# Active learning of introductory optics: Strategies for the U.S. and the developing World

**David R. Sokoloff**
*Department of Physics, 1274 University of Oregon, Eugene, Oregon 97403-1274, USA.*

**E-mail:** sokoloff@uoregon.edu

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**Abstract**
Widespread physics education research has shown that most introductory physics students have difficulty learning essential optics concepts—even in the best of traditional courses, and that a well-designed active learning approach can remedy this. This paper will describe strategies for promoting active involvement of students in their learning. The focus will be on *Interactive Lecture Demonstrations (ILDs)*—a learning strategy for large (and small) lectures, and on *RealTime Physics* laboratories. These materials have been used successfully in introductory, college-level physics courses. Recently, they have also been used by the author in a series of teacher enhancement workshops in developing countries, Active Learning in Optics and Photonics (ALOP). These workshops introduce college-level and secondary teachers to active learning. They are sponsored by UNESCO, ICTP, SPIE, OSA and NAS. Details on the ALOP project will be presented.

**Keywords:** Active learning, introductory physics, teacher enhancement.

**Resumen**
La amplia investigación didáctica de la Física ha demostrado que la mayoría de los estudiantes de Física introductoria tienen dificultades para aprender los conceptos-incluso esenciales de la óptica, en el mejor de los cursos tradicionales, y que un método de aprendizaje activo bien-diseñado puede remediar esto. En este documento se describen las estrategias para promover la participación activa de los estudiantes en su aprendizaje. La atención se centrará en las *Clases Demostrativas Interactivas* (*ILDs*)—una estrategia de aprendizaje para las grandes (y pequeñas) lecturas, y en los laboratorios de *Física en Tiempo Real*. Estos materiales han sido utilizados con éxito en cursos de introducción a la Física a nivel universitario. Recientemente, también han sido utilizados por el autor de una serie de talleres de mejoramiento docente en los países en desarrollo, Aprendizaje Activo en Óptica y Fotónica (ALOP). Estos talleres se introducen a nivel-universitario y los profesores de secundaria para el aprendizaje activo. Ellos son patrocinados por la UNESCO, ICTP, SPIE, OSA y NAS. Los detalles sobre el proyecto ALOP serán presentados.

**Palabras clave:** Aprendizaje activo, introducción a la Física, mejoramiento docente.

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## I. INTRODUCTION

There is considerable evidence that traditional approaches are ineffective in teaching physics concepts, including light and optics concepts [1, 2]. A major focus of the work at the University of Oregon and at the Center for Science and Mathematics Teaching (CSMT) at Tufts University has been on the development of active, discovery-based curricula like *RealTime Physics* labs [2, 3] and *Interactive Lecture Demonstrations* [4, 5]. Among the characteristics of these curricula are:

- Use of a learning cycle in which students are challenged to compare predictions—discussed with their peers in small groups—to observations of real experiments.
- Construction of students' knowledge from their own hands-on observations. Real observations of the physical world are the authority for knowledge.
- Confronting students with the differences between their observations and their beliefs.
- Observation of results from real experiments in understandable ways—often in real time with the support of computer data acquisition tools.
- Encouragement of collaboration and shared learning with peers.
- Laboratory work often used to learn basic concepts.

With the use of the learning cycle and the computer data acquisition tools it has been possible to bring about significant changes in the lecture and laboratory learning environments at a large number of universities, colleges and high schools without changing the lecture/laboratory structure of the introductory physics course. *RealTime*

*Physics* and *Interactive Lecture Demonstrations* are described briefly below.

## II. REALTIME PHYSICS ACTIVE LEARNING LABS (RTP)

*RealTime Physics* is series of lab modules for the introductory physics course that often use computer data acquisition tools to help students develop important physics concepts while acquiring vital laboratory skills. Besides data acquisition and analysis, computers are used for basic mathematical modeling, video analysis and some simulations. *RTP* labs use the learning cycle of prediction, observation and comparison. They have been demonstrated 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* [3]. Each lab includes a pre-lab preparation sheet to help students prepare, and a homework, designed to reinforce critical concepts and skills. A complete teachers' guide is available online for each module.

Here are a couple of examples of how technology is used in *RealTime Physics Module 4* to help students learn physical optics. Fig. 1 shows the apparatus used to examine polarization of light in Lab 5, "Polarized Light." It consists of an analyzer fabricated from a Polaroid disk mounted on a precision rotary motion sensor [6] with a light sensor [7] mounted behind it.

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

Using a light source consisting of a flashlight with a piece of Polaroid mounted on its lens, the graph in Fig. 2 is traced out as the analyzer is rotated through one full rotation. The data may be modeled as a function of angle. Fig. 2 also shows a graph of $A\cos^2\theta$, that has been adjusted both in amplitude and phase to match the collected data very well. (Malus' Law.)

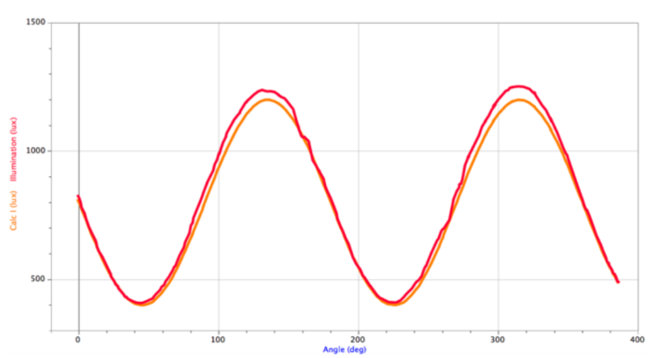



**FIGURE 2.** Graphs of the data collected with the apparatus in Fig. 1, and of an $A\cos^2\theta$ model for Intensity vs. Angle.

In Lab 6, the same rotary motion and light sensors are used to analyze the intensity patterns in interference and diffraction patterns. The apparatus is shown in Fig. 3, and the measured intensity distributions for a single slit and for two slits of the same width are shown in Fig. 4.

Two fairly "high-tech" examples have been chosen to illustrate the power of the computer data acquisition tools in displaying the results of student observations of the physical world in understandable ways, often in real time. These tools are very nifty, but it is the changes in pedagogy enabled by their careful design that is most important! Many of the activities in *RTP* are conceptual, designed to lead students to discover basic physics concepts from their observations. Many colleges and universities in the U.S. have adopted *RTP* to replace their traditional cookbook, confirmation labs.


**FIGURE 3.** Apparatus used to measure intensity distribution in interference and diffraction patterns in *RealTime Physics Module 4*, Lab 6.

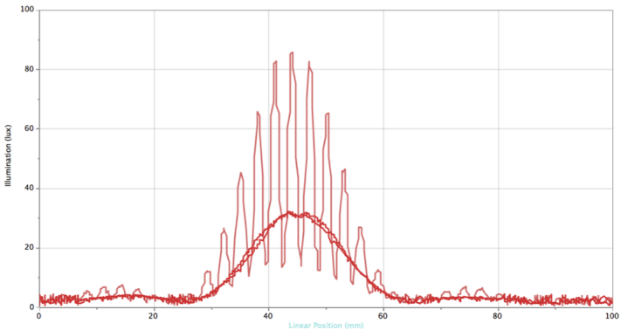



**FIGURE 4.** Graphs of the data collected with the apparatus in Fig. 3, Intensity vs. Linear Position, for (a) a single slit and (b) two slits of the same width.

Since most introductory physics students spend most of their time in a lecture class—and often a large one—setting up an active learning environment in lecture is an important pedagogical challenge. *Interactive Lecture Demonstrations* address this need.

## III. INTERACTIVE LECTURE DEMONSTRATIONS (ILDS)

*Interactive Lecture Demonstrations (ILDs)* [4, 5] are designed to enhance conceptual learning in large (and small) lectures. Real physics demonstrations are shown to students, who then make predictions about the outcomes on a prediction sheet, and collaborate with fellow students by discussing their predictions in small groups. Students then observe the results of the live demonstration (often with data collected and graphs displayed in real-time using computer data acquisition tools), compare these results with their predictions, and attempt to explain the observed phenomena. Besides data acquisition and analysis, computers are used for interactive video analysis.

Table I summarizes the eight step *ILD* procedure incorporating the learning cycle of prediction, observation and comparison. This procedure is followed for each of the basic, single concept demonstrations in an *ILD* sequence.

*ILDs* have been demonstrated to enhance student learning of physics concepts [1, 5]. Complete materials—including student sheets and teachers' guides—are available for most introductory physics topics [4].

The *Image Formation with Lenses* sequence of *ILDs* is designed to help students understand the process of image formation by a lens, and the concept that a perfect lens focuses all of the light from a point on the object that hits the lens surface (an infinite number of rays) to a corresponding point on the image. Many students reach incorrect conclusions about image formation because they are confused by the ray diagrams with only two or three rays that they have been taught to draw [8].

In this sequence, two small light bulbs are used as point sources and a large cylindrical lens (like the one available in Blackboard Optics sets [9]) is used. Fig. 5 shows the apparatus, and Fig. 6 shows the result with the bulbs illuminated. Fig. 7 is a sample of the Prediction Sheet used by students to record their predictions for this sequence of *ILDs*. After sketching a ray diagram, students are asked to predict what will happen when various changes are made. For example, for Demonstration 2 students are asked to predict what will happen to the image if the top half of the lens is blocked with a card. After predictions are made, small group discussions are carried out, and a poll of the class is conducted, the demonstration is carried out. The result is shown in Fig. 8. Volunteers describe and explain the result in the context of the demonstration. As can be seen in Fig. 8, the image is still formed at the same location, and has the same size. However, since only half as much light reaches the image (half as many rays), it is dimmer. Students are asked if they know of any examples of this, and hopefully volunteer the aperture of a camera and the iris of the human eye.

**TABLE I.** The eight-step *ILD* procedure.

| |
|---|
| 1. The instructor describes the demonstration and does it for the class without measurements. |
| 2. The students record their individual predictions on a Prediction Sheet, that will be collected, and that can be identified by each student's name written at the top. (The students are assured that these predictions will not be graded, although some course credit is usually awarded for attendance at these *ILD* sessions). |
| 3. The students engage in small group discussions with their one or two nearest neighbors. |
| 4. The instructor elicits common student predictions from the whole class. |
| 5. The students record their final predictions on the Prediction Sheet. |
| 6. The instructor carries out the demonstration with measurements displayed. |
| 7. A few students describe the results and discuss them in the context of the demonstration. Students may fill out a Results Sheet, identical to the Prediction Sheet, that they may take with them for further study. |
| 8. The class and instructor discuss analogous physical situation(s) with different "surface" features. (That is, different physical situation(s) based on the same concept(s)). |

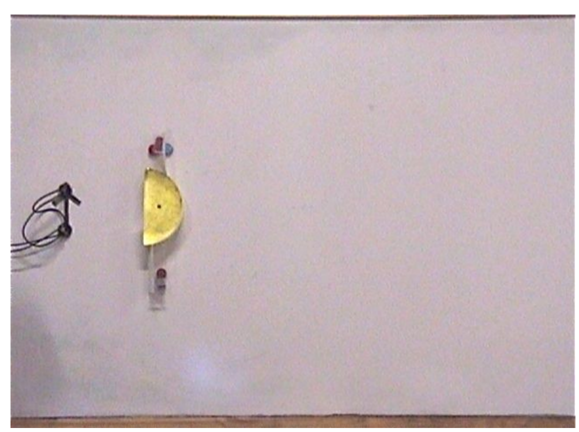


**FIGURE 5.** Apparatus for the *Image Formation with Lenses ILD* sequence, consisting of two small light bulbs and a large acrylic cyllindrical lens.

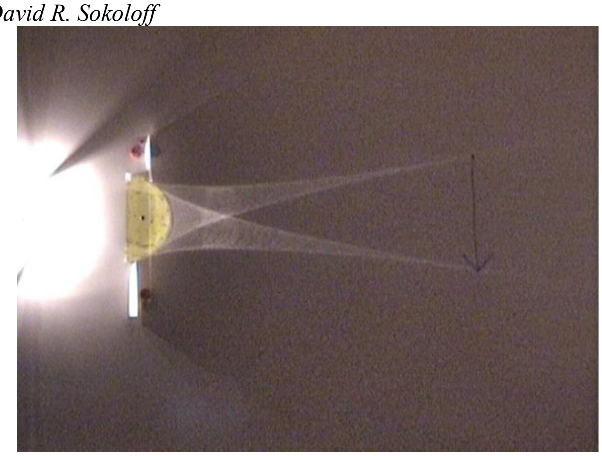
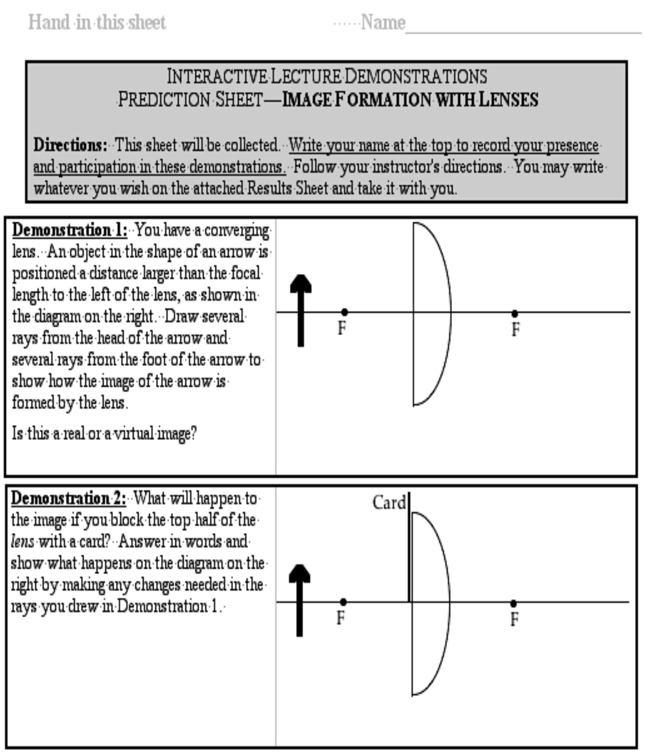


**FIGURE 6.** Apparatus pictured in Fig. 5 with the two light bulbs lighted. The location and size of the image can be seen clearly on the white board surface behind the lens.



Hand in this sheet Name______________________

INTERACTIVE LECTURE DEMONSTRATIONS
PREDICTION SHEET—**IMAGE FORMATION WITH LENSES**

**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:** You have a converging lens. An object in the shape of an arrow is positioned a distance larger than the focal length to the left of the lens, as shown in the diagram on the right. Draw several rays from the head of the arrow and several rays from the foot of the arrow to show how the image of the arrow is formed by the lens.

Is this a real or a virtual image?

F F

**Demonstration 2:** What will happen to the image if you block the top half of the *lens* with a card? Answer in words and show what happens on the diagram on the right by making any changes needed in the rays you drew in Demonstration 1.

Card

F F

**FIGURE 7.** Excerpt from the Prediction Sheet on which students record their predictions for the *Image Formation with Lenses ILD* sequence.

Do students learn optics concepts from *ILDs*? Here we report on assessments of learning gains for the *Image Formation with Lenses ILD* sequence. Students in the algebra-trigonometry-based general physics course at the University of Oregon had only a 20% normalized learning gain on our physics education research-based *Light and Optics Conceptual Evaluation* [10] after all traditional instruction on image formation. With just one additional lecture consisting of this *ILD* sequence, their learning gain from the pre-test was 80%. In addition, the last question on the test 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. 9). 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. While after traditional instruction, only 33% were able to continue these rays correctly, after experiencing the *ILD* sequence, 76% could do so.

**FIGURE 8.** Apparatus in Figs. 5 and 6 with the top half of the lens blocked by a card, for Demonstration 2. The image still forms at the same location, and has the same size, but it is dimmer than in Fig. 6.

## IV. ACTIVE LEARNING IN OPTICS AND PHOTONICS

Beginning in 2004, Dr. Minella Alarcon, Program Specialist (now retired) for Physics and Mathematics at the United Nations Educational Scientific and Cultural Organization (UNESCO) in Paris worked with an international team of physics educators to develop a five-day workshop for teachers of introductory physics at the college and secondary levels on Active Learning in Optics and Photonics (ALOP). While UNESCO has coordinated and funded the project, additional support has come from the Abdus Salam International Center for Theoretical Physics (ICTP), the International Society for Optical Engineering (SPIE), the American Association of Physics Teachers (AAPT), the National Academy of Sciences, the Association Francaise de l'Optique et Photonique, and Essilor.

UNESCO chose to develop this workshop curriculum on optics and photonics because it is an emerging field in contemporary physics and is relevant and adaptable to research and educational conditions in many developing countries. Photonics is basically applied geometric and physical optics—topics that teachers in developing counties often shy away from due to lack of equipment and lack of familiarity with the topics. ALOP is a professional development workshop targeted specifically to opening up jobs and research opportunities in fields such as optometry, atmospheric physics research and communications for students in the emerging global economy.

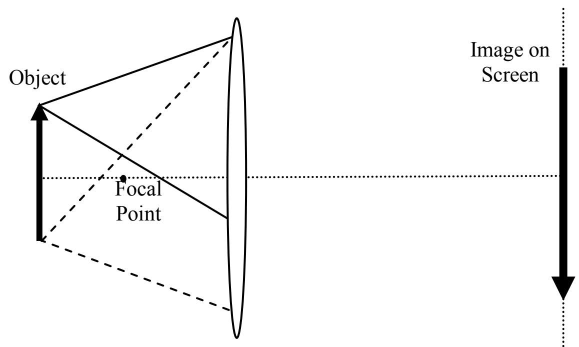



**FIGURE 9.** Question from *Light and Optics Conceptual Evaluation* in which students are asked to continue the four rays to illustrate how the image is formed on the screen.

ALOP has the following attributes:

1. It is designed for secondary and first year introductory faculty in developing countries.
2. It includes teacher updating and introduction to active learning approaches.
3. Workshops are locally organized.
4. It uses simple, accessible, inexpensive apparatus available locally or easily constructed.
5. Equipment sets are distributed at the end of each workshop.
6. It was designed by an international team of teacher trainers from developing and developed nations who volunteer their time as facilitators. The team has broad experience with a variety of teaching environments, cultural differences and the educational needs of peoples from many nations.
7. It provides teachers with tools for motivating student learning because the topics are introduced in a coherent and inherently fascinating way.
8. It replaces lectures with sequenced activities involving direct engagement with the physical world, informed by Physics Education Research (PER).
9. It provides participants with a PER-based conceptual evaluation that allows teachers to measure student learning.
10. It provides illustrated and guided inquiry materials for students and teacher guides with descriptions of apparatus that can be translated into local languages and adapted to meet local needs.

The original ALOP team that designed the ALOP curriculum (now led by Dr. Joseph Niemela of ICTP) includes David Sokoloff (University of Oregon, U.S.), Zorha Ben Lakhdar (University of Tunis, Tunisia), Vasudevan "Vengu" Lakshminarayanan (University of Waterloo, Canada), Ivan B. Culaba and Joel Maquiling (Ateneo de Manila University, The Philippines), and Alex Mazzolini (Swinburne University of Technology, Australia). More recent but significant additions to the team have included Souad Lahmar (University of Tunis, Tunisia), Khalid Berrada (Cadi Ayyad University, Morocco), Cesar Mora (National Polytechnic Institute, Mexico) and Angela Guzman (University of Central Florida, U.S.). Each member of the team brings a unique set of experiences and talents to ALOP.

ALOP's intensive workshop illustrates the pedagogy of active learning through carefully crafted learning sequences that integrate conceptual questions and hands-on activities like those found in *RealTime Physics*. Topics that require more expensive equipment or extra time on the part of students are presented as *Interactive Lecture Demonstrations*. Some ALOP curricular materials can be introduced in either format.

The ALOP Training Manual [10] contains six modules, each of which has embedded applications that are designed to intrigue students and help them realize that the basic physics has vital practical applications. The applications are designed to help students understand their everyday world and become aware of career opportunities based on the principles they are learning. Among the questions explored by these modules are:

**Introduction to Geometrical Optics:** How does an understanding of refraction explain how a broken test tube can be tossed in a container of "Magic" fluid and brought out whole? How can the concept of critical angle be used to explain why a laser beam can be confined inside a stream of water that moves in a parabolic path? Why does covering half a lens result in a different image than covering half the object?

**Lenses and Optics of the Eye:** How do spherical and cylindrical lenses focus light? How can spherical lenses be used to model a normal eye? How can external lenses correct near and far sightedness. How do cylindrical properties of the lenses in the eye cause astigmatism?

**Interference and Diffraction:** How do we infer that light can behave like waves? How can diffraction and interference be explored with equipment teachers and students can make for themselves at almost no cost?

**Atmospheric Optics:** Why do clouds sometimes appear white or grey or black? How can scattering be used to explain why skies are blue and sunsets red? How does scattered light become polarized?

**Optical Data Transmission:** How can information be carried by light waves? How can light be re-coded as an electrical signal? How does total internal reflection allow optical fibers to transmit information?

**Wavelength Division Multiplexing:** What is optical multiplexing and how has its use led to a dramatic increase in the information transferred by an optical fiber and decrease in the price of international phone calls and internet communications?

Fig. 10 shows some of the low-cost equipment used in these modules, while Fig. 11 shows a low cost alternative to the acrylic lens shown in Figs. 5, 6 and 8, a clear plastic storage container filled with water.

**FIGURE 10.** Low cost equipment used in ALOP: Inexpensive lasers, diffraction gratings from discarded CDs, slits scratched into coated mirrors, cellophane color filters and spectrometer made from a diffraction slide.

**FIGURE 11.** Low cost cylindrical lens—clear plastic food container filled with water.

To date, there have been sixteen ALOPs: Dhulikhel, Nepal, 17-21 December, 2011, Kigali, Rwanda, 14-18 November, 2011, Quezon City, The Philippines, 14-19 November, 2010, Constantine, Algeria, 14-19 May, 2010, Santiago, Chile, 11-15 January, 2010, Dhulikhel, Nepal, 11- 16 July, 2009, Bogota, Colombia, 23-27 June, 2009, Douala, Cameroon, 2-6 Dec., 2008, Lusaka, Zambia, 22-26 September, 2008, San Luis Potosi, Mexico, 5-11 December, 2007, Sao Paula, Brazil, 22-27 July, 2007, Dar es Salaam, Tanzania, 5-11 July, 2007, New Delhi, India, 6-11 November, 2006, Marrakech, Morocco, 23-28 April, 2006, Monastir, Tunisia, 22 March-2 April, 2005, and Cape Coast, Ghana, 15-19 November, 2004. Fig. 12 shows some active participants at ALOP Tunisia.

There has also been a second generation of ALOPs taught by previous participants in their local language. The ALOP Training Manual has been translated into French and Spanish, and is being translated into Arabic for a secondary teacher training program in Morocco.

**FIGURE 12.** A group of participants in ALOP Tunisia (2005).

Two good examples of the potential multiplying effect of a single ALOP and the impact on active learning teacher enhancement in Latin America are ALOP Sao Paulo, Brazil and ALOP San Luis Potosi, Mexico, both held in 2007. ALOP Sao Paulo was one of three mandated by the World Conference on Physics and Sustainable Development held in Durban, South Africa in 2005 [11]. Participants in this ALOP, principally those from Argentina began meetings during the ALOP that led to the creation of a workshop series "Aprendizaje Activo" in Optics (2008), Mechanics (2009), Electricity and Magnetism (2010), Thermodynamics and Fluids (2011) with funding independent of UNESCO. The principal members of this team were Julio Benegas, Graciela Punte, Graciela Romero, and Graciela Utges, all from Argentina, and Cesar Mora from Mexico. As for ALOP San Luis Potosi, Angela Guzman (Colombia/Florida) who attended then organized two additional ALOPs in Bogota, Colombia (2009) and Santiago, Chile (2010). Angela has also arranged to have ALOPs co-located with LACCEI engineering conferences in Arequippa, Peru (2010) and Medellin, Colombia (2011), and scheduled in Panama City, Panama (2012), all with funding independent of UNESCO. Note that all of these ALOPs have been attended by participants from all over Latin America.

A similar multiplying effect has taken place in North Africa, organized by the Tunisian and Moroccan participants in ALOP Tunisia (2005) and ALOP Morocco (2006).

The *Light and Optics Conceptual Evaluation* has been administered as a pre and post-test at each ALOP. This is done both to introduce learning assessment and action research to the participants, and to assess their learning in the workshop. The most recent data available are from ALOP Quezon City (November, 2010). Participants—who were mostly secondary physics teachers from all over The Philippines—averaged 80% on the post-test, a 63% gain from the pre-test. On the image formation question illustrated in Fig. 9, they improved from 48% on the pre-test to 79% on the post-test.

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” [12].

## V. CONCLUSIONS

This paper has presented some innovative applications of active learning to the teaching of optics, in both the developed and developing worlds. *RealTime Physics* and *Interactive Lecture Demonstrations* are used extensively in introductory physics classes in the U.S. to enhance student learning of physics concepts. The Active Learning in Optics and Photonics international series of workshops has been highly successful in introducing these active learning strategies in the developing world.

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[7] See for example http://www.vernier.com/products/sensors/ls-bta/

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[9] See for example http://sciencekit.com/blackboard-optics-kit/p/IG0023843/. A much less expensive alternative is to use a sufficiently large clear plastic food storage container filled with water as a cylindrical lens. See Fig. 11.

[10] Sokoloff, R. D., *Active Learning in Optics and Photonics Training Manual*, (UNESCO, Paris, 2006).

[11] See http://www.cospa.ntu.edu.tw/aappsbulletin/data/16-1/16_1_p37p38.pdf.

[12] See http://spie.org/x45049.xml.