Active Learning of Optics and Photonics Including Virtual Options

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ABSTRACT

Active learning strategies have been developed to enhance students' understanding of optics and photonics in the introductory physics course at the university, college and secondary levels. This paper will present examples of such activities that are designed to actively engage students in the learning process. These include activities using low-cost commonly available materials, those using technology and those designed for active, virtual learning. Research evidence of improved learning will also be presented.

Keywords: Active learning, introductory physics, optics, photonics, virtual learning

1. 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 in understandable ways—often in real time with the support of computer-based 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-based tools it has been possible to bring about significant changes in the laboratory *and lecture* 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*, with examples from optics, are described in the next two sections.

2. *REALTIME PHYSICS ACTIVE LEARNING LABS (RTP)*

RealTime Physics is a series of lab modules for the introductory physics course that often use computer-based 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.[6] Figure 1 shows the apparatus used to examine polarization of light in Lab 5, "Polarized Light." It consists of an

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Seventeenth Conference on Education and Training in Optics and Photonics: ETOP 2023,
edited by David J. Hagan, Mike McKee, Proc. of SPIE Vol. 12723, 127230U

analyzer fabricated from a Polaroid disk mounted on a precision rotary motion sensor[7] with a light sensor[8] mounted behind it. Using a light source consisting of a flashlight with a piece of Polaroid mounted on its lens, the graph in Figure 2 is traced out as the analyzer is rotated through one full rotation. The data may be modeled as a function of angle. Firgure 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 1. Apparatus used to analyze polarized light in RealTime Physics Module 4, Lab 5.

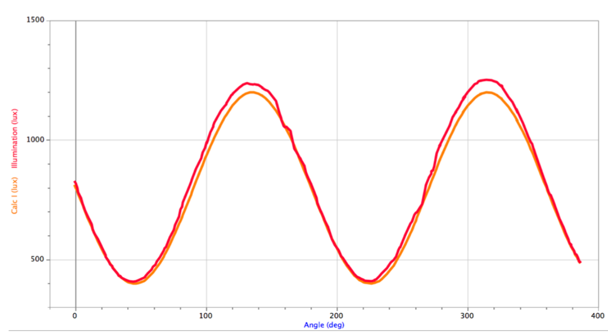


Figure 2. Graphs of the data collected with the apparatus in Figure 1, and of an $A\cos^2\theta$ model for Intensity vs. Angle

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 Figure 3, and the measured intensity distributions for a single slit and for two slits of the same width as the single one are both shown in Figure 4.

Two fairly "high-tech" examples have been chosen to illustrate the power of the computer 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! There are also many activities in *RTP* that use simple apparatus and 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.

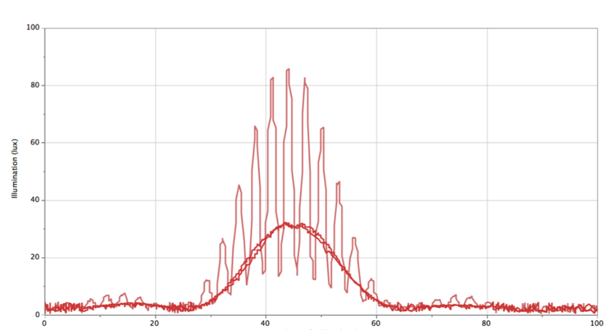


Figure 4. Graphs of the data collected with the apparatus in Figure 3, Intensity vs. Linear Position, for (a) a single slit and (b) two slits of the same width as the single one.

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

3. *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 demonstrations (often with data collected and graphs displayed in real-time using computer-based tools), compare these results with their predictions, and attempt to explain the observed phenomena.

Table 1 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.[1,4,5] 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.[9]

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) is used. Figure 5 shows the apparatus, and Figure 6 shows the result with the bulbs illuminated. Figure 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 Figure 8. Volunteers describe and explain the result in the context of the demonstration. As can be seen in Figure 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.

Assessments of learning with the *Image Formation with Lenses ILD* sequence demonstrate that students learn optics concepts better. Algebra-trigonometry-based general physics students at the University of Oregon had only a 20% normalized learning gain on the PER-based *Light and Optics Conceptual Evaluation* [6] 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%. 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 Figure 9.) Students are asked to continue these four rays through the lens to illustrate how the image is formed. 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.

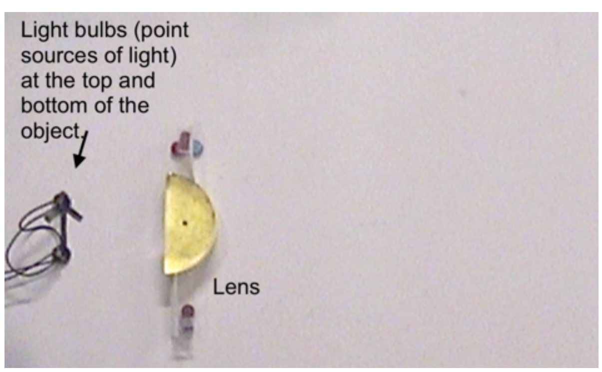


Figure 5. Apparatus for the *Image Formation with Lenses ILD* sequence, consisting of two small light bulbs and a large acrylic cyllindrical lens.

Table 1. The steps of the In-Class and Home Adapted *ILD* procedures

Steps of In-Class *ILDs*	**Steps of Home Adapted *ILDs***
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, i.e., different physical situation(s) based on the same concept(s) or applications of the concepts. This procedure is followed for each demonstration in the sequence.	1. Student downloads the Prediction Sheet (a Word document). 2. Student reads written description of the demonstration, and may view a photo, sketch or video of the apparatus. 3. Student records individual predictions on the Prediction Sheet. 4. *Only after recording predictions*, student views the demonstration as photo(s), video(s), or simulation(s) and observes the results. 5. Student describes the results on the Prediction Sheet, compares it with predictions and often answers probing questions that guide critical thinking about the results. (The instructor may choose to have student send in the filled-out prediction sheet.) This procedure is followed for each demonstration in the sequence. There is no Results Sheet, but student may keep a record on a sheet of paper.

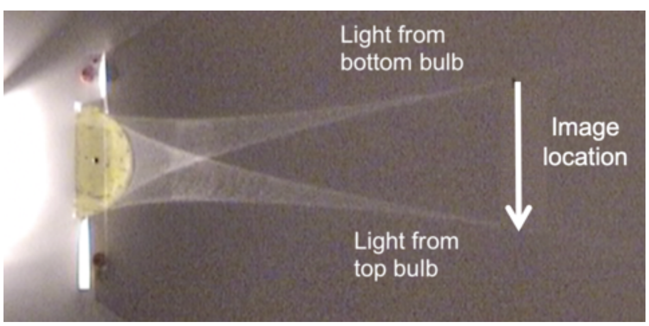
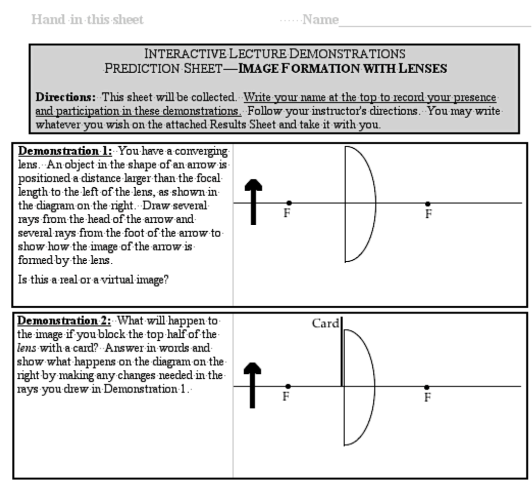


Figure 6. Apparatus pictured in Figure 5 with the two light bulbs lighted. The location and size of he image can be seen clearly on the white board surface behind the lens.



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?

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.

Figure7. Excerpt from the Prediction Sheet on which students record their predictions for the *Image Formation with Lenses ILD* sequence

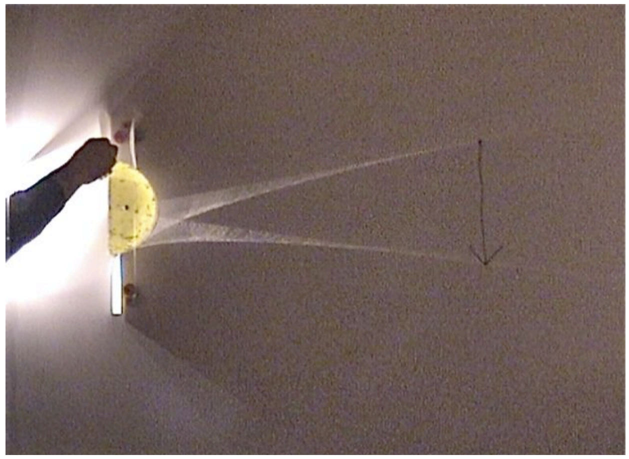


Figure 8. Apparatus in Figures 5 and 6 with the top half of the lens blocked by a card, for Demonstration 2. The image still forms at the same location, and has the same size, but it is dimmer than in Figure 6.

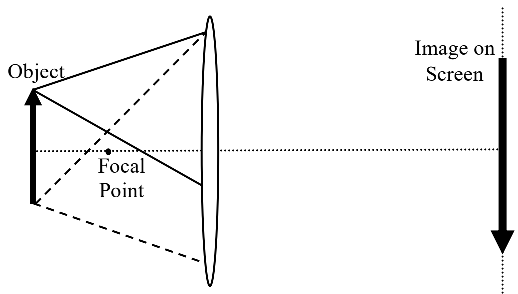


Figure 9. Question from Light and Optics Conceptual Evaluation in which students are asked to continue the four rays to illustrate how the image is formed on the screen.

4. HOME-ADAPTED INTERACTIVE LECTURE DEMONSTRATIONS

When in March, 2020 it became apparent that we were experiencing a pandemic from Covid-19 that would severely limit students' in-class experiences around the world for an unknown period of time, the author began a project to adapt the available *ILD* sequences for use by students online at home. This *Home Adapted ILD* project[10] was based on the following design principles:

1. The Home *ILDs* are largely based on in-class ones in the ILD book.[6]
2. As with the in-class *ILDs*, they are designed to introduce concepts or review/clarify them.
3. They are envisioned as one of a number of at-home components of a course.
4. Since many faculty had little experience with the features of online platforms like Zoom, the *ILDs* were designed for students working online, with no collaboration through group work (although breakout groups could be used).
5. In place of live demonstrations, the *Home Adapted ILDs* make use of available multimedia (photos, videos, graphs, and simulations--e.g., PhETs[11], Physlets[12], etc.) for students' experimental observations.

These considerations led to a modification of the eight-step in-class ILD procedure. The right side of Table 1 lists the revised five steps. Small group discussions and sharing of ideas with the entire class are dropped, while predictions are retained to engage the students' attention and enhance critical thinking.

As an example, the "Image Formation with Lenses" *Home Adapted ILDs* are based on the original in-class *ILDs* described in Section 3. Figure 10 shows a screenshot of the webpage for these *ILDs*. For observations, students follow linke to photos of the experimental apparatus shown in Figures 5, 6 and 7.

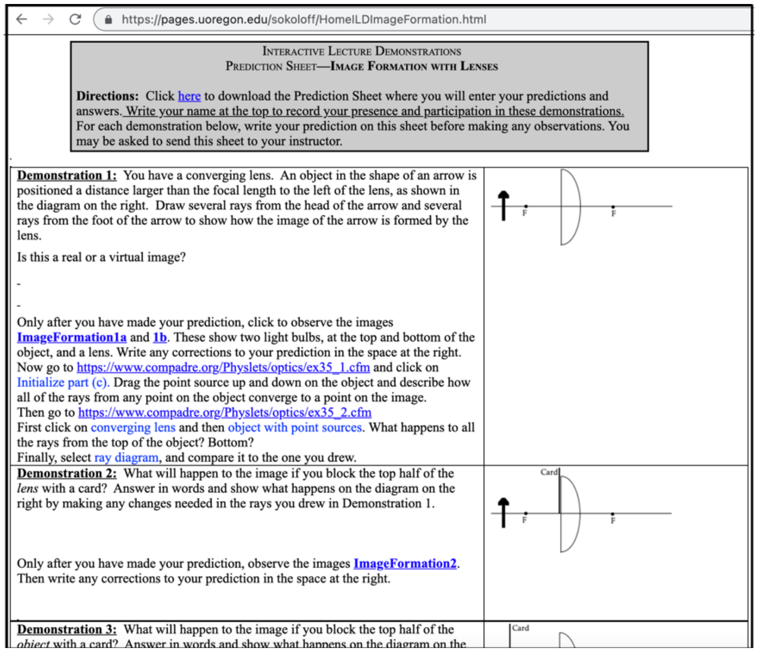


Figure 10. Screenshot of a portion of the webpage for the "Image Formation with Lenses" Home Adapted ILDs.

To complete Demonstration 1, there are two links to parts of the Physlet "Lenses"[12], helping the students to visualize the infinite number of rays (cone of light) that emanate from each point on the object and to compare their ray diagram to a correctly drawn one. Screen shots from this Physlet are shown in Figure 11.

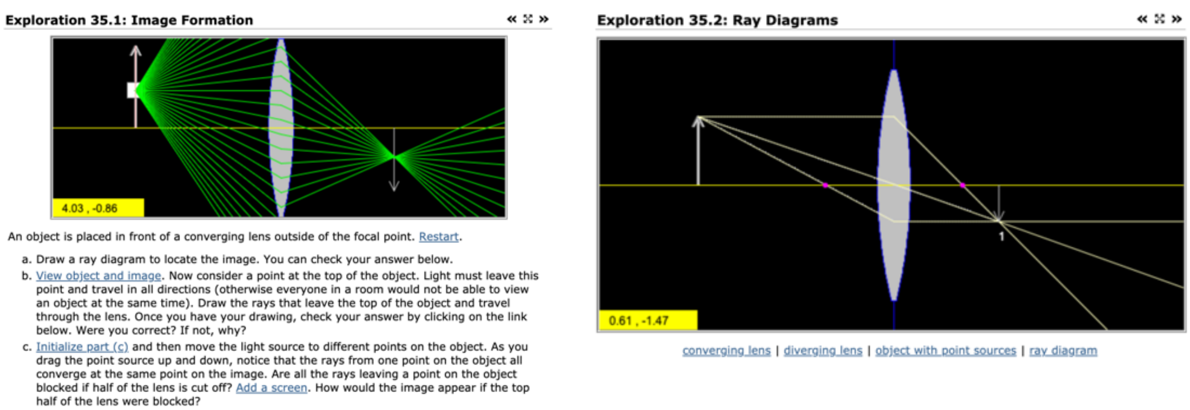


Figure 11. Screenshots from the Physlet "Lenses" used in the Home Adapted ILDs "Image Formation with Lenses."

5. ACTIVE LEARNING IN OPTICS AND PHOTONICS

Beginning in 2004, Dr. Minella Alarcon, Program Specialist (now retired) for Science 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 Optics and Photonics (SPIE), the American Association of Physics Teachers (AAPT), the National Academy of Sciences, the Association Francaise de l'Optique et Photonique, and Essilor.

ALOP [6,11,12] 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.
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 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.

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* [12] 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. Starting with geometrical optics concepts and optics of the eye, the modules progress through physical optics and atmospheric optical phenomena, ending with a capstone Module 6 that builds upon everything else to explore optical communications. The applications are designed to help students understand their everyday world and become aware of career opportunities based on the principles they are learning. Figure 10 shows some of the low-cost equipment used in these modules, while Figure 11 shows a low-cost alternative to the acrylic cylindrical lens shown in Figures 5, 6 and 8--a clear plastic storage container filled with water.

To date, there have been 37 full 5-day ALOP workshops (15 in Africa, 10 in Asia, 9 in Latin America, and 3 in E. Europe/Eurasia) and two truncated "Introduction to ALOP" virtual versions, presented at international physics education conferences. Figure 12 shows some active participants at one of the first ALOPs (in Tunisia in 2005).

Figure 12. 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 13. Low-cost cylindrical lens—clear plastic food container filled with water.

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 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.” [14]

Figure 14. A group of participants in one of the first ALOPs (Monastir, Tunisia, 2005).

6. 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.

ACKNOWLEDGEMENTS

The author is indebted to Priscilla Laws of Dickinson College and Ronald Thornton of Tufts University for their contributions to the development of *RTP* and *ILDs*. He thanks the members of the ALOP Team--Alex Mazzolini, Joe Niemela, Ivan Culaba, Joel Maquiling, Vengu Lakshminarayanan, Zohra Ben Lakhdar, Souad Lahmar, Khalid Berrada, Angela Guzman, Omar Ormachea, and Cesar Mora--for their collaboration on this exciting adventure in active learning.

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

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