Active Learning Strategies for Introductory Light and Optics

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There is considerable evidence that traditional approaches are ineffective in teaching physics concepts, including light and optics concepts.[1-3] A major focus of the work of the Activity Based Physics Group[4] has been on the development of active learning curricula like RealTime Physics (RTP) labs[2,5] and Interactive Lecture Demonstrations (ILDs).[6,7] Among the characteristics of these curricula are: (1) use of a learning cycle in which students are challenged to compare predictions—discussed with their peers in small groups—to observations of the physical world, (2) use of guided hands-on work to construct basic concepts from observations, and (3) use of computer-based tools. It has been possible to change the lecture and laboratory learning environments at a large number of universities, colleges, and high schools without changing the structure of the introductory course. For example, in the United States, nearly 200 physics departments have adopted RTP,[8] and many others use pre-publication, open-source versions or have adopted the RTP approach to develop their own labs. Examples from RTP and ILDs (including optics magic tricks) are described in this paper.

RealTime Physics: Active Learning Labs (RTP)

RealTime Physics is a series of lab modules that makes significant use of computer-based tools to help students develop important physics concepts while acquiring vital laboratory skills.[2,5] Besides data collection and analysis, computers are used for basic mathematical modeling, video analysis, and some simulations. RTP labs use a learning cycle of prediction, observation, and comparison. They incorporate a guided discovery approach in which students carry out structured, sequenced experiments in small groups. Students are guided by PER-motivated questions designed to help them reach conclusions from clearly displayed observations of the physical world. RTP labs have been shown to enhance student learning of physics concepts.[1,2] There are four RTP modules—Module 1: Mechanics, Module 2: Heat and Thermodynamics, Module 3: Electricity and Magnetism, and Module 4: Light and Optics.[5] Each lab includes a pre-lab preparation sheet to help students prepare and homework designed to reinforce critical concepts and skills. A complete teacher's guide is available online for each module. Here are two examples of activities from RTP Module 4.[9]

- ***Polarized light:*** As an example of an activity that makes use of technology, Fig. 1 shows the apparatus used to examine polarized light in Lab 5. It consists of an analyzer fabricated from a Polaroid disc mounted on a precision rotary motion sensor[10] with a light sensor[11] mounted behind it. Using a flashlight with a Polaroid sheet mounted on its lens as the light source, the graph in Fig. 2 traces out as the analyzer is rotated. Figure 2 also shows a graph of $A\cos^2\theta$ that has been adjusted both in amplitude and phase to model the collected data very well (evidence for Malus' law).

- ***Image formation:*** Many of the most innovative RTP optics activities are low-tech. This activity from Lab 3 is inspired

Fig. 1. Apparatus used to analyze polarized light in RealTime Physics Module 4, Lab 5.

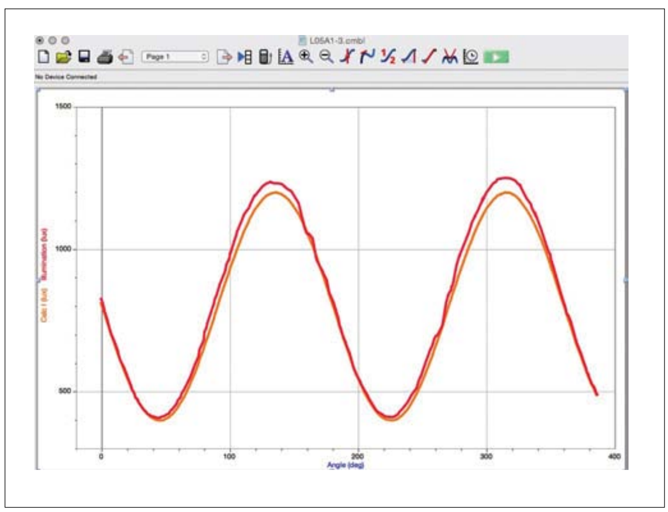

Fig. 2. Graphs of the data collected with the apparatus in Fig. 1, and of an $A\cos^2\theta$ model for intensity vs angle.

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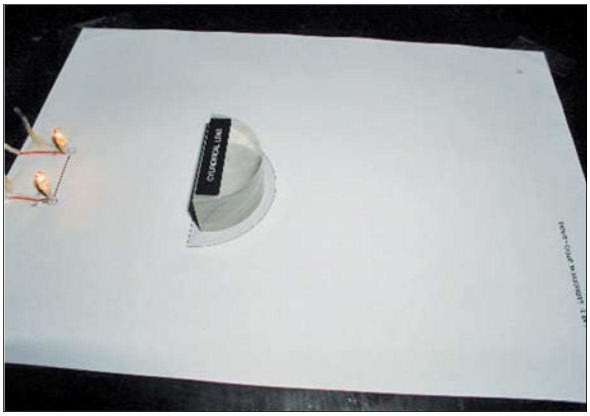


Fig. 3. Setup of two miniature light bulbs and a cylindrical lens, used to explore image formation.

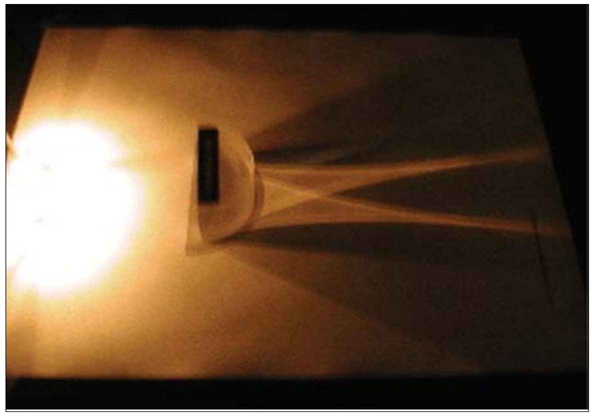


Fig. 4. The same setup as in Fig. 3 with the two bulbs illuminated.

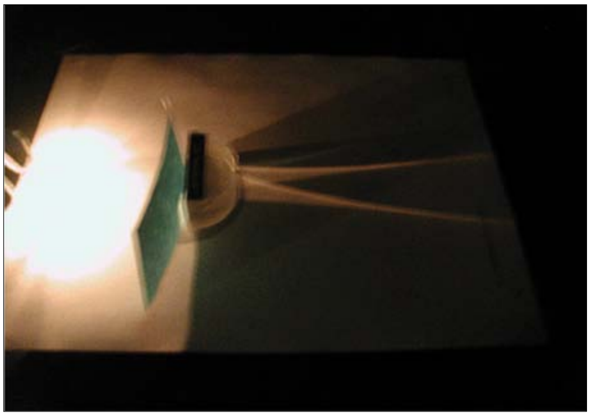


Fig. 5. The same setup as in Fig. 4, but with half of the lens blocked by a card.

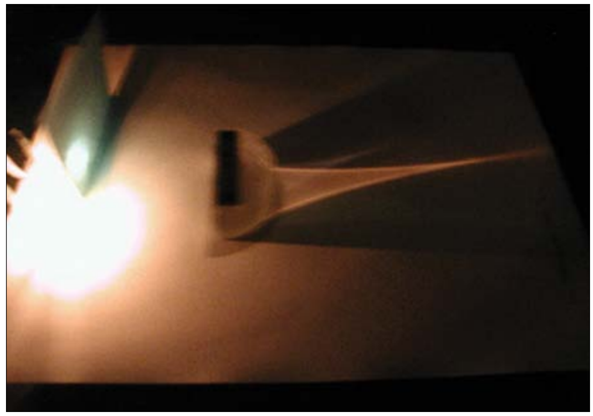


Fig. 6. The same setup as in Fig. 4, but with one of the bulbs blocked with a card.

by the research of Goldberg et al.,[3] which shows that after traditional instruction, most students have little understanding of the function of a lens in forming an image. Focusing on two or three special rays causes students to fail to recognize the infinite number of rays (light flux[12]) emanating from each point on the object and focused to a corresponding point on the image. In this activity, students use miniature light bulbs (or LEDs) as two point sources on the object, and a cylindrical lens[13] to view the situation clearly in two dimensions.

Figure 3 shows the setup, and Fig. 4 shows what appears when both bulbs are illuminated. The two image points can be recognized as the points to which the light flux leaving each of the bulb filaments (viewed in two dimensions) is focused. Next, students are asked to predict what will happen when various changes are made. For example, what happens if half of the lens is blocked with a card? (Research shows that the majority of students predict that either half or the entire image disappears.[3]) Figure 5 shows that light from both point sources is still focused to the same two image points, but now only half as much light. Therefore, the image is the same in every way as in Fig. 4, except that it is dimmer. In contrast, Fig. 6 shows what happens when half of the object is blocked by the card. Figure 7 shows an excerpt from the lab. In other activities, students are asked to explore what happens when the lens is moved further away or closer to the object, and when the lens is removed.

Prediction 1-3: Suppose that you covered half of the side of the lens facing the arrow with a card, i.e., covered the top half of the lens as seen in the diagram above. How would the image be changed? Would the whole image of the arrow still be formed?

10. Move the lens back on the outline. Block the top half of the lens (as seen in the diagram above) with a card.

Question 1-9: Carefully describe what happens to the image. Explain your observations based on what happens to rays from each of the bulbs that hit the unblocked half of the lens.

Fig. 7. Excerpt from RealTime Physics Module 4, Lab 3 showing the activity illustrated in Fig. 5.

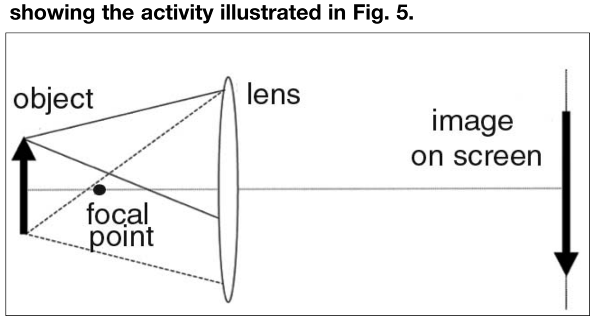
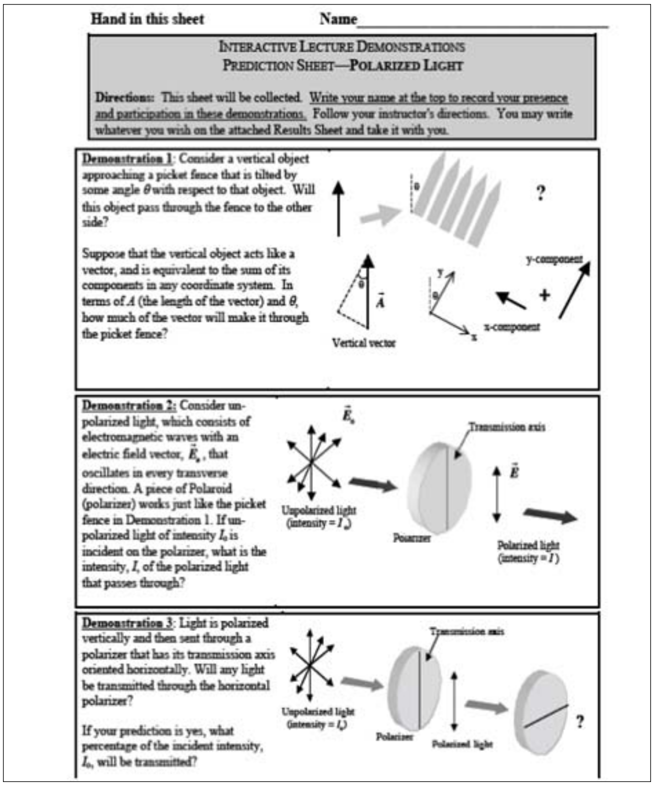


Fig. 8. Question from the "Light and Optics Conceptual Evaluation" in which students are asked to continue the four rays to illustrate how the image is formed on the screen.


Hand in this sheet Name ____________________

INTERACTIVE LECTURE DEMONSTRATIONS
PREDICTION SHEET—POLARIZED LIGHT

Directions: This sheet will be collected. Write your name at the top to record your presence and participation in these demonstrations. Follow your instructor's directions. You may write whatever you wish on the attached Results Sheet and take it with you.

Demonstration 1: Consider a vertical object approaching a picket fence that is tilted by some angle θ with respect to that object. Will this object pass through the fence to the other side?

Suppose that the vertical object acts like a vector, and is equivalent to the sum of its components in any coordinate system. In terms of A (the length of the vector) and θ, how much of the vector will make it through the picket fence?

Demonstration 2: Consider unpolarized light, which consists of electromagnetic waves with an electric field vector, $\vec{E}_o$, that oscillates in every transverse direction. A piece of Polaroid (polarizer) works just like the picket fence in Demonstration 1. If unpolarized light of intensity I_o is incident on the polarizer, what is the intensity, I, of the polarized light that passes through?

Demonstration 3: Light is polarized vertically and then sent through a polarizer that has its transmission axis oriented horizontally. Will any light be transmitted through the horizontal polarizer?

If your prediction is yes, what percentage of the incident intensity, I_o, will be transmitted?

Fig. 9. Excerpt from the Polarized Light ILD Prediction Sheet.

Do students learn optics concepts from these RTP image formation activities? Students in the algebra-trigonometry-based general physics course at the University of Oregon (predominantly biology, pre-health, and architecture majors) had only a 20% normalized learning gain on the six image formation questions of the PER-based "Light and Optics Conceptual Evaluation" (LOCE) after completing all traditional instruction on optics. After this lab, their learning gain from the pre-test was 90%. In addition, the last question on the LOCE shows the real image of an arrow formed by a lens, with two (non-principal) rays from the bottom of the arrow and two (non-principal) rays from the top of the arrow drawn incident on the lens (see Fig. 8). Students are asked to continue these four rays through the lens to illustrate how the image is formed by the lens. This task is easy if one understands the function of a perfect lens. After traditional instruction, only 33% of the students were able to draw these rays correctly, but after experiencing the RTP image formation activities, 76% could do so.[14]

Interactive Lecture Demonstrations (ILDs)

Since the majority of introductory physics students spend most of their time in a lecture—often a large one—creating an active learning environment in lecture is an important pedagogical challenge. Interactive Lecture Demonstrations (ILDs)[6,7] address this need. Real physics demonstrations are described and shown to students (without displaying the results). The students then make individual predictions about the outcomes on a Prediction Sheet, and collaborate with fellow students by discussing their predictions in small groups. Volunteers present their predictions to the entire class. Next the class observes the results of the live demonstrations (often with data displayed using computer-based tools). Students compare the results with their predictions, and volunteers attempt to explain the observed phenomena to the entire class. The eight-step ILD procedure has been described elsewhere.[6,7] ILDs have been demonstrated to enhance student learning of physics concepts.[1,7] Complete materials—including student sheets and teacher's guides—are available for most introductory physics topics.[6] The ILDs on the two RTP topics discussed in the "RealTime Physics" section will be described very briefly here.

• ***Polarized light ILDs:*** Figure 9 shows excerpts from the Prediction Sheet. The demonstrations can be carried out easily with sheets of Polaroid and a projector, or can also be done more quantitatively using the apparatus shown in Fig. 1.

• ***Image formation with lenses ILDs:*** When done as ILDs, two flashlight bulbs are used as the point sources of light, and a large cylindrical lens[15,16] is used to make the demonstration visible to the entire class. The normalized gain on the LOCE image formation questions for students experiencing just one hour of these ILDs (but not the RTP lab) is 80%![14] This sequence of ILDs has also been presented at Oregon using clickers (personal response systems) for students to record their predictions. Learning gains, while not quite as large, were still substantial. These results will be reported elsewhere.

Optics magic tricks

A number of years ago, the author compiled a set of 12 simple optics demonstrations presented as magic tricks to use in Saturday morning magic shows at the hands-on science center that he directed (the Eugene, OR, version of the Exploratorium). He has since used them in general physics classes at the University of Oregon. Students are actively engaged in the learning process by discussing questions in small groups. The first four tricks on geometrical optics are (1) Reappearing Test Tube (reflection from a transparent object and index of refraction—details presented below), (2) Candle Burning Under Water (properties of the image formed by a plane mirror), (3) Coal to Silver (total internal reflection), and (4) Falling Laser Beam (total internal reflection and fiber optics). Complete information is available from the author.

Reappearing Test Tube

A test tube is held up in the air for all to see, then placed in an envelope and smashed. The demonstrator then pours the glass pieces into a transparent container filled with a "magic" fluid. A magic wand is waved over the container, and, after the demonstrator says the magic word (e.g., "PHYSICS"), a whole test tube is pulled from the container. For dramatic effect—and to elicit a good laugh—it is fun to then pull a second whole test tube from the magic fluid! Figure 10

Fig. 10. Container of "magic" fluid and pieces of shattered glass test tube.

Fig. 11. Whole test tube removed from the "magic" fluid after the magic wand is waved over it and the magic word is recited.

shows the container with the "magic" fluid, and Fig. 11 shows a whole test tube being removed.

Figure 12 shows the questions used for small group discussions about this magic trick. The use of small group discussions, with these guiding questions, makes the pedagogy similar to ILDs, but without the prediction step. As with ILDs, lively small group discussions erupt in lecture, suggesting that students are engaged by this strategy. To help students in thinking about these questions, the demonstrator also holds a clean test tube in the air and then submerges it under water in a separate, identical transparent container. For one more dramatic effect after the class discussion, the demonstrator can slowly submerge another dry test tube open side up so that the oil flows over the rim. It appears to disappear from the bottom up—seemingly in a flash!

Discussion Questions for Optics *Magic:* *Reappearing Test Tube*

1. How do you think that the test tube was made to reappear?
2. Why can you see a test tube in air or in water, but not in the magic fluid? What is special about the magic fluid?
3. What property of transparent media determines whether reflection takes place at the boundary between them? What has to be true about this property for the two materials in order for reflection to take place?
4. What about the light that is transmitted through the test tube? How is it affected when the test tube is in the magic fluid and when the test tube is in air?

Fig. 12. Questions used for small group discussions about the Reappearing Test Tube magic trick.

• *Preparation and materials:* The easiest way to do this trick is to use vegetable oil as the magic fluid and a Pyrex© glass test tube. Any vegetable oil has nearly the same index of refraction as Pyrex©, so that the whole test tube (or two test tubes) placed in the container before class cannot be seen by the students. (In fact, the author has "performed" this trick all around the world [see next section] and the local vegetable oil provided has always worked—unless it was opaque at room temperature!) Alternatively, a mixture of light and heavy mineral oils can be used to match the index of any common glass.

• *Explanation:* Transparent objects only reflect and refract light when they are in a medium with a different index of refraction. Since the "magic" fluid has the same index as the tube, no light is reflected to the students' eyes by the submerged tube. However, students can see the tube in air or water because these have different indexes than glass. When volunteers share their small group's discussions with the whole class, they are always able to explain that the "optical properties" of the glass are the same as the "magic" fluid, even if they do not yet know the meaning of "index of refraction." For students who have studied index of refraction, the observations in this trick help support the $(n_1 - n_2)^2$ dependence of the reflectance at the plane interface between two transparent media.

Active Learning in Optics and Photonics (ALOP)

This paper has presented some innovative uses of active learning in teaching optics in the introductory physics course. RTP and ILDs are now used extensively in classes in the United States to enhance student learning of physics concepts.

Since 2004, active learning pedagogy has also been the basis for a series of UNESCO Active Learning in Optics and Photonics workshops for physics instructors in developing countries.[17,18] These ALOP workshops (1) are designed for secondary and first-year college faculty, (2) include teacher updating and introduction to active learning, (3) are locally organized, (4) use simple, inexpensive apparatus available locally or easily fabricated, (5) are presented by an international team of volunteer educators, (6) include the LOCE to measure student learning, (7) provide complete teacher's guides, and (8) distribute equipment sets to facilitate local implementation. Figure 13 shows some of the low-cost apparatus used in these workshops, while Fig. 14 shows a large low-cost cylindrical lens—a plastic food storage container filled with water.

ALOP's intensive workshops share active learning pedagogy like that found in RTP and ILDs. Some ALOP activities

Fig. 13. Low-cost equipment for ALOP: lasers, diffraction gratings from discarded CDs, slits scratched into coated mirrors, cellophane color filters, and spectrometer from a diffraction slide.

Fig. 14. Low-cost cylindrical lens—clear plastic food container filled with water.

can be introduced in either format. The *ALOP Training Manual* [14] includes six modules: (1) Introduction to Geometrical Optics, (2) Lenses and Optics of the Eye, (3) Interference and Diffraction, (4) Atmospheric Optics, (5) Optical Data Transmission, and (6) Wavelength Division Multiplexing. Each of these includes practical applications designed to intrigue students, helping them to understand their everyday world and become aware of career opportunities based on the principles they are learning. To date, 27 ALOP workshops have been presented in Africa, Asia, Latin America, and Eastern Europe. The ALOP team was awarded the 2011 SPIE Educator Award "in recognition of the team's achievements in bringing basic optics and photonics training to teachers in the developing world."[19] For more details on ALOP, see Refs. 14, 17, and 18.

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15. See, for example, the acrylic lens from a Blackboard Optics set, http://sciencekit.com/blackboard-optics-kit/p/IG0023843/.
16. A clear plastic food storage container filled with water can be used as a cheaper alternative. See Fig. 14.
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