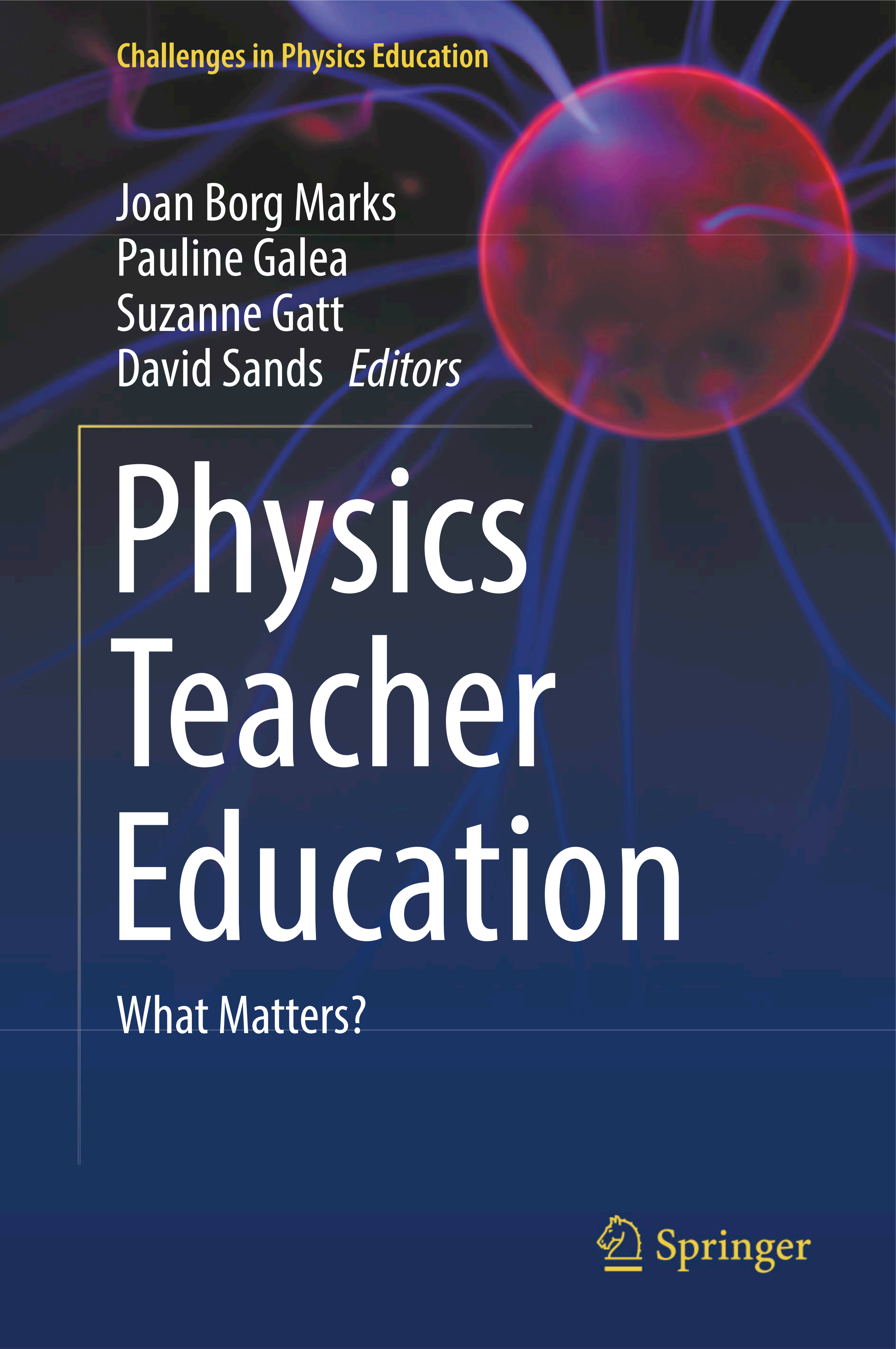

Challenges in Physics Education

Joan Borg Marks
Pauline Galea
Suzanne Gatt
David Sands *Editors*

Physics Teacher Education

What Matters?

Springer

Challenges in Physics Education

Series Editor

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This book series covers the many facets of physics teaching and learning at all educational levels and in all learning environments. The respective volumes address a wide range of topics, including (but not limited to) innovative approaches and pedagogical strategies for physics education; the development of effective methods to integrate multimedia into physics education or teaching/learning; innovative lab experiments; and the use of web-based interactive activities. Both research and experienced practice will feature prominently throughout.

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Challenges in Physics Education addresses professionals, teachers, researchers, instructors and curriculum developers alike, with the aim of improving physics teaching and learning, and thereby the overall standing of physics in society.

Book proposals for this series my be submitted to the Publishing Editor: Marina Forlizzi; email: Marina.Forlizzi@springer.com

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Contents

Papers from Keynote Contributions

Initial Teacher Training

Teacher Professional Development

Teaching Approaches to Facilitate Learning

Papers from Keynote Contributions

Exploring Multimedia to Adapt Interactive Lecture Demonstrations (ILDs) for Home Use

David R. Sokoloff

Abstract With the need for distance learning materials thrust upon us alarmingly and suddenly by the Covid-19 pandemic, it is not unreasonable that many have fallen back on passive presentation of lectures and black/whiteboard notes using some mode of video conferencing. But is it possible to maintain some element of active learning for our introductory physics students? This paper will describe attempts to use the wealth of multimedia materials currently available (videos, simulations, photos, computer-based laboratory graphs, etc.) to adapt Interactive Lecture Demonstrations (ILDs*)* into a form that can be used by students at home. While recognizing that small-group discussions—and sharing in any way—may be difficult for many, these Home-Adapted ILDs retain student predictions as an essential element in engaging students in the learning process. This paper will review the design features of ILDs, describe some of the multimedia resources that are freely available, and present some examples of Home-Adapted ILDs. As we enter an uncertain future, this approach could have important applicability for pre-service and in-service teacher preparation programs, as well as for undergraduate physics students.

Keywords Active learning · Interactive lecture demonstrations · Distance learning · Virtual learning · Multimedia

1 Introduction

Interactive Lecture Demonstrations (ILDs) are an active learning strategy first developed in the 1990s and designed to promote the active engagement of students in learning physics concepts from live lecture demonstrations (Sokoloff and Thornton 1997, 2004; Sokoloff 2016). Students, including those planning to be teachers, come into their first introductory physics course at the high school or college level with definite views about physics concepts (often wrong) based on their life experiences that are not changed by traditional, passive instruction. Physics Education Research

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(PER) has demonstrated that the vast majority of these students leave a traditionally taught course with the same (incorrect) views, and little understanding of physics concepts, regardless of the skill of the instructor (Hake 1998; McDermott 1991).

In summary: *if no effort is made to engage students in the learning process, they will not learn physics concepts!* During the pandemic, we are faced with many learning environments *that are worse than traditional!* Are there ways that can help us maintain active learning for our students through virtual learning? This paper describes a strategy adapted from ILDs that students can use online, at home—Home-Adapted Interactive Lecture Demonstrations.

2 In-Class Interactive Lecture Demonstrations (ILDs)

Active learning environments, like ILDs, have the following characteristics:

(1) The instructor's role is as a guide—not as the authority;
(2) Students construct knowledge from observations of the physical world as much as possible;
(3) A learning cycle of prediction/observation/comparison is used—challenging students' beliefs;
(4) Collaboration with peers is encouraged;
(5) Laboratory work is often used to learn basic concepts;
(6) PER-validated, active learning materials are used as components of the course.

Students generally enjoy watching traditional lecture demonstrations, so does that mean that they are engaged by and learn from them? Research has shown that unless a special effort is made to engage students (e.g., by asking them to make predictions about the outcome of the demonstration), the majority of students cannot even correctly describe the result of a demonstration they experience in lecture after class (Crouch et al. 2004).

In-class ILDs are designed to engage students in the learning process as they observe and think critically about lecture demonstrations. Sequences of *single*-concept demonstrations are presented using an eight-step procedure. The left side of Table 1 lists the steps.

ILDs are designed to introduce or review the most important concepts to be learned in the course. In a typical course, one lecture a week might be devoted to ILDs. Once students have mastered these concepts, other lectures can build upon this understanding. ILDs have also been used in conjunction with laboratories to introduce students to the concepts to be explored and to the apparatus that they will use, before beginning lab work.

Using the ILD procedure with carefully designed ILD sequences has been demonstrated to improve students' understanding of physics concepts (Sokoloff and Thornton 1997; Sokoloff 2016). Complete written materials (prediction and results sheets) for ILDs in 28 different topic areas from the introductory calculus-based or

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

Steps of In-Class ILDs	Steps of Home-Adapted ILDs
1. Describe the demonstration and do it for the class without displaying the results	1. Student downloads the prediction sheet (a word document)
2. Ask students to record individual predictions on a prediction sheet. (Students are assured that predictions are not graded right or wrong, although a small amount of credit might be awarded for attendance on days that ILDs are carried out in lecture.)	2. Student reads written description of the demonstration and may view a photo, sketch, or video of the apparatus
3. Have the class engage in small-group discussions	3. Student records individual predictions on the prediction sheet
4. Elicit common student predictions from the whole class	4. *Only after recording predictions*, student views the demonstration as photo(s), video(s), or simulation(s) and observes the results
5. Ask students to record their final predictions on the prediction sheet (which will be collected at the end of lecture)	5. Student describes the results on the prediction sheet, compares them with predictions and often answers probing questions that guide critical thinking about the results. (The instructor may choose to have students send in the filled-out prediction sheet.)
6. Carry out the demonstration and display the results in an understandable way	This procedure is followed for each of the demonstrations in the sequence. There is no results sheet, but student may keep a record on a sheet of paper
7. Ask for a few student volunteers to describe the results and discuss them in the context of the demonstration	
8. If appropriate, ask for a few student volunteers to discuss analogous physical situations with different “surface” features, or describe an application of the illustrated concept	
This procedure is followed for each of the demonstrations in the sequence. Students may fill out a results sheet as a record to take home with them	

algebra-based physics course are available in the book, *Interactive Lecture Demonstrations*, published by Wiley (Sokoloff and Thornton 2004). The book also contains background information on the origins of ILDs, teachers’ guides on each of the sequences, and teacher preparation notes to aid with presentations in class.

3 Home-Adapted Interactive Lecture Demonstrations (ILDs)

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 at home, online. This Home-Adapted ILD project [1] was based on the following design principles:

(1) The ILDs are largely based on in-class ones in the ILD book (Sokoloff and Thornton 2004);
(2) As with the in-class ILDs, they are designed to introduce concepts or review or clarify them;
(3) They are envisioned to be one of a number of at-home components of a course;
(4) Since many faculty users might have little experience with the features of online platforms like Zoom[2], the ILDs envision students working alone online, with no requirement of collaboration through group work (although individual faculty could choose to add such features);
(5) In place of live demonstrations, the Home-Adapted ILDs make use of available multimedia (photos, videos, graphs, and simulations, e.g., PhETs[3], Physlets[4], 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 critical thinking.

Table 2 contains a list of the 26 sequences of Home-Adapted ILDs that have been developed. The remainder of this paper describes some examples from these, and how the available multimedia resources were incorporated in them in place of live demonstrations.

4 Image Formation with Lenses Home-Adapted ILDs

The "Image Formation with Lenses" Home-Adapted ILDs are based on the original in-class ILDs of the same name (Sokoloff and Thornton 2004; Sokoloff 2016). They deal with the real image formed by a converging lens, the representation of this process with a ray diagram, and the effect on the image of various changes in the experiment, for example blocking half of the lens, blocking half of the object, removing the lens, etc. Figure 1 shows a screenshot of the webpage for these ILDs.

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[1] https://pages.uoregon.edu/sokoloff/HomeAdaptedILDs.html

[2] See, for example, https://zoom.us

[3] https://phet.colorado.edu/en/simulations

[4] https://www.compadre.org/Physlets

Table 2 The 26 Home-Adapted ILD sequences

1. Kinematics 1-Human Motion	14. Magnetic Forces
2. Kinematics 2-Changing Motion	15. Electromagnetic Induction and Faraday's and Lenz's laws
3. Force and Motion-Newton's 1st and 2nd Laws	16. Reflection and Refraction
4. Force and Motion-Newton's 3rd Law	17. Image Formation with Lenses
5. Vectors	18. Polarized light
6. Two-Dimensional Motion: Projectile Motion	19. Interference of light
7. Kinetic and Potential Energy	20. Diffraction of light
8. Momentum	21. Simple Harmonic Motion
9. Rotational Motion	22. Sound
10. Electrostatic Field, Force, and Potential	23. Introduction to Heat and Temperature
11. Introduction to DC circuits	24. Specific Heat
12. Current in series and parallel circuits	25. Phase Change
13. RC circuits	26. Heat Engine

Note that students first download the Prediction Sheet for these ILDs by clicking in the Directions box. They are then presented with a scenario of an object outside the focal point of a converging lens and asked to draw a ray diagram. After they have completed their diagram, they can click on two links to see photos of the experimental apparatus, consisting of two light bulbs (point sources) and an acrylic lens. Figure 2a and b show the photos viewable at these two links, first with the light bulbs off and then with them illuminated.

To complete demonstration 1, there are two links to parts of the Physlet "Lenses"[5], 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. As can be seen in Fig. 1, demonstration 2 explores what will happen if the top half of the lens is blocked by a card. This demonstration in its in-class form (along with the ones that follow) has been demonstrated to help students understand the consequences of cones of light from a point source, rather than thinking of a small number of discrete rays (Sokoloff 2016).

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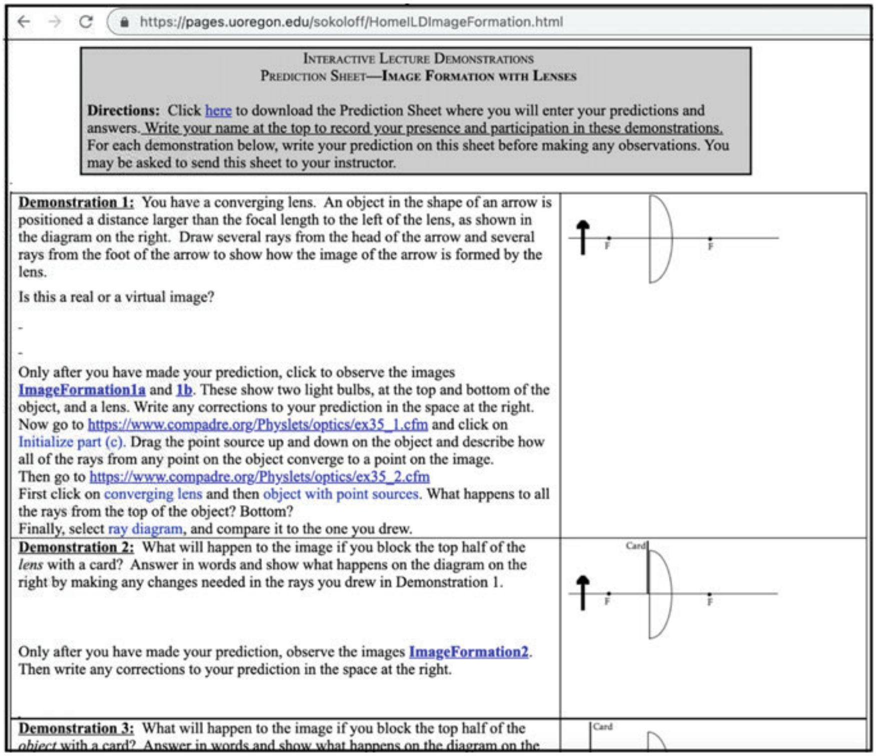
[5] https://www.compadre.org/Physlets/optics/intro35.cfm



https://pages.uoregon.edu/sokoloff/HomeILDImageFormation.html

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

Directions: Click here to download the Prediction Sheet where you will enter your predictions and answers. Write your name at the top to record your presence and participation in these demonstrations. For each demonstration below, write your prediction on this sheet before making any observations. You may be asked to send this sheet to your instructor.

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?

-

-

Only after you have made your prediction, click to observe the images **ImageFormation1a** and **1b**. These show two light bulbs, at the top and bottom of the object, and a lens. Write any corrections to your prediction in the space at the right.
Now go to https://www.compadre.org/Physlets/optics/ex35_1.cfm and click on Initialize part (c). Drag the point source up and down on the object and describe how all of the rays from any point on the object converge to a point on the image.
Then go to https://www.compadre.org/Physlets/optics/ex35_2.cfm
First click on converging lens and then object with point sources. What happens to all the rays from the top of the object? Bottom?
Finally, select ray diagram, and compare it to the one you drew.

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.

Only after you have made your prediction, observe the images **ImageFormation2**. Then write any corrections to your prediction in the space at the right.

Demonstration 3: What will happen to the image if you block the top half of the *object* with a card? Answer in words and show what happens on the diagram on the

Fig. 1 Screenshot of portion of the webpage for the "Image Formation with Lenses" Home-Adapted ILDs

5 Force and Motion-Newton's 3rd Law Home-Adapted ILDs

The "Force and Motion-Newton's 3rd Law" Home-Adapted ILDs are again based on the original in-class ILDs (Sokoloff and Thornton 2004). They deal with:

(1) identifying action-reaction pairs of forces and
(2) establishing, through a number of scenarios, exactly what Newton's 3rd Law means, namely that these pairs are always equal in magnitude and opposite in direction.

The experiments make use of two force sensors mounted on carts that interact with each other in various ways. Videos simultaneously display the motions of the carts and the force versus time graphs. IOLab smart carts [6] were used to create the videos, although any computer-based laboratory system and carts could be used[7].

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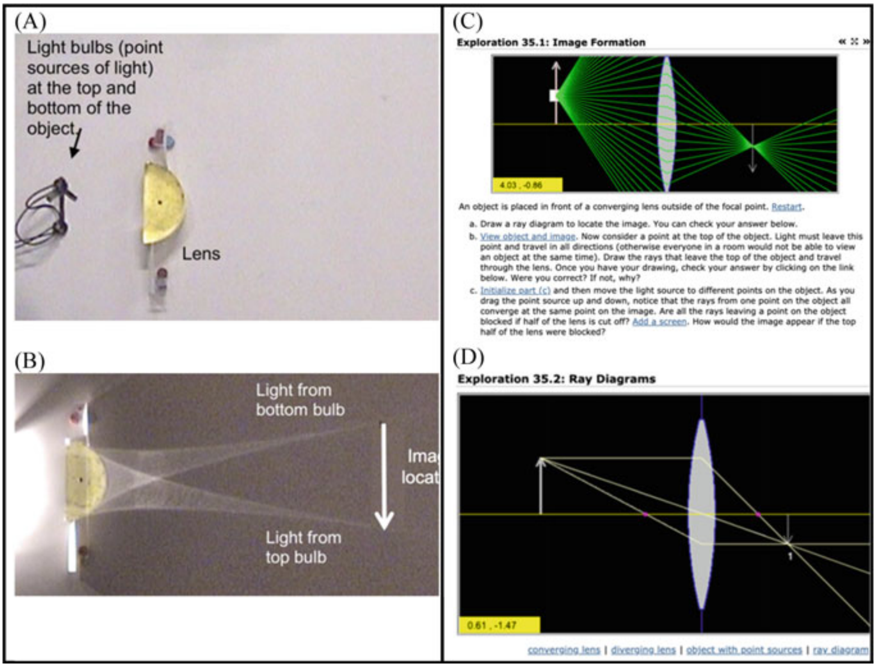
[6] https://store.macmillanlearning.com/us/product/iOLab-Version-2.0/p/1464101469

[7] https://www.vernier.com; https://www.pasco.com



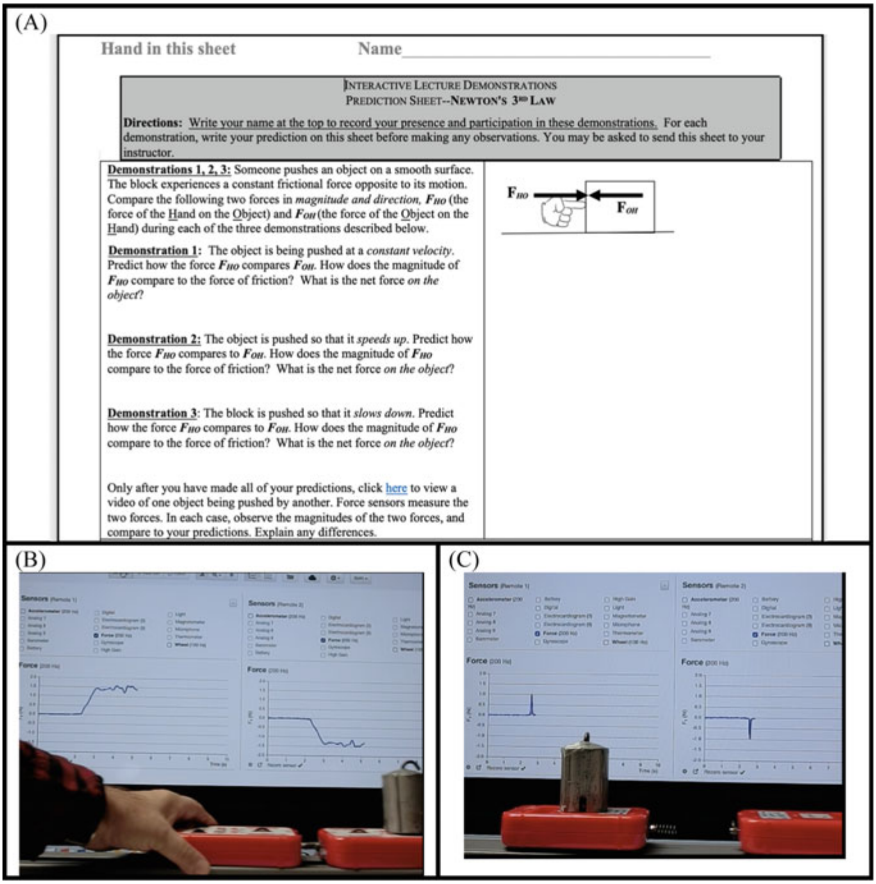
An object is placed in front of a converging lens outside of the focal point. Restart.

a. Draw a ray diagram to locate the image. You can check your answer below.
b. View object and image. Now consider a point at the top of the object. Light must leave this point and travel in all directions (otherwise everyone in a room would not be able to view an object at the same time). Draw the rays that leave the top of the object and travel through the lens. Once you have your drawing, check your answer by clicking on the link below. Were you correct? If not, why?
c. Initialize part (c) and then move the light source to different points on the object. As you drag the point source up and down, notice that the rays from one point on the object all converge at the same point on the image. Are all the rays leaving a point on the object blocked if half of the lens is cut off? Add a screen. How would the image appear if the top half of the lens were blocked?

Fig. 2 Images from the Home-Adapted ILDs "Image Formation with Lenses" demonstration 1. **a** Experimental apparatus. **b** Formation of real image. **c** Simulation of multiple rays with movable point source on the object from the physlet "lenses." **d** Ray diagram from the physlet "lenses"

Figure 3a shows an excerpt from the downloadable Prediction Sheet. Students are first asked to make predictions for demonstrations 1–3 in which a heavier cart is pushed by another, first speeding up, then moving at a steady speed, and finally slowing down to a stop. Figure 3b shows the final frame of the video of this demonstration. It is clear from the force-time graphs that the two forces are equal and opposite during all three parts of the carts' motion. Demonstrations 4–8 involve different collisions between the two carts. In each case, students are asked to predict the forces before observing the video. Figure 3c shows a frame from the video for demonstration 6, an asymmetrical collision between heavy and light carts, with the heavy cart initially moving and the lighter one at rest. Having been engaged by the predictions, the observations convince the vast majority of students that action-reaction forces are always equal and opposite.

The in-class form of these ILDs has been demonstrated through pre and post-testing to significantly improve students' understanding of these concepts (Sokoloff and Thornton 1997).



Hand in this sheet Name________________________

INTERACTIVE LECTURE DEMONSTRATIONS
PREDICTION SHEET--NEWTON'S 3RD LAW

Directions: Write your name at the top to record your presence and participation in these demonstrations. For each demonstration, write your prediction on this sheet before making any observations. You may be asked to send this sheet to your instructor.

Demonstrations 1, 2, 3: Someone pushes an object on a smooth surface. The block experiences a constant frictional force opposite to its motion. Compare the following two forces in *magnitude and direction*, F_{HO} (the force of the Hand on the Object) and F_{OH} (the force of the Object on the Hand) during each of the three demonstrations described below.

Demonstration 1: The object is being pushed at a *constant velocity*. Predict how the force F_{HO} compares F_{OH}. How does the magnitude of F_{HO} compare to the force of friction? What is the net force *on the object*?

Demonstration 2: The object is pushed so that it *speeds up*. Predict how the force F_{HO} compares to F_{OH}. How does the magnitude of F_{HO} compare to the force of friction? What is the net force *on the object*?

Demonstration 3: The block is pushed so that it *slows down*. Predict how the force F_{HO} compares to F_{OH}. How does the magnitude of F_{HO} compare to the force of friction? What is the net force *on the object*?

Only after you have made all of your predictions, click here to view a video of one object being pushed by another. Force sensors measure the two forces. In each case, observe the magnitudes of the two forces, and compare to your predictions. Explain any differences.

Fig. 3 **a** Excerpt from prediction sheet for the Home-Adapted ILD sequence "Force and Motion-Newton's 3rd Law." **b** Force-time graphs of action-reaction pair of forces when a heavy IOLab is pushed along by a lighter one (demonstrations 1–3). **c** Force-time graphs for a heavier IOLab colliding with a lighter one (demonstration 6)

6 Introduction to DC Circuits Home-Adapted ILDs

Adapted from the original in-class ILDs of the same name, "Introduction to DC Circuits" introduces students to basic ideas about Ohm's law, ohmic and non-ohmic devices, series and parallel connections, and the basic relationships between currents and voltages in these. Figure 4a shows an excerpt from the downloadable Prediction Sheet for these demonstrations.

To facilitate student observations at home with simple circuits, we make use of the PhET "Circuit Construction Kit"[8]. This simulation enables students to construct

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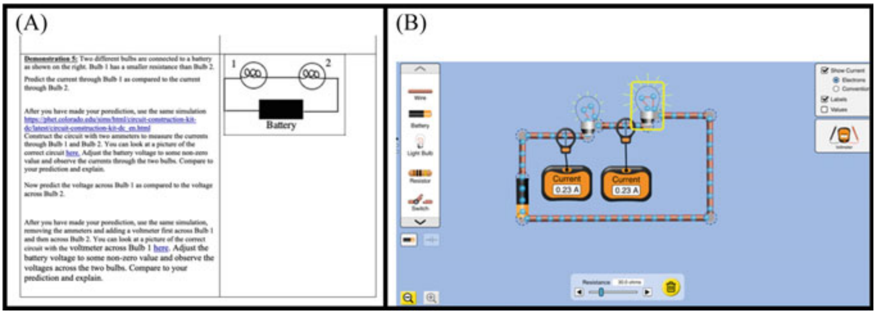
[8] https://phet.colorado.edu/en/simulation/circuit-construction-kit-dc



Demonstration 5: Two different bulbs are connected to a battery as shown on the right. Bulb 1 has a smaller resistance than Bulb 2.

Predict the current through Bulb 1 as compared to the current through Bulb 2.

After you have made your porediction, use the same simulation https://phet.colorado.edu/sims/html/circuit-construction-kit-dc/latest/circuit-construction-kit-dc_en.html
Construct the circuit with two ammeters to measure the currents through Bulb 1 and Bulb 2. You can look at a picture of the correct circuit here. Adjust the battery voltage to some non-zero value and observe the currents through the two bulbs. Compare to your prediction and explain.

Now predict the voltage across Bulb 1 as compared to the voltage across Bulb 2.

After you have made your porediction, use the same simulation, removing the ammeters and adding a voltmeter first across Bulb 1 and then across Bulb 2. You can look at a picture of the correct circuit with the voltmeter across Bulb 1 here. Adjust the battery voltage to some non-zero value and observe the voltages across the two bulbs. Compare to your prediction and explain.

Fig. 4 **a** Excerpt from the prediction sheet used by students for the Home-Adapted ILDs "Introduction to DC Circuits." **b** Simple series DC circuit with two light bulbs of different resistances connected in series with a battery, set up in the PhET "Circuit Constriction Kit."

simple DC circuits of their choice by dragging circuit elements (bulbs, wires, batteries, switches, meters, etc.) into the workspace, and observing the resulting currents and voltages. Figure 4b shows a screenshot illustrating the observations for demonstration 5, comparing the currents flowing through two light bulbs of different resistances connected in series. Before an active intervention like this, the majority of students in an introductory course would predict that current is "used up" flowing through a light bulb, and therefore, the current flowing through the bulb on the right would be larger than that flowing through the one on the left.

7 Introduction to Heat and Temperature Home-Adapted ILDs

As a last example of Home-Adapted ILDs, Fig. 5a shows an excerpt from the downloadable Prediction Sheet for "Introduction to Heat and Temperature." This sequence of ILDs, like the original in-class ones, is designed to intervene with student confusion about the concepts of "heat" and "temperature". A number of demonstrations are set up to look at situations in which it is clear that temperature change and heat flow are related, but are decidedly not the same thing.

In demonstrations 1 and 2 (the latter illustrated in Fig. 5) a hot piece of metal cools to room temperature under two scenarios:

(1) coming to equilibrium in the air and
(2) coming to equilibrium in room-temperature water

In demonstration 2 the temperatures are measured by two Vernier [9] temperature sensors, one in the water and the other embedded in a small brass cylinder. The data are displayed with Vernier LoggerPro software, and the entire scenario—both

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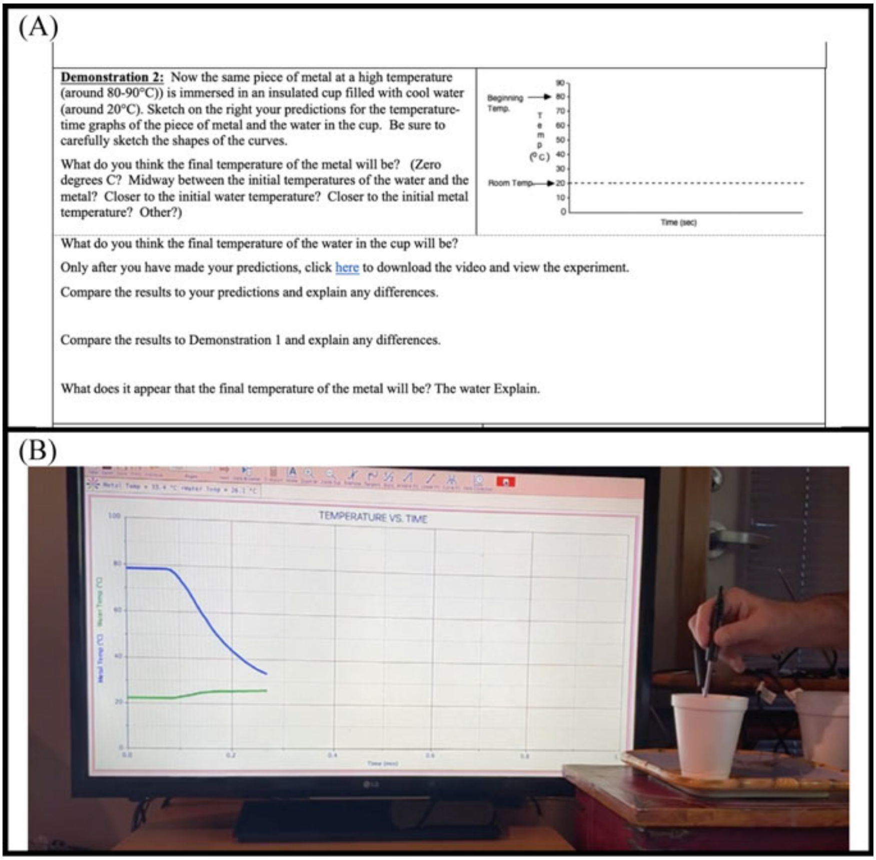
[9] https://www.vernier.com



Demonstration 2: Now the same piece of metal at a high temperature (around 80-90°C)) is immersed in an insulated cup filled with cool water (around 20°C). Sketch on the right your predictions for the temperature-time graphs of the piece of metal and the water in the cup. Be sure to carefully sketch the shapes of the curves.

What do you think the final temperature of the metal will be? (Zero degrees C? Midway between the initial temperatures of the water and the metal? Closer to the initial water temperature? Closer to the initial metal temperature? Other?)

What do you think the final temperature of the water in the cup will be?

Only after you have made your predictions, click here to download the video and view the experiment.

Compare the results to your predictions and explain any differences.

Compare the results to Demonstration 1 and explain any differences.

What does it appear that the final temperature of the metal will be? The water Explain.

Fig. 5 **a** Excerpt from downloadable prediction sheet for Home-Adapted ILDs "Introduction to Heat and Temperature" showing demonstration 2. **b** Frame from a video showing the experiment and the evolution of graphs of the temperatures of a hot piece of brass (blue) immersed in cold water (green) as they come to thermal equilibrium

experiment and data display—is recorded on a video. Figure 5b shows a frame from this video. After comparing the observed results to their predictions, the students are asked to compare the results to the ones when the brass cools in air.

8 Conclusions

ILDs were first developed 30 years ago as one strategy to make a large (or small) lecture class a more active learning environment. Research evidence has demonstrated the effectiveness of this classroom strategy (Sokoloff and Thornton 1997; Sokoloff 2016). The availability of vast multimedia resources has enabled the author to develop Home-Adapted ILDs in which these resources substituted for live demonstrations allow students to carry out the prediction, observation, and comparison components of ILDs. Using these resources, Home-Adapted ILDs in most topic areas from the introductory physics course has been developed.

Because the Home-Adapted ILDs were developed under the duress caused by the Covid-19 pandemic beginning in March 2020, it has not been possible to organize research studies on their effectiveness. If they are to be used in the future, studies using pre- and post-testing should be carried out, similar to those carried out for in-class ILDs (Sokoloff and Thornton 1997; Sokoloff 2016). However, it is speculated that retention of the prediction, observation, and comparison steps should result in robust conceptual learning.

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References

Crouch C, Fagen A, Callan JP, Mazur E (2004) Classroom demonstrations: learning tools or entertainment? Am J Phys 72:835

Hake R (1998) Interactive-engagement versus traditional methods: a six-thousand-student survey of mechanics test data for introductory physics courses. Am J Phys 66:64

McDermott LC (1991) Millikan lecture 1990: what we teach and what is learned—closing the gap. Am J Phys 59:301

Sokoloff DR (2016) Active learning of introductory light and optics. Phys Teach 54(1):18–22

Sokoloff DR, Thornton RK (1997) Using interactive lecture demonstrations to create an active learning environment. Phys Teach 35(6):340

Sokoloff DR, Thornton RK (2004) Interactive lecture demonstrations. Wiley, Hoboken, NJ

QuILTs: Validated Teaching–Learning Sequences for Helping Students Learn Quantum Mechanics

Emily Marshman and Chandralekha Singh

Abstract We have been developing and validating teaching–learning sequences for use in quantum mechanics courses, called Quantum Interactive Learning Tutorials (QuILTs). Here we describe the development and validation of a guided inquiry-based QuILT focusing on a Mach–Zehnder interferometer with single photons that strives to help students develop the ability to apply fundamental quantum principles to physical situations in quantum optics. We describe how cognitive task analyses and empirical investigations of student difficulties informed the development of the QuILT and discuss specific examples of how the QuILT was iteratively refined. We present the findings from in-class evaluations suggesting that the QuILT was effective in helping students learn abstract quantum concepts in the context of a Mach–Zehnder interferometer experiment. Implications for developers of teaching–learning sequences and learning progressions researchers are discussed.

Keywords Physics education research · Quantum physics · Research-validated learning tools · QuILTs · Teaching-learning sequences · Single-photon experiments

1 Introduction

Many researchers have been focusing on developing teaching–learning sequences, which are well-validated learning activities that use research on student reasoning as a guide, based on empirical research (Meheut and Psillos 2004; Andersson and Bach 2004; Psillos and Kariotoglou 2015). For example, in physics, researchers have developed Interactive Learning Tutorials (McDermott and Shaffer 1992, 2002; McDermott 1996; McDermott et al. 1994) that are used frequently in the teaching and learning of physics concepts. Interactive learning tutorials are a type of Teaching–Learning Sequence (TLS) that aim to deepen students' conceptual understanding and reasoning skills. They are based upon a cognitive task analysis from an expert perspective (Wieman 2015; Reif 1995) and empirical research on student reasoning

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and the common difficulties. Interactive learning tutorials use a guided inquiry-based approach and use student difficulties as resources to help them develop a robust understanding of physics.

TLSs are positioned within broader learning progressions, which are descriptions of the successively more sophisticated ways of thinking about a topic that can follow one another as students learn about and investigate a topic; they layout in words and examples what it means to move toward more expert understanding (Maries et al. 2017a; National Research Council. Learning Progressions 2007; Masters and Forster 1997; Alonzo and Steedle 2008). Development of effective TLSs involves knowledge of where students are in the learning progression—i.e., the prior knowledge students need to bring to bear in order to develop expertise in a topic. Developers of TLSs also need to identify "expert understanding" in the topic at hand. Identifying the knowledge and skills required for expertise in a particular topic involves performing a cognitive task analysis with experts in the field. However, content experts' cognitive processes are often implicit and automated (Singh 2002; Singh 2008a; Singh 2008b; Lin and Singh 2015, 2013, 2011) and experts may overlook steps, skills, or processes in the learning progression. As a result, it is imperative that educational researchers also refine TLSs via interviews with students to fill in any "gaps" that content experts may have overlooked. Other issues such as the use of technology and providing students with additional resources as appropriate (e.g., quantitative models to help them understand concepts) should also be considered.

Here, we focus on the development and validation of TLSs for use within a broader quantum mechanics learning progression. Quantum mechanics can be a challenging subject for many students since one does not generally observe quantum phenomena in everyday experience and the formalism is unintuitive. Several studies have focused on student understanding and difficulties in quantum mechanics, cognitive issues related to learning quantum mechanics, and instructional strategies to improve teaching and learning in quantum mechanics (Jolly et al. 1998; Johnston et al. 1998; Müller and Wiesner 2002; Singh 2001, 2008a, 2008b; Wittmann et al. 2002; Zollman et al. 2002; Domert et al. 2005; Singh et al. 2006; McKagan et al. 2008; Lin and Singh 2009a; Kohnle et al. 2010a, 2010b; Michelini and Zuccarini 2014; Singh and Marshman 2015a; Marshman and Singh 2015a; Emigh et al. 2015; Gire and Price 2015; Michelini et al. 2020). We have been investigating the difficulties students have in learning quantum mechanics and developing guided, inquiry-based Quantum Interactive Learning Tutorials (QuILTs) to help students in upper-level quantum mechanics courses learn about foundational topics in quantum mechanics (Singh 2005, 2006a, 2006b, 2007; Singh and Zhu 2009; Mason and Singh 2009, 2010; Zhu and Singh 2009, 2012a, 2012b, 2012c, 2012d, 2012e, 2012f, 2013; Lin and Singh 2009b; Zhu 2011; Singh and Marshman 2014a, 2014b, 1509, 2015b, 2016; Marshman 2014, 2015, 2016; DeVore and Singh 2015, 2020; Brown 2015; Marshman and Singh 2015b, 2016, 2017a, 2017b, 2017c, 2018, 2019; Maries et al. 2015; Sayer et al. 2015, 2016a, 2016b; Keebaugh et al. 2016, 2018a, 2018b, 2019a, 2019b, 2019c; Brown et al. 2016; Siddiqui and Singh 2017; Singh et al. 2018, 2021; Asfaw, et al. 2108). A QuILT is a type of TLS based upon a cognitive task analysis (Wieman 2015; Reif 1995) from an expert perspective and empirical research on student