know what I am saying? And then it is going to be from all of the sides, from every point *(pointing to many points on the actual bulb).* Do you know what I mean?"

R: "Wait.....What is this? *(R points to the reproduction pattern of the bulb on the screen.)* This is on the screen?"

L: "Yes. *(She moves her finger around the reproduction)* The upside down bulb. Yes"

R: "This? On this here?"*(pointing to the side view of the screen)*

L: "Yes. O.K., here we have the bottom.."

R: "Ahhhhhh....."

R gives off a loud and extended sigh, suggesting she has understood something that had been troublesome for her. Apparently, she seemed to have had some difficulty understanding that the view on the screen was a two dimensional representation of basically a three dimensional phenomenon. L helped clarify this for her.

L: "See, here we have the bottom *(points with her left forefinger to the bulb).* So the light, *(switches to her right hand)* all this light, the light from this whole surface right here *(she cups her right hand and moves it around supposedly tracing out the curved surface of the bulb facing the pinhole)* is going through at different angles (moving her fingers along monitor going through the pinhole)..."

R: ".... and reversing."

L: "(Moving her two forefingers up to the bulb reproduction) Yeah, like reversing, *(tracing out the shape of the bulb reproduction)* but drawing essentially an image. Know what I mean, drawing it with the light? .... Do you understand what I am saying?"

R: "Yeah."

L: "Do you think?"

R: "We can't do that though. We can't draw it, it's three dimensional." .

L: "Yeah, but we could have just said it."

R: "Oh."

L: "You know what I mean?

R: "I would never have guessed."

L: "I would never had, but I think that it kind of makes sense that that would be it *(moves finger along ray leaving bottom of bulb)*, do you know what I mean? *(R nods affirmatively.)* Because,..., it's funny how this came all the way up here *(moves finger along ray leaving bottom of bulb to top of screen, then traces ray from top of bulb to bottom of bulb, then goes up to reprocuction and does a quick movement with her finger tracing around the shape of the bulb.)* Uh, mmm.

L puts her hands behind her head and gives off a sigh suggesting that she feels she understands what is happening and feels comfortable about that.

R: "Right" *(Points toward reproduction).* Look how bright it is in the center.

L: "Yep. *(Inaudible comment.)*

R: *(She reads from the Ponder which suggests they might want to erase their diagram after seeing what actually happens in the demonstration.)* "Do you want to erase your previous diagram? Not really, I think we understand it."

In her explanation of what she thinks is happening ("Like in the angle... it's essentially redefining, shaping the bulb") L has essentially invented in her own words the one-to-one mapping idea which leads to the next powerful idea to be discussed in class, the *Reproduction of a Source* idea. See Figure 2.

After students respond to prediction-type tasks, like the pinhole task discussed above, they can receive multiple forms of feedback. They are always shown (with either graphics or video annimation) the outcome of the task. In some cases the computer provides additional diagrammatic and verbal feedback. However, the programs do not analyze the students' diagrams. Instead, the students are shown an "expert" diagram and asked to carefully compare that diagram with the one that they had drawn themselves. Additional commentary is provided which calls the students' attention to various features of the diagram. The choice of which features to highlight and discuss was guided by previous research on student learning in optics.[1,2,5,6] Sometimes the diagrammatic feedback is accompanied by animated graphics and audio.

The sequencing of the computer tasks guides students to develop for themselves many of the powerful ideas. The remaining ones emerge during hands-on experiments and instructor-led demonstrations and discussions. The ideas in Figure 2 are incorporated into a drop-down menu at the top of the computer screen. Each idea is available for student perusal and review only *after* they have completed the portion of the optics unit in which the idea is developed.

Some of the Ponder questions are explicitly intended to help students differentiate between two ideas that to them seem closely related. For example, Figure 5 shows a graphic of a set-up from the next-to-last section of the *Converging Lens* program. The aim of that section was to have students compare and contrast the behavior of pinhole and converging lens systems as a means of addressing the explicit differences between the *reproduction of a source* idea and the *real image* idea. This was part of our instructional strategy, described earlier, in which we wanted students to use their understanding of the *reproduction of a source* idea to develop an understanding of the more complex *real image* idea. The holder shown in Figure 5, mounted on the optical bench between the bulb and screen, has a pinhole in the top and a converging lens in the bottom. On the screen (displayed in the upper right) appears two inverted reproductions of the bulb, the upper one from the pinhole and the lower one from the lens. Students are asked to discuss and draw diagrams to account for what would be seen on the screen if it were first moved closer to the pinhole/lens apparatus, then farther from it. (As the screen is moved the pinhole reproduction changes size, but remains sharp. The lens reproduction, however, becomes blurry and unrecognizable.) In the following section of the program the Ponder question asks what an observer situated to the far right of the screen would see if the screen was removed. (In this case the pinhole reproduction would disappear and only a dot of light would be seen through the pinhole. With the converging lens, however, there would still be an image that would be seen in the air at the same location where the screen had been.)

We believe the social interaction that occurs when students work through the Ponder questions in groups of twos and threes is crucial for their construction of meaningful new knowledge.[11] The interaction provides the opportunity for students to make their own ideas explicit, to have them critiqued by their peers, and to consider alternative ideas. The ray diagrams that they draw on the screen on top of the pictures of the apparatus become vehicles for promoting communication between the students. The students use the diagrammatic tools to construct arguments to help explain their way of thinking.[19] Presenting an argument with the use of the graphic images removes some of the ambiguity of language.[20] Students are often in animated conversation, gesturing with their hands and pointing to the monitor as they discuss their particular ideas. The hand gesturing and the ray diagrams together seem to be important aids in helping students construct and present their verbal explanations of the phenomena.

Occasionally students need help from the instructor. Normally, the process of helping students work out a particular difficulty requires the instructor and student to engage in a substantive dialog so that the instructor can explore the students' thinking and identify the root of the difficulty. This dialog takes time. The fact that students represent their ideas diagramatically on the screen can expedite this exploratory process. An instructor knowledgeable about common learning difficulties can use the students' diagrams to help diagnose their difficulty. The instructor can then point to specific features on the diagram while offering appropriate guidance to the students.

Usually, students also have simple apparatus on the table next to their computers. At appropriate times while working through the programs they are encouraged to repeat demonstrations presented as part of Ponder questions and to explore other phenomena using the actual apparatus. This combination of interacting with the multimedia computer programs, drawing ray diagrams on top of pictures of the apparatus, and manipulating actual apparatus along side the computer, was intended to help students make the important connections between the conceptual ideas, their diagrammatic representations and the corresponding real world phenomena.

Overall our students have reacted very positively to our use of the computer programs. They have commented that they really like the fact that they can express their own ideas and discuss these with their partners without embarrasment or fear of being wrong. Here is a comment that one student wrote in a journal entry:

I feel I gained a lot from the ponder questions in the computer and interacting with Wendy's [her partner's] *ideas. This is such a valuable experience. Not only because we are "self-learning" concepts, but I'm also learning to evoke thoughts & questions with my partner. It's like reaching into 2 minds instead of one!*

Evaluation of Students and the Curriculum Unit

As part of our unit exam on optics we present students with a challenging (novel) task and expect them to spend approximately one hour developing their response. The set-up used for the question we asked during the Spring 1993 term is diagrammed in Figure 6. At first we showed students a bulb, converging lens and screen. The apparatus was arranged so a sharp inverted bulb image could be seen on the screen. Then the screen was removed displaying a 30 cm by 30 cm plane mirror about 30 cm behind the previous screen position. When looking into the mirror from a position to the side of the lens one could observe a mirror reflection of an inverted bulb. The task was for students to write a comprehensive explanation with accompanying diagrams to explain this phenomenon. (A major activity in the course involves students writing explanations, so writing an explanation for an exam was not an unusual assignment.[17]) Students were free to come up and "play" with the apparatus, but they could not converse with each other.

Seven of the eight powerful ideas are needed to construct a complete explanation of the phenomenon shown in Figure 6. The scores reported here were assigned in the following way. One point was awarded for each necessary idea that was *appropriately applied* (not just listed) in the text, and one point was awarded for each necessary powerful idea that was appropriately represented in the accompanying ray diagram. In analyzing the results, the average score for the entire class was 72% (N=30). Considering the complexity of the phenomenon to be explained, and our fairly strict criteria for evaluation, we believe the students did reasonably well.

We have been working on the development of our conceptual approach to teaching geometrical optics for about four years. We have also continually modified the computer programs and each semester have introduced new, or have modified existing, instructional strategies. Prior to our introduction of these strategies we carried out a set of interviews with students from this course to document their understanding. The population was very similar in academic background to the present one. One of the tasks we set for students during these interviews involved a concave mirror and light bulb.[5] Students could observe the inverted image of the bulb (an aerial image without a screen) and were asked to explain the observation, both verbally and diagramatically. We repeated this question two years later, in another set of interviews after our first implementation of the optics computer programs.[21] We also asked a very similar question as a demonstration task on the optics exam we administered in the Fall 1993 semester. In all three cases the concave mirror task was a novel one for the students. Table II shows the diagrammatic results, where we have grouped the data into three general categories for comparison.

During the same set of interviews in which we asked the concave mirror question described above we also asked a question involving a rod and a large plastic 45^0-90^0-45^0 triangular prism.[5] The prism was held with its flat parallel faces horizontal. The rod was held vertically and close to the wide leg of the prism. The students viewed this rod through the opposite apex. What they observed were two images of the rod, displaced to the left and to the right of the original rod (which could still be observed both above and below the prism.) Figures 7(a) and 7(b) show a top view of the set-up and a graphic representation of what the students actually saw. We repeated this question two years later, in another set of interviews after our first implementation of the optics computer programs.[21] We also asked a very similar question as a demonstation task on the optics exam we administered in the Fall 1992 semester. Finally, in Fall 1993 we asked this task as one of the comprehensive explanation assignments. In all cases the prism task was a novel one for the students. Table III shows the general diagrammatic results, where we have grouped the data into three categories for comparison.

Although the data displayed in Tables II and III is limited to only two tasks, the improvement in students' performance over the time frame of our course development efforts provides some evidence of the effectiveness of the approach. The students seemed to be able to reason qualitatively about novel geometrical optics situations using the powerful conceptual model developed in class.[22,23]

Summary

In this paper we briefly analyzed student and expert conceptual knowledge in geometrical optics and then described part of a curriculum unit that we had implemented in a physics course for prospective elementary teachers. We outlined a set of powerful ideas that we aimed for students to develop in the unit and described a multimedia computer program that we believe played an important role in facilitating that development. We provided a detailed example of how one of the ideas was developed by students (*reproduction of a source*), and then described how students would use this particular idea as a bridge to develop a conceptually more difficult idea (*real image*). This strategy took explicitly into account what we referred to as intermediate states of learning, a strategy used successfully by others. Finally, we provided some evidence to show the growth in students' conceptual understanding over the four year period during which we had introduced our new instructional strategies.

Acknowledgments

During the development of this optics unit we were fortunate to receive many helpful comments from Igal Galili, who had also participated extensively in our initial research. The work described here was supported in part by the National Science Foundation under grants MDR-8751901 and TPE-9053803.

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22. The *Learning about Light* computer programs have been developed in both Macintosh and Windows versions. For more information about the programs write to one of the authors (FG).

28. Our particular approach to promoting conceptual understanding through the development of powerful ideas does not require the high technology computer programs. We have implemented a "low tech" version of this approach as part of the NSF-supported PSI-PET project, *Physical Science Education for Preservice Elementary Teachers.* In developing a curriculum unit for that project we integrated material on color and vision with the material on geometrical optics. The resulting *Light and Color* unit is one of several that have been developed for use in a model one semester physics course called *Powerful Ideas in Physical Science.* For more information about the model course contact: Jack Hehn, American Association of Physics Teachers, One Physics Ellipse, College Park, MD 20740-3845, 301-209-3300, aapt@aip.org.

1.1

Table I: Summary of Computer Programs

Program	Tasks	General Description
Light and Illumination	*How does light leave a source?* *How does light illuminate a screen?*	The light emission from a source and traveling in straight lines ideas are developed by students while pondering how light must leave a point on a source if several observers are to see the point at once. Students then apply these ideas to account for how light from a source produces full illumination on a screen. All of the tasks in subsequent programs require the use of these ideas.
Shadows	*What causes a shadow?* *How does the shadow change if the bulb is moved? The object is moved? There are two bulbs? The two bulbs are moved apart?*	Students are shown a point light source, a card and a screen. When the source is turned on, light is blocked by the card and a shadow is seen on the screen. Following several Ponder questions involving this simple apparatus, the students are next asked questions involving two point sources.
Pinholes	*What can a pinhole do?* *Explaining a pinhole** *What happens if the screen is moved toward the pinhole? Away from pinhole? Removed? The pinhole is made larger?*	In the first task students develop the *reproduction of a Source* idea. The remaining tasks provide opportunities for students to apply the *reproduction* idea to new situations.
Reflection and Refraction	*Converging light by reflection* *Regular and diffuse reflection** *What is a translucent screen?** *What happens when light travels through a solid block of material?* *Converging light by refraction*	Prior to the beginning of this program, two powerful ideas are developed in class: *reflection of light* and *refraction*. In each task in the program students must apply these ideas. A concave mirror is modeled by a series of plane mirrors. A converging lens is modeled using a series of prisms. (The term "lens" however is not introduced until the next program.) Reflection and transmission of light by a translucent screen is considered.

Converging Lenses	*How does a lens form an image?* *The formation of a real image* * *How a converging lens works** *What happens if: Screen is moved toward the lens? Away from lens? Part of lens is covered?* *How your eye sees an object** *What happens if the screen is removed?* *The purpose of a screen** *How do pinholes and converging lenses compare?*	A light bulb, converging lens and translucent screen are introduced. In one quadrant of the monitor is a screen view with an image of an upside down bulb on it. Students draw a diagram and discuss how the image is formed, making use of several previously developed ideas. Through this endeavor students develop the *real image* idea. Subsequent tasks require the use of these ideas. The latter part of the program discusses how the eye works, aerial images, and the purpose of the screen. The *seeing an object* idea is developed. In the final task students compare the pinhole and lens systems, noting similarities and differences regarding the bulb's reproduction. Since this program is so lengthy, it is used during two periods.
Looking into Plane Mirrors	*How is an image formed with a plane mirror?* *A closer look at the mirror image: drawing the ray diagram** *Comparing a plane mirror and a converging lens*	The *virtual image* powerful idea is developed. The role of the eye in the formation of virtual images is explicitly addressed.
Looking through transparent Materials	*Why does an object appear displaced when under water?* *Accounting for virtual images formed by refraction* *Why does an object appear displaced when partially immersed in water? Viewed through a rotated block? Viewed through a triangular prism?* *When looking through a triangular prism, where do the two images come from?*	Students make use of the powerful ideas *refraction of light* and *virtual image* to predict and account for the tasks. The role of the eye is explicitly addressed.

* Asterisks denote explanatory segments. These segments are usually narrated, animated explanations, and may include Ponder questions embedded in them.

Table II: Concave Mirror (Aerial Image) Diagrammatic Data

	1988 Interviews (N = 25)	1990 Interviews (N = 29)	1993 Exam (N = 29)
Complete representation	8%	41%	52%*
Incomplete representation or minor errors	24%	17%	28%
Major errors	68%	41%	20%

*The students were also expected to include an observer's eye, and to show at least two diverging light rays entering the eye, as part of the complete representation.

Table III: Prism Task Diagrammatic Data

	1988 Interviews (N = 14)	1990 Interviews (N = 28)	1992 Exam (N = 30)	1993 Explanation (N = 29)
Complete representation	7%	32%	27%	55%
Incomplete representation or minor errors	14%	39%	37%	21%
Major errors	79%	29%	34%	24%

Verbal Knowledge about Image Formation

Pre-Instruction Knowledge

1. Presence of light is necessary for image formation and observation, but there is little or no awareness of the role of light in these processes.

2. A "potential image" goes from the object to the optical device, is affected by it in some way, and then the final image appears on a surface.

3. An observer just looks at the image to see it. The observer's eye plays a passive role.

Post-Instruction Hybrid Knowledge

1. Light diverges in all directions from each object point, but only light traveling in one particular direction from each object point will form the corresponding image point.

2. Each light ray emitted from each object point carries with it the structural information about that object point.

3. An optical device bends light rays to create the image.

4. The formation and observation of virtual images occur separately.

5. For an observer to see an image, light from the image must enter the eye.

6. A light ray diagram shows how light rays carry information from each object point to its corresponding image point.

Expert Formal Knowledge

1. An extended object is an assembly of object points; an image is an assembly of image points.

2. Light diverges from each object point in all directions away from the surface of the object.

3. The entire flux of light diverging from each object point and interacting with the optical component contributes to the image point. (We are assuming a unique image point and are ignoring aberration effects.)

4. An optical device redirects the flux of light diverging from an object point into a flux that:

a. converges to a unique point where the real image point is formed; light diverging from the real image point must then enter an observer's eye for the image point to be observed, or

b. diverges from a different unique point; if part of this light flux then enters an observer's eye, the virtual image point will be simultaneously formed and observed.

5. A screen is only a convenience for observing real image points from many different observation points.

6. The image formation process can be represented by a light ray diagram; the light ray is a theoretical tool to represent the direction of light propagation.

Figure 1a. Comparison of verbal knowledge of pre-instruction students, post-instruction students and experts.

Diagrammatic Knowledge about Image Formation

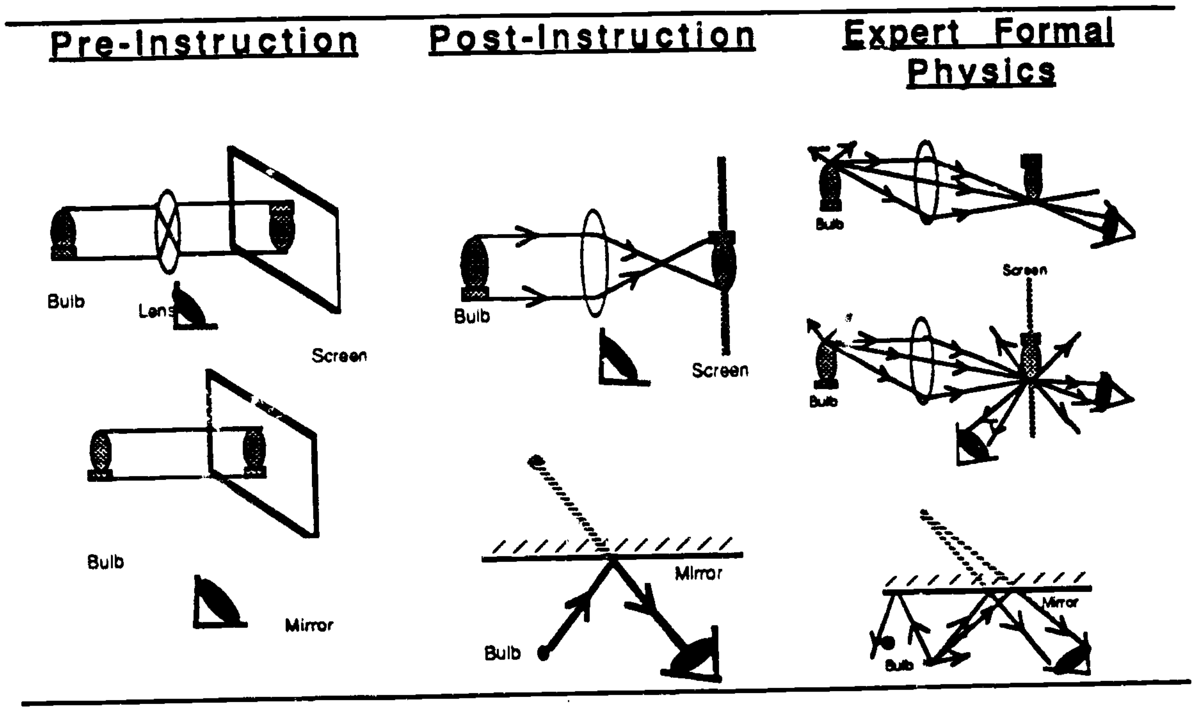
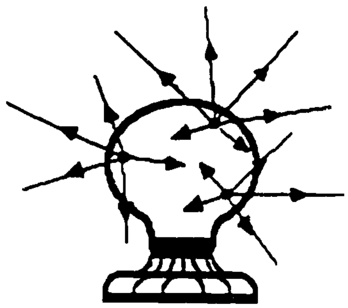


Figure 1b. Comparison of diagrammatic knowledge of pre-instruction students, post-instruction students and experts.

(a) ***Light emission from a source***

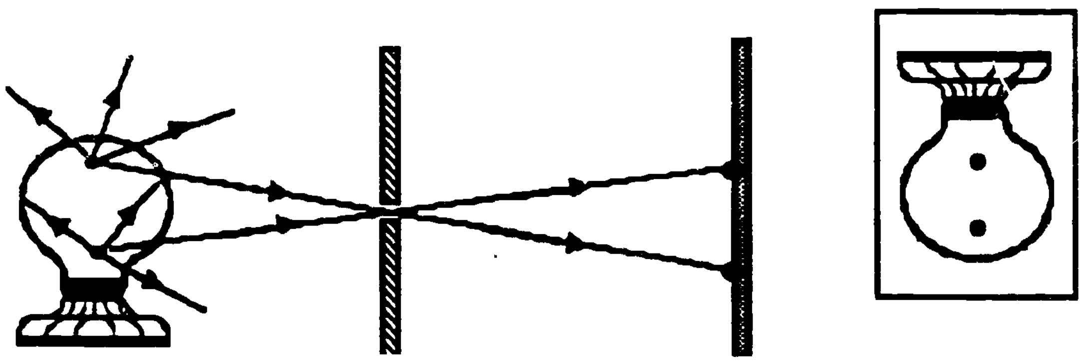


From <u>each</u> point on a source, light travels outward in <u>all</u> directions.

(b) ***Traveling i straight lines***

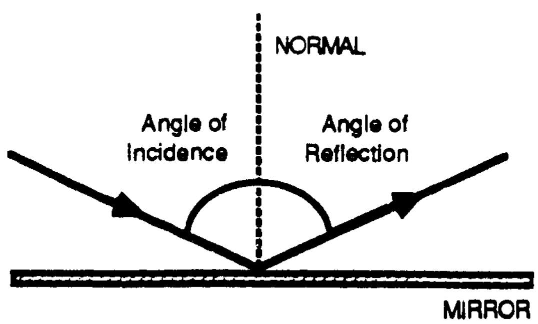
Light travels in straight lines until it strikes a surface.

(c) ***Reproduction of a source***



To produce a pattern of light which is a reproduction of a source, light at <u>each</u> point in the pattern must have originated from <u>only one</u> corresponding point on the source.

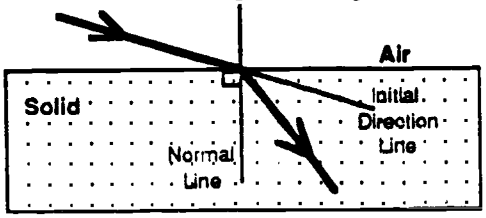
(d) ***Reflection of light***



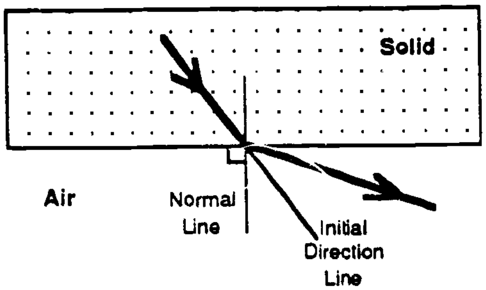
When light reflects from a surface the angle of reflection equals the angle of incidence.

(e) *Refraction of light*

Light changes direction when traveling from one transparent material into another, a process called refraction. In sketching a light ray diagram, we can **approximate** the amount that the light changes direction with the following simple rules:



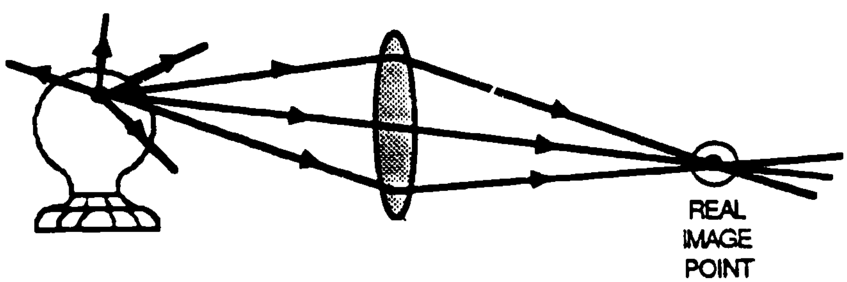
(1) When traveling from air into a solid or liquid material, the light bends toward the normal line. Its new direction is approximately half-way between the initial direction line and the normal line.



(2) When traveling from a solid or liquid material into air, the light bends away from the normal line. Its new direction is approximately as far away from the initial direction line as the initial direction line is from the normal line. (If application of this second rule suggests the light will not travel out into the air, then the light will be totally reflected at the surface back into the material, following the law of reflection.)

The normal line is defined as the line that is perpendicular (at 90 degrees) to the surface at the point where the light strikes the surface. The initial direction line represents the direction that the light would continue to travel if it did not change direction at the surface.

(f) *Real image*



A real image point is formed when light:

(1) diverges from an object point and

(2) is redirected by an optical device to converge to another point in space.

A real image is a collection of all the real image points.

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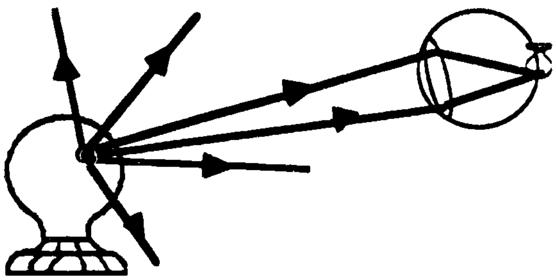
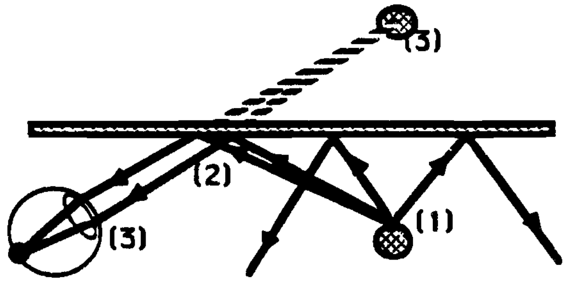
(g) ***Seeing an object***



To see a point, light must diverge from that point and enter the eye of the observer. The lens of the eye must then adjust its shape (becoming thinner for distant objects, and thicker for nearby objects) so that a sharp image is formed on the retina.

(h) ***Virtual image***



A virtual image point is formed when light:

1. diverges from an object point,

2. is redirected by an optical device so as to appear to diverge from another point in space, and then

3. enters the eye of an observer. The observer perceives the image to be located at that other point.

A virtual image is a collection of all the virtual image points.

Figure 2. List of *Powerful Ideas* for unit on Light

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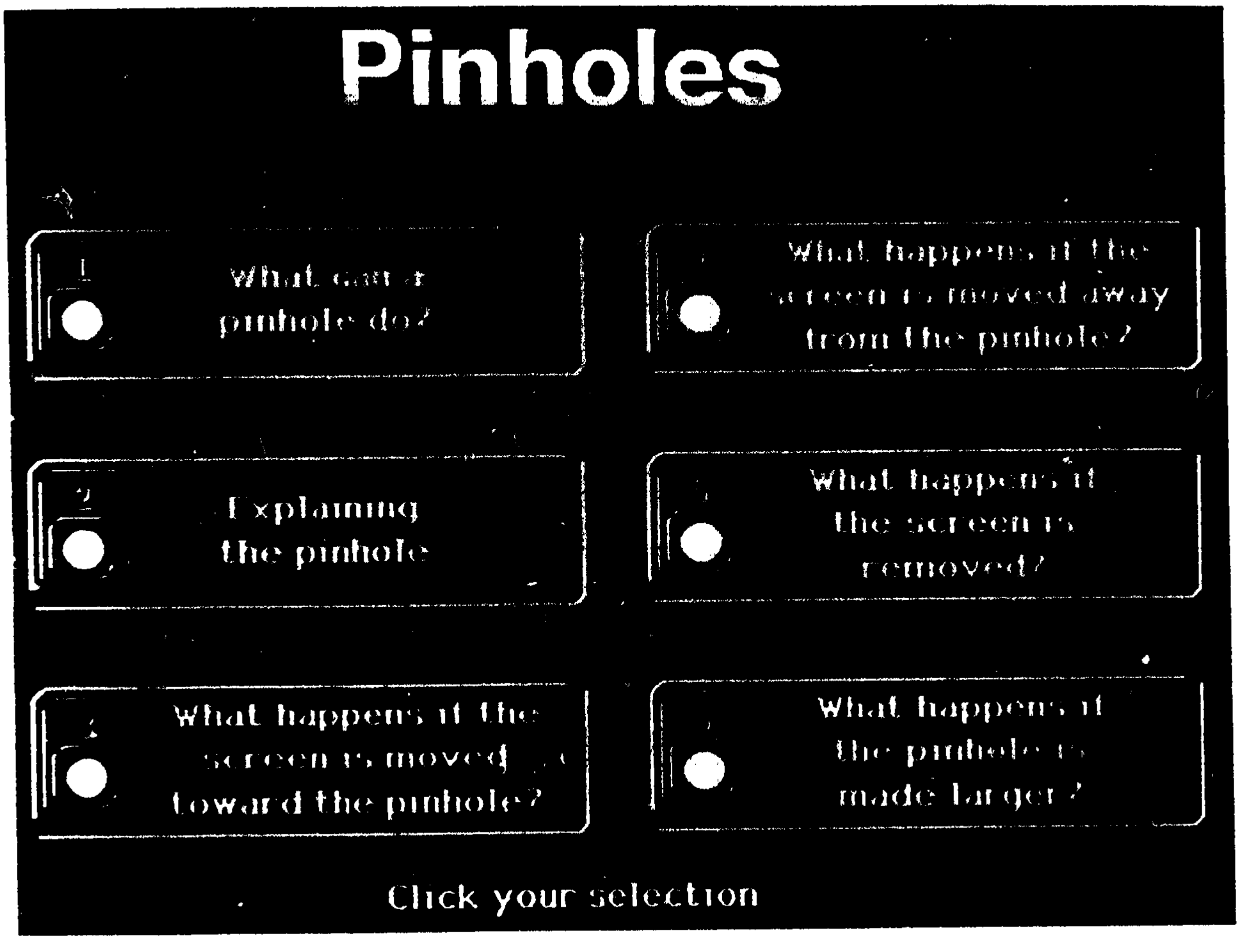

Figure 3. Menu screen for the Learning about Light program on Pinholes.

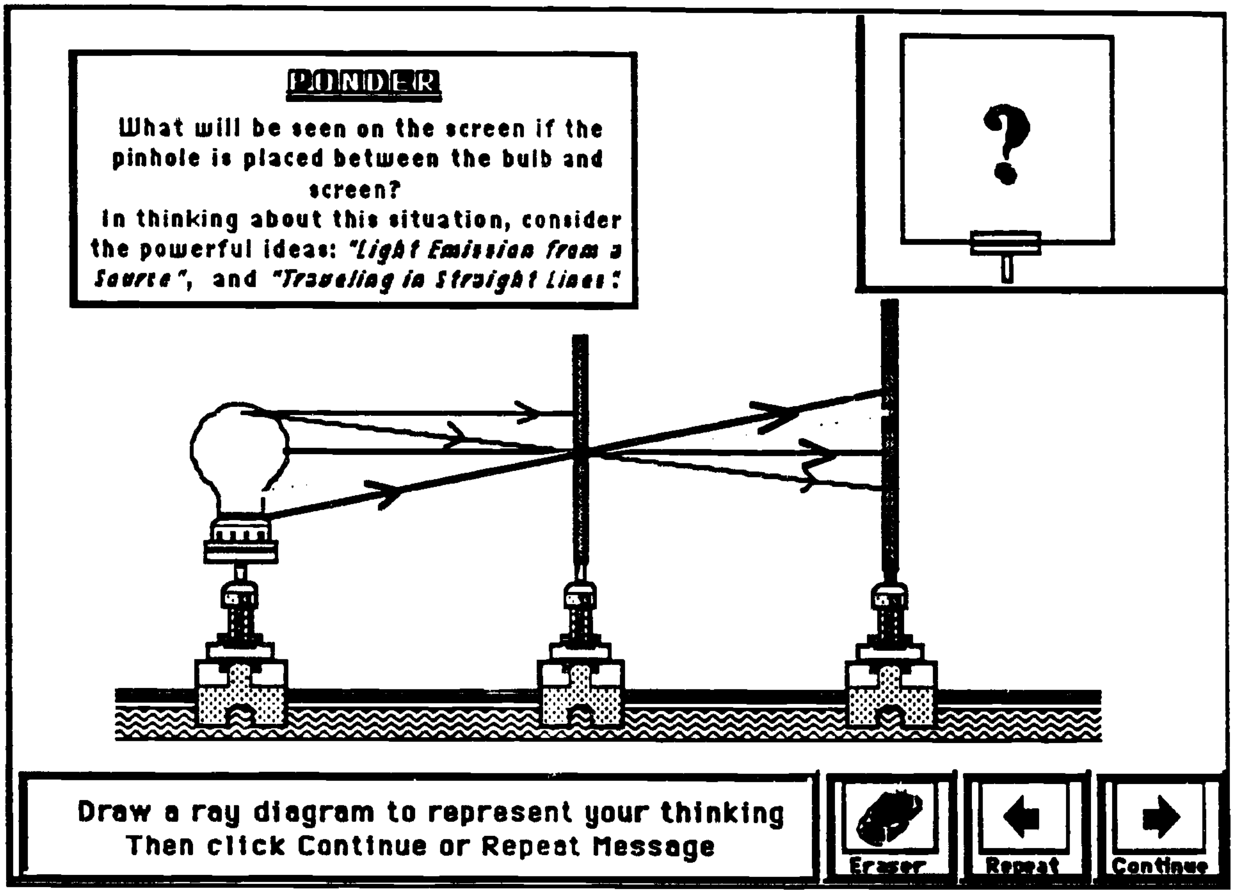

Figure 4. Representation of the first task in the *Learning about Light* program on*Pinholes*. The light rays were drawn by two students considering the task.

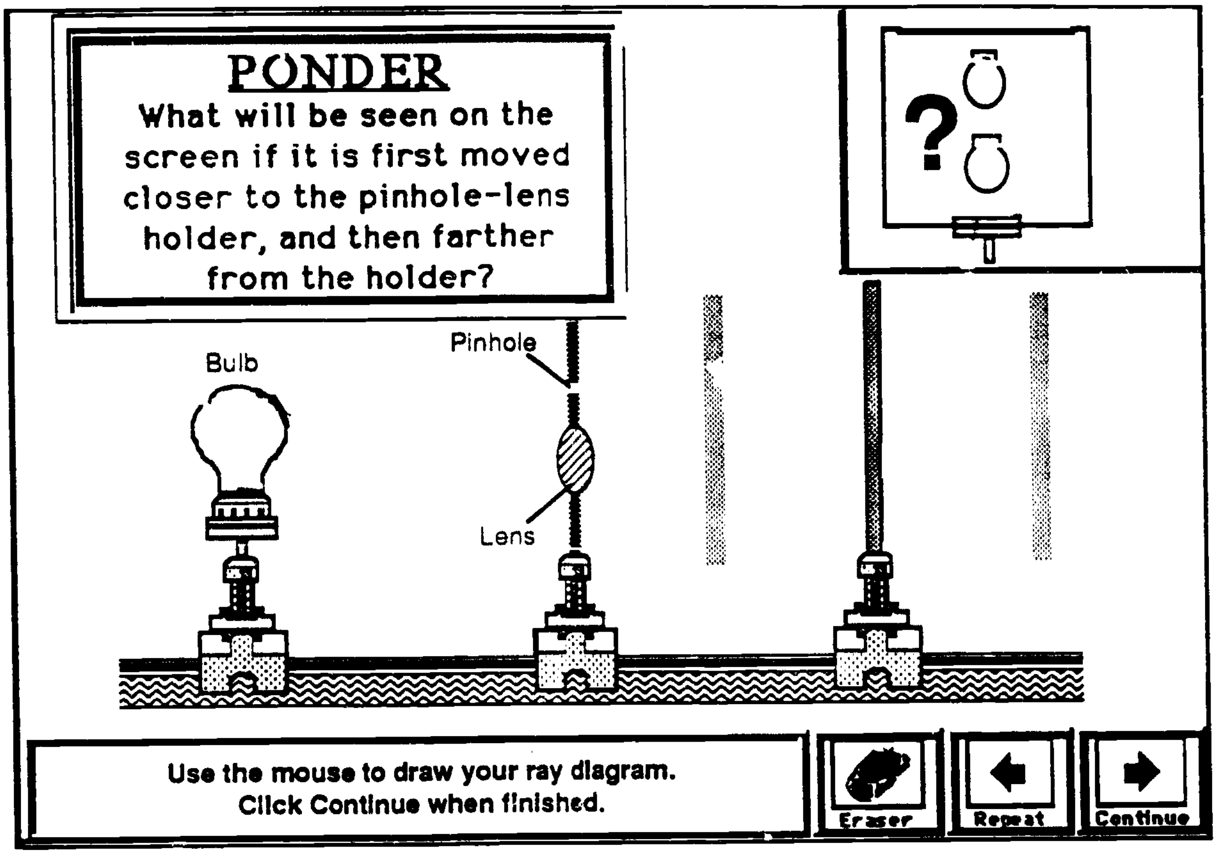

Figure 5. Representation of one of the tasks in the Learning about Light program on Converging Lenses. 'n this case students need to compare the behaviors of both the pinho e and lens systems.

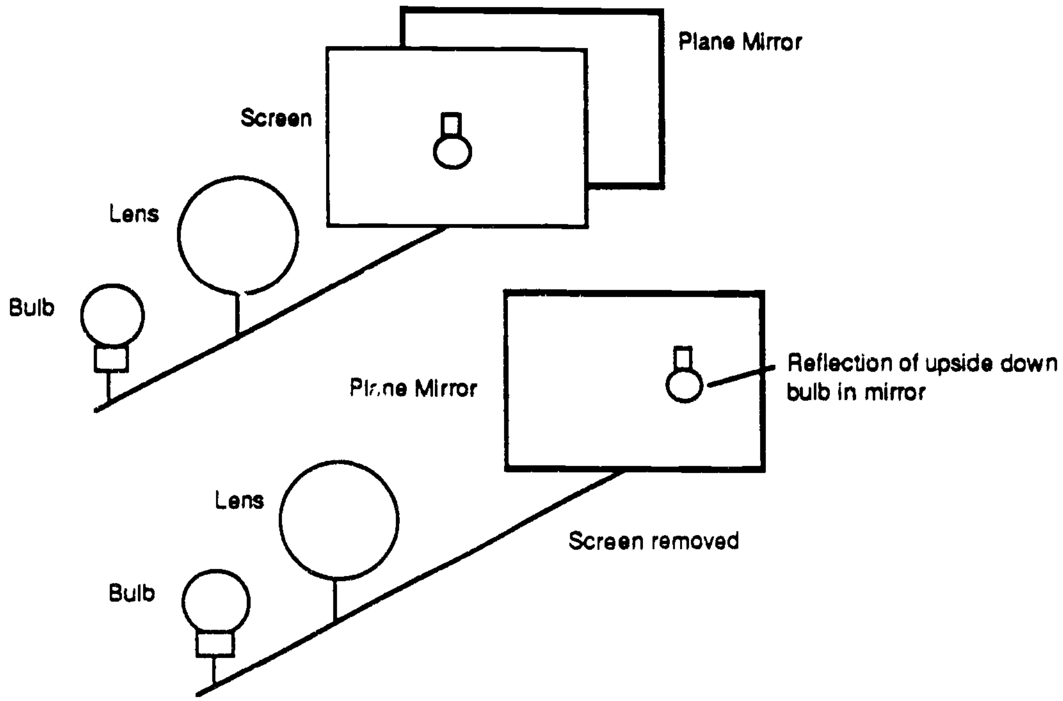

Figure 6. One of the questions asked on the geometrical optics unit exam. This figure accompanied an actual demonstration performed in front of the class. See text for description of the question.

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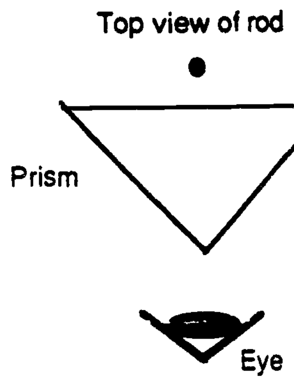

Figure 7(a)

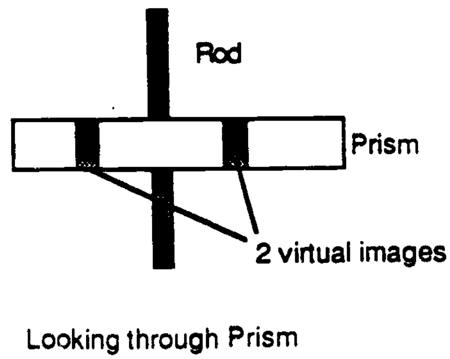

Figure 7(b)

Figure 7. Prism task. (a) Top view of set-up. Student looks through apex of flat triangular prism at a rod held vertically. (Prism is held in horizontal plane.) (b) Looking through prism apex one can see two images of the rod, each displaced to the side of the original rod.