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Windows into students' thinking: using multimedia to promote meaningful learning in geometrical optics

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Introduction

In this paper we describe a set of multimedia programs that we have developed to promote meaningful learning of geometrical optics. The programs are incorporated into a physics course for prospective teachers and are designed to complement extensive hands-on experimentation and whole-class discussion. The entire class environment is built on a constructivist epistemology (Scott, Dyson & Gater, 1987) and most class activities involve collaborative learning. The classroom activities provide opportunities for students to examine their own ideas, have them critiqued, and grapple with other ideas. In the computer activities our students work in groups of twos and occasionally threes. The social interaction promotes meaningful learning (Collins, Brown & Newman, 1986).

The unit on geometrical optics occupies about 25% of the semester-long course. During this unit we aim to help students develop a qualitative conceptual model to explain observable phenomena in optics. The model consists of a set of eight powerful ideas, and a set of rules for drawing and interpreting ray diagrams. The names of these ideas are listed in Table I, and a few of them will be discussed in detail later in this paper. These powerful ideas can be used to account qualitatively for a wide variety of phenomena in geometrical optics, ranging from simple to complex. The domain of geometrical optics is one of a few in physics in which the prospective teachers can reasonably be expected to develop a deep and thorough conceptual understanding.

The computer programs

We have designed a set of seven programs (Goldberg & Bendall, 1992) to guide students to an understanding of the powerful ideas listed in Table I. These programs are entitled: *Light and Illumination*, *Shadows*, *Pinholes*, *Reflection and Refraction*, *Converging Lenses*, *Looking Into Plane Mirrors*, and *Looking Through Transparent Media*. Students work on these programs in groups of two or three per work station in a special computer room that is adjacent to a wet laboratory room. Through the use of the programs students develop and apply the powerful ideas both conceptually and diagrammatically. The general format for the programs is that students ponder and discuss a task, construct their own diagram to account for it, and then are shown the task outcome. After students discuss the outcome the program presents feedback including a model diagram with key features circled and described. The choice of which features to highlight is based on previous research on student difficulties in understanding these phenomena (Galili, Bendall & Goldberg, 1993; Bendall, Galili & Goldberg, in press). At times questions are posed for students to consider, then an audio segment is played discussing the issue. These audio segments are accompanied by simple animation. We summarize here some important features of the computer programs.

Elicit and challenge students' existing knowledge

Each program consists of a set of tasks in which the students are asked to predict what would happen if a change is made in an optical system, or to account for some observed optical phenomenon. All tasks provide a problem solving context in which students develop a need for new knowledge, which has been shown to be important to learning (Anderson, Boyle, Corbett & Lewis, 1990). The tasks are carefully sequenced to build on the students' evolving knowledge. Later tasks present new challenges to the students, requiring them to modify or extend their existing knowledge.

Promote development of powerful ideas

The tasks, in particular the initial tasks in each program, are designed to elicit students' prior knowledge. Since the task outcomes are often a surprise to students their prior ideas are challenged and they are motivated to consider changing them. The nature of the tasks and the feedback following their presentation are intended to promote development of specific powerful ideas. Students can compare their predictions, diagrams and explanatory reasoning to that provided in the feedback. Once students have had the opportunity to develop a powerful idea, it is formally introduced by the computer program. When pondering a new task the students often are prompted to use previously developed powerful ideas to guide their thinking in the new situation. This helps the students come to recognize that these ideas collectively can account for a wide range of new phenomena, and gives meaning to the term "powerful."

Facilitate making explicit connections between diagrammatic representations and optical phenomena

Scientists often use diagrammatic representations to help guide their thinking about phenomena, but research has shown students have difficulty developing this skill (McDermott, Rosenquist & van Zee, 1987; Goldberg & Bendall, 1992). To help learners develop this skill the computer programs are designed to enable students to learn the rules of ray diagram construction while they are viewing actual optical phenomena. Psychological research supports this dual encoding strategy (Tulving and Thompson, 1973; Tulving, 1983). On the computer monitor students see video scenes via a videodisc of the tasks. Sometimes these scenes are video stills, and other times they are dynamic scenes. Students then use a mouse-controlled cursor to construct the appropriate ray diagram directly on top of video of the apparatus. Thus they are dually encoding both the actual optical phenomenon *and* the ray diagram.

Promote meaningful conversations between student pairs

All of the computer tasks engage students in conversations about underlying explanatory ideas. The computer allows students to represent their ideas diagrammatically by drawing ray diagrams on the computer screen. Drawing the light rays provides an external mechanism which facilitates the generation of a collaborative understanding of the phenomenon (Pea & Gomez, 1993). Once the students have drawn the diagrams they often point to the rays on the computer screen and gesture with their hands when discussing their ideas with each other. Explicitly representing their ideas on the screen also helps reduce demands on the students' working memory when they try to use the ideas to reason about particular task questions.

Facilitate effective interaction between students and instructor

The diagrammatic representations drawn by the students on the computer display provide a window into their thinking. This not only facilitates meaningful conversations between the students themselves, as suggested above, but it also facilitates effective interaction between the instructor and the students. When the students call over the instructor for help on a particular task, the instructor can look at what the students have drawn on the computer screen and infer the probable difficulties that need to be addressed.

Examples from two programs

We will show how several powerful ideas are developed or used in the computer programs. Two of the ideas are shown in detail in Table II. The first idea in Table II explicitly shows how light goes out from each point on a source. In our research (Galili, Bendall & Goldberg, 1993; Bendall, Galili & Goldberg, in press) we found that pre-instruction students rarely thought of light leaving a point on a source as going out in all directions. Instead, they most often thought of light going out from a source radially (see Figure 1.) After traditional instruction, when students were queried specifically on how light leaves a source, they would respond as shown in Table II, but they seemed not to recognize the importance of this idea and often would not apply it to account for optical phenomena. Thus we help students develop the *Light emission from a source* idea early in the optics unit and students need to use this idea to be successful in subsequent tasks..

The *Reproduction of a source* idea describes in a qualitative and fundamental way a criterion for reproducing a source at another point in space. We use the term reproduction rather than image because the former is a more general term and can be applied to pinhole patterns as well as real and virtual images. The distinction between pinhole patterns and images is discussed in a prior publication (Goldberg, Bendall & Galili, 1991). The sketch in Table II is of a pinhole set-up because that is the context in which the idea is first developed.

In the spring of 1993, as part of an ongoing effort to document student learning, we videotaped two students working through the optics unit (which lasted for seven two hour periods). These students were scholastically high achievers and were among a group of students who volunteered to participate in the videotaping. The two students, Rachel and Leona (fictitious names) were chosen because during a trial videotaping session they were able to easily verbalize their thoughts while working through the activities. In addition to videotaping Rachel (R) and Leona (L), we also collected copies of all of their written work including daily journals, homework assignments and the unit examination.

During the first class period of the optics unit the students worked through the programs entitled *Light and Illumination* and *Shadows* and developed the first and second ideas listed in Table I. The following class period they worked through the next program in the series, *Pinholes*. As the program begins, a side view of a bulb and translucent screen is introduced. In one quadrant of the computer monitor is a front view of the illuminated screen. Students then see a short movie of a pinhole being formed by piercing a piece of aluminum foil with a pin. Next students are asked to ponder and discuss what would be seen on the screen if the foil with the pinhole were placed between the bulb and screen (see Figure 2). What would be seen is an upside down reproduction of the bulb. Actually, the crucial feature in the formation of a pinhole pattern is that a small flux of light from each point on a source travels through the small pinhole and strikes only one small corresponding area on a screen. Thus, there is essentially a one-to-one correspondence between a point on the source and a point on the pattern. When this task was posed to R and L, and <u>before</u> they saw the outcome, Leona immediately said,

L: We'll see some light coming through, and it's going to be a bit bigger than the pinhole.

The pair engaged in *ten* minutes of discussion about the behavior of the light and the size of the spot on the screen. The length and intensity of their discussion indicates that they were very much engaged in thinking the task through, and challenged by it. During this discussion they applied the powerful ideas that had been developed in the previous class session, particularly the *Light emission* idea. After some discussion L said,

L: Do you think, then, that only ones (rays) that are able to continue in a straight line, then, are going come through here (the pinhole)?

This is a close approximation to what happens. Through their discussion with each other, R and L were able to make a deduction about the task outcome by applying the powerful ideas in a meaningful way. After their discussion they drew a suitable diagram of the behavior of the light (see Figure 2), but were never able to infer from it that an inverted bulb would be seen on the screen. That is not unusual. We have observed numerous pairs of students working through this task on our computer program. Many of them come up with a good diagram, but we have never seen any students deduce from the diagram that an inverted reproduction of the bulb will be seen on the screen. After discussion their prediction and drawing their diagram, R and L were shown what really happens. R said,

R: Check it out! The bulb upside down! Cool!

L: (reading from screen) Why does the screen show a reproduction of the bulb?

R: But we've got it here. We didn't figure out what we drew, but look. (A little talking together.) Here's this one, and it comes down there (follows one of the rays with her finger). We drew it, but we didn't see the inference.

R: So we figured out how we see this reproduction of the bulb.

The above discussion took place before they saw any feedback diagrams or text. From the diagram drawn, and the foundation of their prior discussion, the pair was able to see immediately how their diagram accounted for what actually happened. Although they did not initially make an accurate inference from their diagram of what would happen when the pinhole is in place, seeing the outcome of the task helped them attribute meaning to the diagram. Later Rachel wrote in her daily journal,

In working through the computer program, I was struck by the fact that even though I understood, (and even properly drew) how the light would strike the screen through the pinhole, I didn't immediately realize that the image would be upside down.

Following the task just described is a narrated animated segment that explains the pinhole pattern in terms of the powerful ideas. At the end of the segment the formal form of the powerful idea *Reproduction of a source* is introduced as it appears in Table II. This idea, however, has already been developed by the students in their own language, when they put together the behavior of light as drawn in their original diagram with what is observed on the translucent screen (the inverted bulb). It is much more meaningful for the students to develop this idea first, then have the formal presentation, than it is for students to be simply told this idea at the outset.

In the third class period students developed the powerful ideas *Reflection of light* (law of reflection) and *Refraction of light* (a qualitative form of Snell's law) and used them in the computer program *Reflection and Refraction*. In the fourth period students worked through the *Converging lens* program. In this program they applied all of the previous ideas (except the *Reflection* idea) to account for real images formed by a converging lens. The apparatus shown in the program consists of a light bulb for an object, a converging lens and a translucent screen (see Figure 3). Towards the beginning of the program, the students were shown an image on a screen, and were asked to account for the image. What actually happens is that light diverging from a single object point is made to converge to a single corresponding image point. This happens for each point on the object facing the lens. The entire image is composed of the collection of all the image points. This was the first time that they had tried to account for an image formed by a lens, but eventually they were able to use the powerful ideas to account for the real image. R began the discussion of the task by commenting, R: Light emission from a source is going out in all directions, and then we're pretending we have a pinhole with reproduction of a source, essentially.

L: Well, what we're wanting to see happen is this, right? The light from here is... (Draws rays from two points on the bulb to two points on screen as if she were accounting for a pinhole pattern of light. A little talking occurs.) I'm kind of at a loss Rachel, are you?

R: No, it's making sense. (R takes control of mouse.) What's going to happen, because of the lens is this. ... (R draws several rays from the top of bulb to the bottom of screen.) ... See these two? If we pretended this was a pinhole here. This little (ray) would go right through the pinhole here, and this one would hit and stop. But this is not a pinhole. So something is happening in the lens ... See what's happening with these? All these are somehow hitting the lens and converging on that (image) point. Making sense?

L: Something's happening here bending all that come here up to here. But I'm not sure how or why.

R: Because of the angles of refraction.

Rachel has applied the powerful ideas (particularly the *Light emission* and *Reproduction of source* ideas) to develop a good accounting for how the image is formed. Subsequent segments of the computer program present a formal discussion of how the real image is formed by the converging lens, and present other converging lens tasks for students to ponder.

Computer requirements

We have 15 computer-videodisc systems that are set-up for running the programs. The systems consist of Macintosh IIcx computers, Sony 1302 multisynch color monitors, Pioneer LDV-4200 videodisc players and two special videocards from Mass Microsystems[1] (the Colorspace IIi videocard and the Colorspace IIfx card). The software which we used to develop the units is Authorware Professional produced by Authorware,

[1]Mass Microsystems, 550 Del Rey Avenue, Sunnyvale, CA 94086. (800) 522-7979.

Inc.[2] The videodisc is one which we have produced at San Diego State University. We are currently developing other versions of the programs which do not require such specialized hardware. Inquiries about the availability of these programs should be addressed to the second author on this paper.

Summary and Conclusion

We have described the general features of a set of multimedia programs that have been designed by our group to facilitate qualitative understanding in geometrical optics[3,4]. These programs were designed to elicit and challenge students' own ideas, to help them make direct connections between diagrammatic representations and real world optical phenomena, to complement hands-on laboratory activities, and to facilitate meaningful conversations between students, and between students and the instructor. The programs promote the evolution of a set of eight powerful ideas which form the basis for a conceptual model in geometrical optics. In this paper we have provided examples of two students working through two of the programs. These examples illustrate how the powerful ideas are developed by the students in their own language, then are presented in a formal manner by the computer programs.

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[2]Authorware, Inc. 8500 Normandale Lake Blvd., Ninth Floor, Minneapolis, MN 55437. (621)921-8555.

[3]This project was funded in part by NSF Grant TPE-9053803 and by the San Diego State University College of Sciences.

[4]Many members of the Physics Learning Research Group at San Diego State University have participated in the design and development of the computer programs. The authors wish to particularly acknowledge Igal Galili, James Sammer and Jim Meyer.

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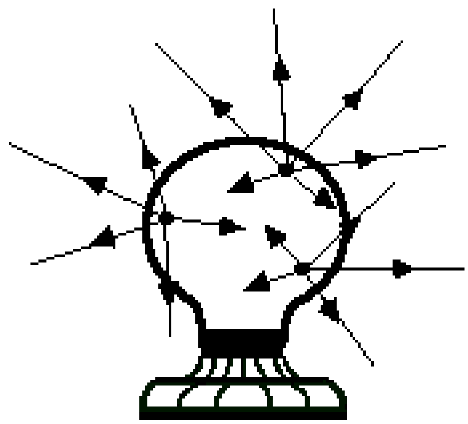
Table I. A list of the names of the powerful ideas used in the optics unit.

Light emission from a source
Light travels in straight lines
Reproduction of a source
Reflection of light
Refraction of light
Real image
Seeing an object
Virtual image

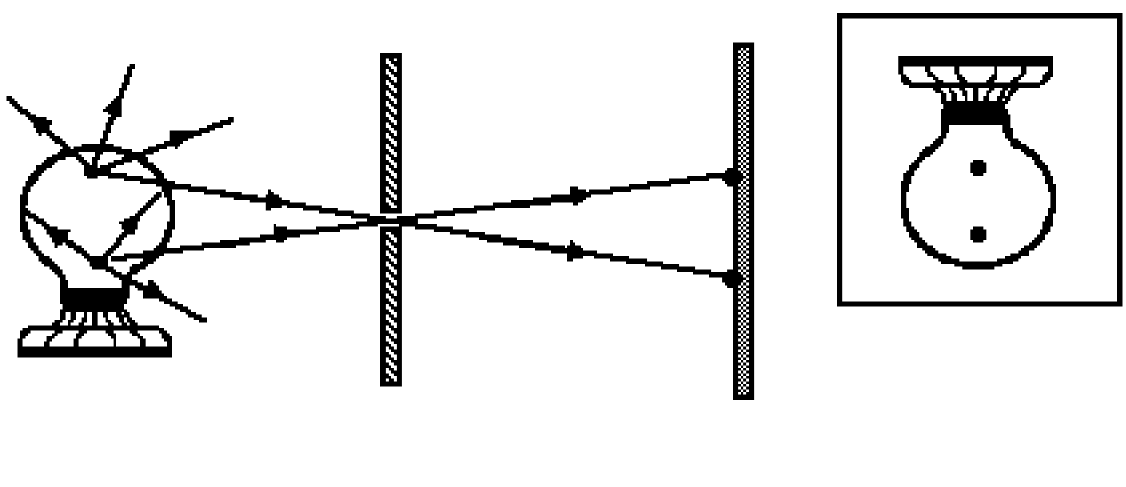
Table II. Two of the powerful ideas.

Light emission from a source



From *each* point on a source, light travels outward in *all* directions.

Reproduction of a source



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

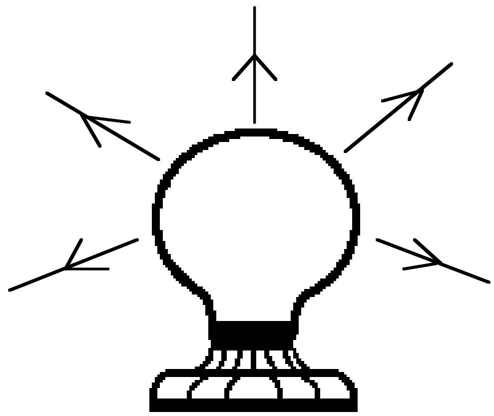


Figure 1. Diagram showing common student conception of how light goes out from a source.

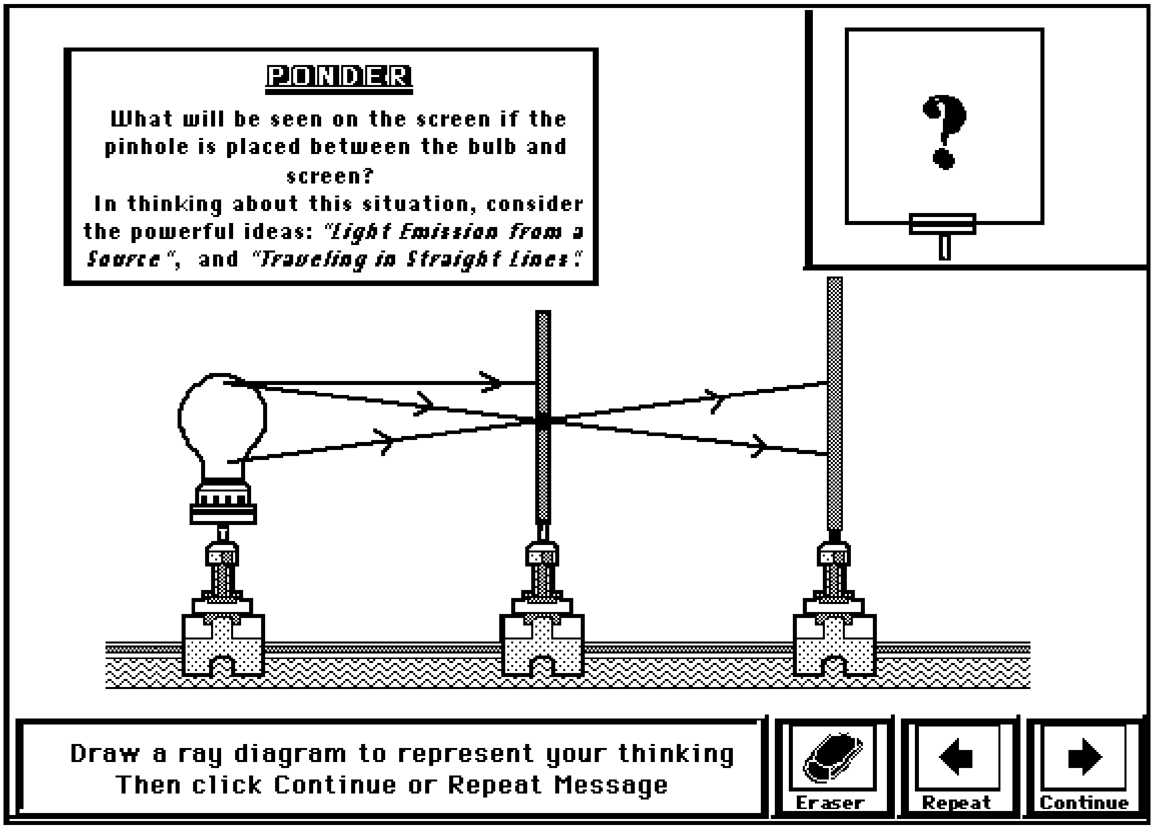


Figure 2. A representation of what students see on the screen in the first pinhole task. The diagram drawn is similar to what R and L drew.

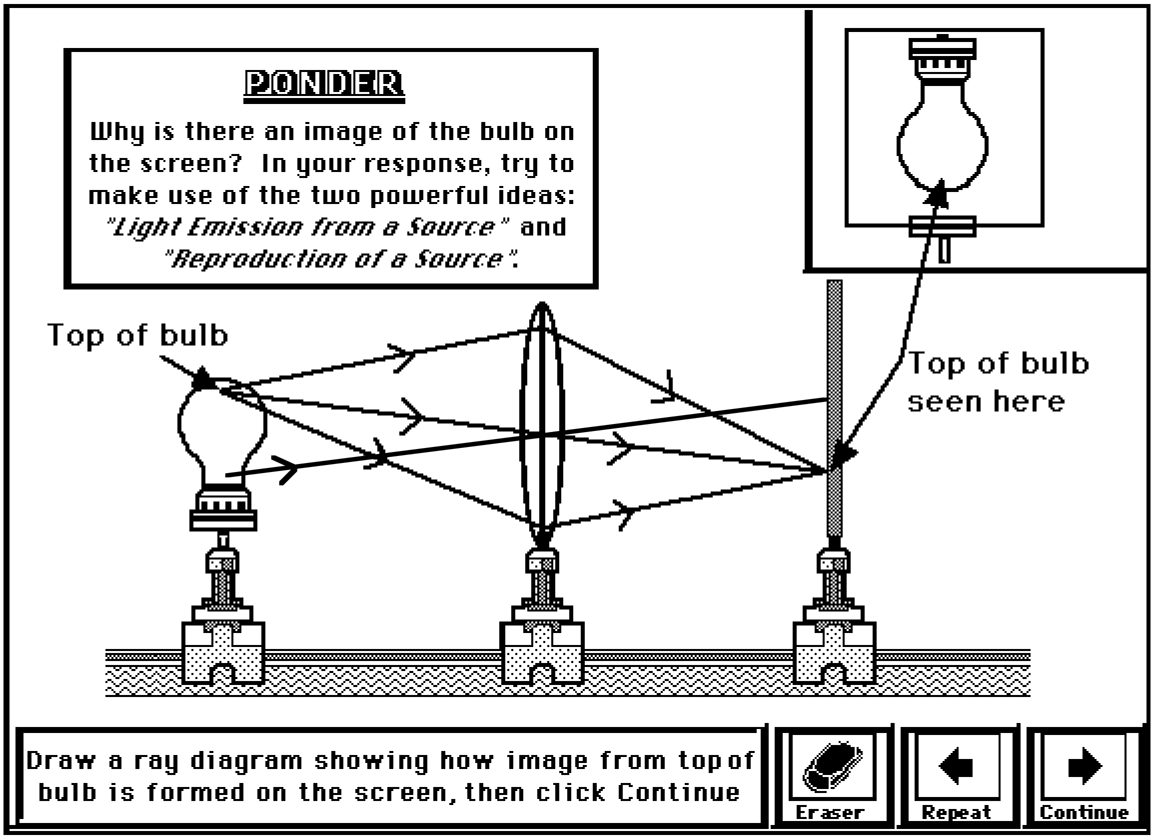


Figure 3. A representation of what students see on the screen in the first lens task. The diagram drawn is similar to the one drawn by R and L.