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Millikan award lecture: Students of physics—Listeners, observers, or collaborative participants in physics scientific practices?

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Millikan award lecture: Students of physics—Listeners, observers, or collaborative participants in physics scientific practices?

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This article is a written version of my acceptance speech upon receiving the Millikan Medal at the 2014 Summer AAPT meeting. In the talk I shared an approach to learning and teaching physics that engages students learning introductory physics in the processes that physicists use to construct physics concepts, physical quantities, and equations, as well as to solve problems. This article describes the origins of the method, its characteristic features, research on its implementation, and available resources.
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I. INTRODUCTION

A. Words of thanks

This paper describes over 30 years of my work as a physics teacher and someone engaged in Physics Education Research (PER). I am profoundly grateful to the AAPT community for recognizing the value of this work by awarding me the Millikan Medal. This is a wonderful event in itself, but its significance becomes even greater if we consider that I am a woman and that I spent the majority of my life behind the iron curtain in the Soviet Union.

That being said, the work for which I received this recognition was not done alone. Before I move forward, I would like to thank all of those who believed in the learning system that I am about to describe when I could not publish anything about it in major journals (including AJP) and who worked over many years to develop materials that are now being used by thousands of students and hundreds of teachers. My deep thanks go first to Alan Van Heuvelen, who saw the value in my ideas and was courageous enough to try my method with his students, while his own curriculum was proven to be very successful, and who continuously advocated and contributed to the development of the method over the years. I am indebted to Suzanne Brahmia and Xueli Zou, our co-PIs on the original NSF grant that made the development of initial curricular materials possible and to David Brookes, Michael Gentile, David Rosengrant, Sahana Murthy, Aaron Warren, Anna Karelina, Maria Ruibal Villasenhor, and Gorazd Planinsic, who worked tirelessly to develop curricular materials, study student learning, and implement the system in different conditions. Finally, I would like to mention almost 100 physics teachers who went through my Rutgers Physics Teacher Preparation program and who implement, improve, and adapt the learning system for their students. Thank you, my students, friends and colleagues, for supporting me all these years.

B. A little history

As I said, my roots are in the Soviet Union, and in particular its capital, Moscow, where I was born, raised, and educated as a physics and astronomy teacher at the premier institution of Soviet teacher preparation—Moscow State Pedagogical University. My degree was equivalent to the master's in physics and master's in education combined. I started my professional life as a physics teacher in one of Moscow's schools. I was a highly motivated teacher who spent hours preparing physics demonstrations and perfecting lessons for my students. The students loved my lessons and I was regarded as one of the best teachers in my school. I thought so of myself, too, until one day I met a former student who had graduated two years prior to that meeting. He finished with an A in physics and we had an excellent relationship. He was learning to be a theatre director. Bursting with excitement he was telling me how they built a *camera obscura* to model a medieval theatre. I asked him if he remembered our lab with a *camera obscura*. His answer stuck in my brain forever: "Honestly, I do not remember anything from physics, except X-rays. Remember, I did a presentation on X-rays? I learned about X-rays by myself." All my years of brilliant teaching and intriguing demonstrations did nothing for him and the only thing that made an impression was what he learned on his own. The year was 1989 and I knew little about constructivism, how the brain works, and many other things that I know now. But his words made me rethink what took place in my classroom. *I was no longer focused on what I would do to teach my students, but on what they would do to learn.*

But what is it that they should be learning? In the Soviet Union at that time all students had 5 years of physics in middle school and high school; by the end they were doing calculus-based physics. At first glance, the answer to this question was kind of obvious—they needed to learn Newton's laws, and Coulomb's law, and magnetic fields, and light interference—all the things we traditionally equate with physics. However, my principal, Zavelsky, who constantly encouraged his teachers to think outside the box, challenged this seemingly flawless approach. Specifically, he said: "Very few of your students will become professional physicists, so what should they *really* learn from you?" This is when I realized that interactive engagement was not enough. My students would learn all of the above things but in their future life they were unlikely to use the ideas of wave superposition or to draw electric circuit diagrams. However, if they learned how physicists come up with ideas and how they evaluate them, this knowledge will be useful for them no matter what they chose to do in the future. I imagined teaching my students to ask, "How do you know this?" every time somebody was trying to convince them of something. Or to ask, "What are your assumptions?" every time someone predicted a certain outcome. Or to ask "Is this evidence or your inference?" If my students could learn to ask these questions and to evaluate the answers, no matter where they chose to work they would become critical and independent thinkers. To summarize, I realized that active engagement is a necessary condition for learning but it does not answer the question of what students should learn. My answer to this question solidified slowly: they should learn how to think like physicists.

Based on these thoughts I developed a system of learning physics that engages students in active learning, not just of the concepts and laws of physics, but more importantly in the processes that mirror processes that physicists use to construct these concepts and laws. Working in small groups, students observed simple experiments and tried to explain them. Their explanations were subjected to experimental testing and the students themselves came up with the experiments to run. They decided what data to collect and how best to analyze it. They came up with the mathematical relations between the various quantities and tested them experimentally (again). They constantly discussed things with each other and my classroom had this continuous "noise" that was not heard from other rooms where the teachers provided careful explanations and students answered questions after raising their hands. To get a feeling for this new approach to learning physics, I will give you an example.

II. AN EXAMPLE OF USING SCIENCE PROCESSES TO ANSWER A QUESTION

Imagine that you shine a laser pointer on a plane mirror as shown in Fig. 1(a) and observe the pattern shown in Fig. 1(b). How would you explain this observation? I encourage you to stop reading now and make a list of possible explanations of the observed phenomenon. (It would be great if you had a colleague nearby to talk to.) I also encourage you to think of what explanations your students (assume physics majors familiar with ray and wave optics) might come up with. The students who did this activity came up with four explanations (see Fig. 2).

As can be inferred from the pictures that students drew and the records of their writing, they came up with the following four models explaining the observation (these explanations are usually not very elaborate or detailed when students construct them at first):

(a) A model that has waves reflected off the glass top and metal bottom of the mirror that interfere constructively to produce bright spots, similar to the light interference explaining the colors of soap films.
(b) A model that is based on a wave scattering off of some regular structure inside the glass that covers the metallic part of the mirror, similar to Bragg interference on the crystal structure; interference of the waves reflected off this structure leads to the presence of bright spots.
(c) A model that has the mirror made of multiple layers of glass; multiple specular reflections off the glass layers (and the bottom metallic layer) produce the pattern.

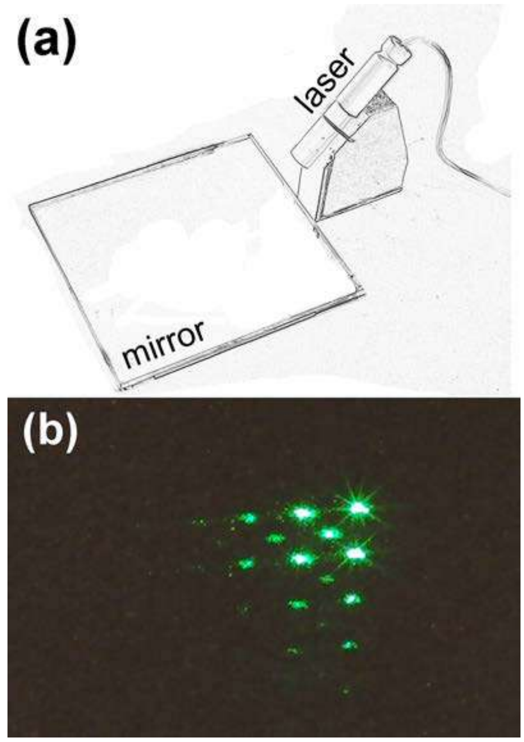

Fig. 1. A laser is shined directly onto a mirror. (a) Sketch of the experimental set-up; (b) The image on the mirror.

(d) A model that has only one glass layer and then the layer of metal at the bottom of the mirror; specular and diffuse reflections of light from the top and the bottom part contributes to the pattern.

What should we do in the classroom when our students have different ideas about a particular phenomenon? I argue that our strategy should be the same as we use in physics: test all of them experimentally. But what does it mean to test something? Although scientists often use the verb "test" in

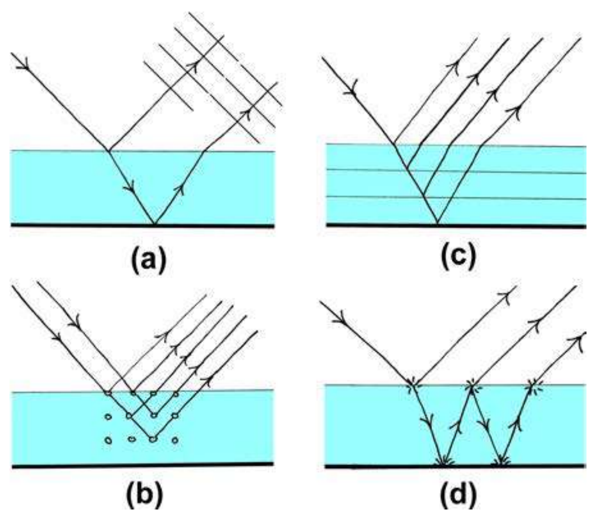

Fig. 2. Models to explain the experiment in Fig. 1. Models (a) and (b) represent interference-based models, while (c) and (d) represent reflection-based models.

discourse, the exact meaning is rarely communicated to students. Testing an idea means:

(1) to temporarily accept the idea as true,
(2) to design an experiment whose outcome can be predicted by the idea, and to make the prediction, and
(3) to conduct the experiment and to compare the outcome to the prediction.[1]

With this approach to testing in mind, how can we test the four proposed models? One suggestion is to use a front-surface mirror. A front-surface mirror has the metallic layer on the top surface and therefore all four models will predict that no pattern should appear. Figure 3 shows the outcome of the testing experiment; we can see clearly the absence of the pattern. Does this mean that this experiment proves all four models are correct? Of course not—this is an example of a "poor" testing experiment: it fails to reject the four models or to discriminate among them. This simple exercise shows how important it is to understand that the outcome of the experiment that matches the prediction based on a model under test does not *prove* the model correct—it fails to reject it. I encourage you to stop reading for a moment and think about the experiences of your students. How often do they have a chance to conduct an inconclusive experiment and to be able to say that they cannot conclude the "correctness" of something based on this experiment?

After an experiment whose outcome matches the predictions of conflicting explanations we are back to the original state: the need for more testing. Only now we will look for experiments whose predicted outcomes will be different based on different explanations. (Knowledge of wave optics helps here.) As we know, all interference effects depend on the wavelength of light. Specifically, we know that for the thin-film interference and Bragg interference, a larger wavelength will lead to larger distances between bright spots. For the simple ray-type reflections, the wavelength should not matter. Therefore, we can make the following testing experiment. We will repeat the original experiment, but this time, we will shine a laser of a different color (red, for example). According to the first two models, the distance between the dots should increase; according to the second two models, this distance should not change. Figure 4 shows the outcome of the experiment: the distances between the bright spots are the same for both colors.

The outcome of this experiment does not match the predictions of the wave-based models and thus we begin to question them. To increase our confidence in their futility,

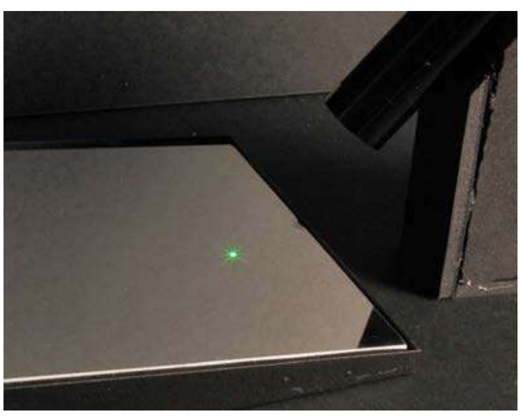

Fig. 3. Shining a laser beam on a front-surface mirror.

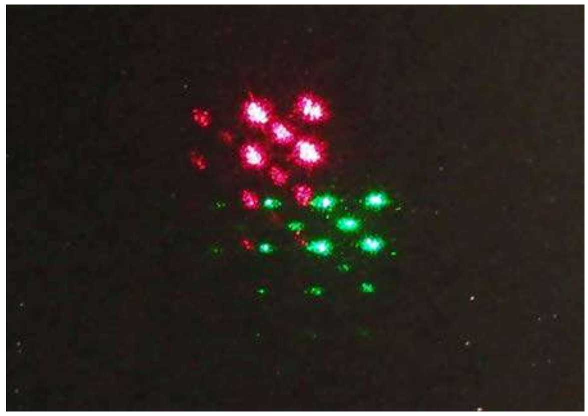

Fig. 4. Observed pattern for red and green lasers simultaneously shining on the mirror. (Color online)

let's think of another experiment. We could use a thinner mirror, keeping the angle of the incident beam the same as in the previous experiments. In this case, we have three different predictions based on four models: model (a) predicts that the distance between the spots should increase; models (b) and (c) predict that the distance should not change (assuming that thinning the mirror would not change its internal structure), and model (d) predicts that the distance should decrease (I encourage you to do the reasoning that leads to these predictions). The outcomes of the experiments are shown in Fig. 5.

These testing experiments also reject the wave-based models of the pattern. Their outcomes also reject ray-based model (c). However, the model (c) is rejected under the assumption that the thinner mirror has fewer layers of the same thickness. What if the layers are thinner in a thinner mirror? Then the predictions for the experiment in Fig. 5 are the same based on both models (c) and (d) and matches the outcome. To differentiate between the two reflection-based models, we need another testing experiment. I encourage the reader to think of a possible experiment before you read on.

Here is one possibility: instead of looking at the mirror, let's examine what we see after the light is reflected onto a vertical screen placed next to the mirror. If the reflection from the metallic layer is stronger than from the glass layers, an important assumption, then the layers explanation predicts that the bottom spot should be brightest as it is the spot due to light reflected off the metal surface. On the contrary, the specular/diffuse model predicts that the bright spot second from top should be the brightest (see Fig. 6).

Having made a prediction, we need to conduct the experiment. Figure 7 shows the outcome, which again rejects the layers model (c) and is consistent with the prediction based on the specular/diffuse reflection model (d). We leave it to the reader to extend this model to explain all of the details of the pattern. (This is easiest if you perform the experiment shown in Fig. 1 yourself.)

The purpose of this example was to show that very simple physical phenomena allow our students to practice authentic physics reasoning and to construct new ideas. While doing this, students need to work together in groups, because in this way they are more likely to suggest "crazy" ideas and test them collectively, similar to the process used in the television show *House* when the doctors engage in differential diagnosis. Such a process not only strengthens and expands their physics but also teaches them to model the same

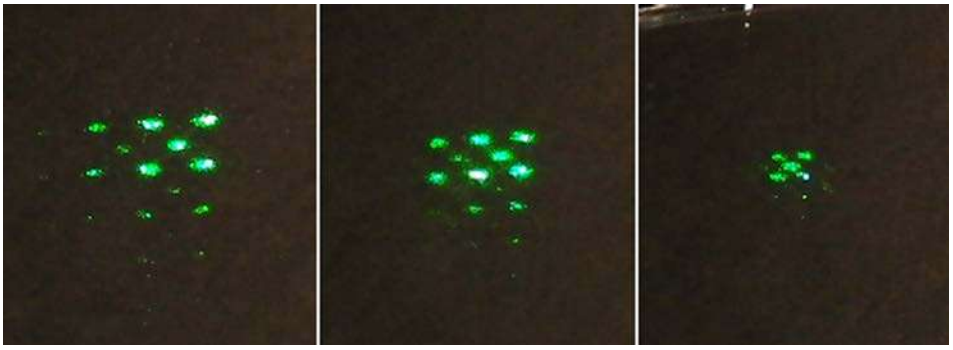

Fig. 5. Experimental patterns observed on the surface of mirrors with progressively decreasing thicknesses (from left to right). The distance between the camera and the mirrors and settings of the camera were the same in all cases.

situation differently, to test ideas experimentally, to evaluate assumptions, to represent their models in different ways, to argue, to collaborate, and to communicate.

III. USING SCIENCE PROCESSES AS A FOUNDATION OF TEACHING AND LEARNING PHILOSOPHY

Is it possible to put the processes, we employed above into everyday learning of physics? The answer is a resounding yes! The Investigative Science Learning Environment (ISLE) is a learning system that engages students in the reasoning processes similar to the ones described above when constructing concepts in a general physics course.[2] The ISLE process follows the steps shown in Fig. 8; the arrows in the diagram represent an approximate progression of logical steps. That being said, the ISLE cycle is not a linear progression. At any step, one can go back and revisit the previous step or examine the assumptions. However, certain aspects are necessary for those who want to implement this philosophy.

(1) Observational experiments should be simple and "clean" enough that students can infer a pattern. No predictions are required before making observations. In fact, the more "open" the students are to their observations, the better.
(2) Students are encouraged to propose as many possible explanations as they can. Sometimes multiple explanations are easy to devise, sometimes not, but the goal should always be to encourage as many as possible. Explanations can be causal and/or mechanistic.
(3) All explanations are considered to be equally valuable until the testing experiments are performed. Testing experiments can be designed by the students (this is the best way) or suggested by the instructor. In any case, students should not rush to perform the experiments and "see what happens." They need to first make predictions based on each proposed explanation and only then conduct the experiments. Predictions should not be based on their intuition or gut feeling, they should be carefully based on the explanations. This is the most difficult part of the cycle.
(4) The outcomes of the testing experiments matching the prediction do not prove the explanations correct, they merely fail to disprove them. The experiments with outcomes that contradict the predictions are in a way better as they allow students (physicists) to think about rejecting an explanation. And this is where the assumptions are important. Checking assumptions that went into the prediction in addition to the explanation is the step whose value cannot be overestimated. Recall the assumption that the reflection off the metal surface is stronger than off the glass surface that we used to make the prediction in the last testing experiment in the mirror example.
(5) Students read the textbook *after* they have devised ideas in class. This is in contrast with some other curricular approaches where students are expected to read a textbook or watch an instructional video *before* they come to class so they are ready to discuss the new material with their peers and the instructor. As ISLE's goal is students learning to think like physicists, listening to a lecture or reading a text before having an opportunity to explore, to create explanations, to connect them to existing

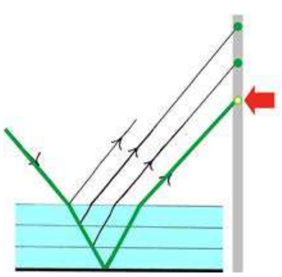

Fig. 6. The brightness of the spots on a vertical screen next to the mirror: the prediction of the layer-based model (left) and the prediction of the specular/diffuse reflection-based model (right).

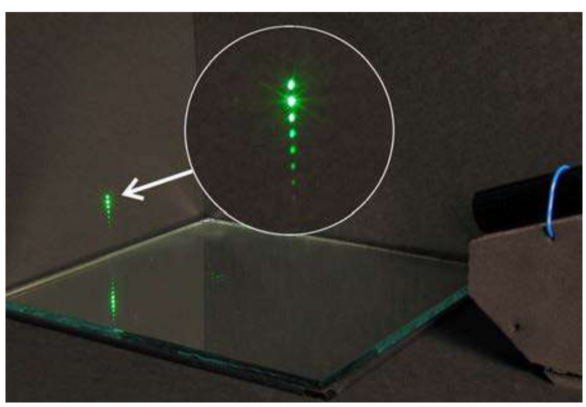

Fig. 7. Observed pattern on a vertical screen next to the mirror.

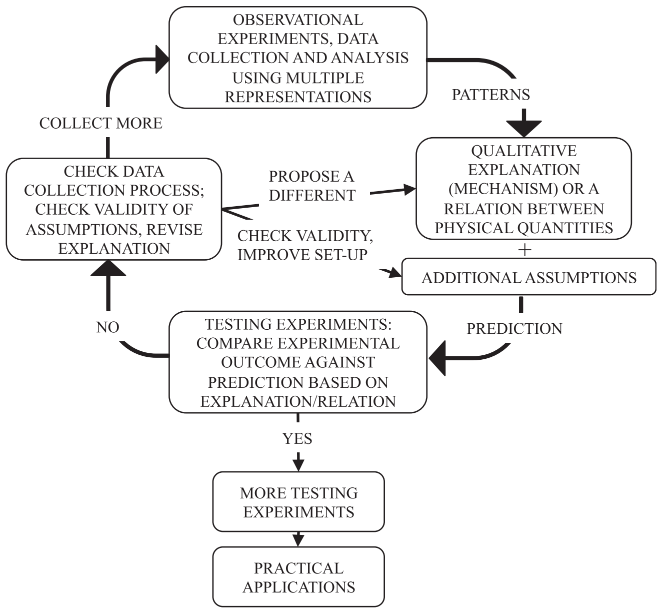

Fig. 8. ISLE cycle diagram.

knowledge, and to test them (even if they turn out to be discarded) does not help achieve this goal.

The issues described above show how ISLE is different from traditional instruction and from many reformed approaches. With ISLE, students construct their ideas by actively participating in the process.

A. Why is the ISLE process important?

Our recent publication in this journal[3] shows that the ISLE cycle is a reasonable simplified picture of scientific reasoning. In the study reported in that paper, we offered pairs of practicing physicists a "light cone" problem.[4] The light cone problem asks the participants to explain a cone formed by a laser beam spreading in a container with water. We videotaped and analyzed their work solving the problem and found that the clockwise progression of the ISLE cycle (see Fig. 8) resembles rather closely the reasoning steps and practical steps taken by the practicing physicists. Moreover, what the experts did during the large majority of the steps could be mapped reasonably well to the "boxes" on the ISLE-cycle diagram (observations, explanations/models, testing experiments, predictions, etc.). Specifically, we found that physicists spend most of the time testing their ideas either in real experiments or in imaginary experiments, and that they collaborate intensely and continuously while solving problems.

Why are these findings important? The changing world demands people who can solve complex problems, evaluate solutions, design experiments, collect and analyze data, and collaborate with other people.[5] In response to different needs in the 21st century, various documents that determine the course of science education in the US, such as the Next Generation Science Standards, America's Lab Report, College Board's AP curriculum, and upcoming revisions to the MCAT, emphasize science *practices* (the activities scientists engage in when constructing and applying knowledge). All of these documents suggest that these practices become an integral part of learning science, and that students should learn science by participating in these practices instead of listening to someone talk about them at the beginning of a course. Not only do these documents emphasize the importance of student participation in these practices while learning but they also insist on assessing student mastery of these practices on such traditional tests as AP exams and MCAT exams.

Although these documents give examples of such practices,[6] there is no guidance on how to structure student learning experiences so that the students participate in these practices when constructing knowledge and when applying it. In addition, one of the key practices of physics—proposing multiple explanations for the same phenomenon and experimentally testing them (for rejection and not support)—is not present in any of the documents. And while there are several reformed curricula for introductory physics that help students develop many of the practices listed in the above documents,[7] none of them emphasize the idea of students systematically learning to test multiple explanations of the same phenomenon. Therefore, I argue that ISLE is the only learning system with fully developed and consistent curricular materials[8] that teaches students the habits of thinking that typify professional physicists.

B. How is ISLE different from other reformed curricula?

There are many aspects of ISLE that are similar to other reformed approaches. It emphasizes active engagement, group work, authentic problem solving, and reconciling students' original ideas with conventional ideas. However, there are three fundamental components of ISLE (see Fig. 9) that, when combined together, make it stand out from other reformed approaches.

Ways of reasoning—The first block of the foundation is the type of reasoning that ISLE helps students develop. The first step in learning a concept always starts with students observing simple phenomena and finding patterns. This step develops inductive reasoning. The next step is for students to construct explanations. This step activates analogical reasoning, as all explanations that students usually devise are based on something they already know. For example, in the ISLE approach students construct the concepts of molecules and their motion by analyzing and explaining what happens to a streak of alcohol smeared on a piece of white paper. They observe a slow, gradual disappearance of the streak. When explaining the gradual part of the observations, they come up with an idea that the alcohol is made of smaller parts (students rarely use the word particles here). But what is the mechanism of disappearance of these smaller parts? Students are invited to propose several "crazy" ideas. The most common ones are: alcohol parts are still in the paper but invisible—the paper kind of "sucked" them in; the alcohol parts were absorbed by air; the alcohol parts fell off the paper; or they floated just like helium balloons. All of those explanations are analogical in nature as they are based on phenomena that the students have previously observed. The next step is to test these explanations by proposing experiments, whose outcomes can be predicted based on the explanations. This is when hypothetico-deductive reasoning is activated. Students need to accept all ideas as true for the time being and then imagine what will happen in a particular experiment based on each of the ideas. For example, we weigh the dry paper on a scale, put alcohol on it, weigh it again, wait for the streak to disappear and weigh it for the third time. The first idea—alcohol parts are absorbed by the paper—predicts that when the paper dries the reading of the scale

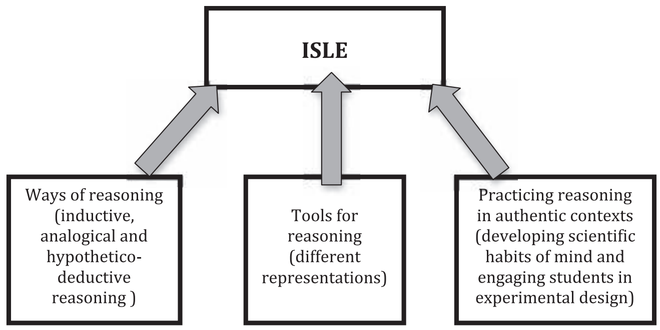

Fig. 9. Three-block foundation of ISLE.

should not change, while the others predict that the reading should go back to the original, dry-paper result. Other ideas are tested in a similar way.[9] Multiple examples of these reasoning steps are implemented in the ISLE-based textbook.[10]

This approach, that students need to make predictions based on the idea being tested and not their intuition, makes ISLE significantly different from the Predict-Observe-Explain approach (POE)[11] where students are expected to make the prediction based on their intuition or prior experience, which might not be relevant to the observed phenomenon.

Tools for reasoning—The ISLE cycle for each concept starts with a simple observational experiment. The data in the experiment need to be analyzed so that the students can identify a pattern. For this analysis, they need special tools such as tables, graphs, force and motion diagrams, ray diagrams, etc. These tools are all examples of concrete representations that eventually allow students to invent relevant physical quantities and find relations between them. The ISLE curricular materials include the use of traditional representations (graphs, ray diagrams, etc.), modified traditional representations (force diagrams and motion diagrams), and more novel representations, such as conserved quantity bar charts (momentum, energy, etc.). What makes ISLE special with respect to representations is that students use them (a) to reason building a bridge between phenomena and their mathematical description, and (b) in the areas of the physics curriculum that traditionally use only mathematics for analyzing the processes and problem solving. Thus, the representations are for sense making as much as answer making.

Let me provide a few examples. In relation to (a): students represent energy-work processes in a system using a work-energy bar chart[12] and then use this bar chart to write a mathematical description of the process; or when analyzing motion in dynamics, students construct both force and motion diagrams to look for consistency.[10] In relation to (b): students use energy bar charts not only in mechanics but in thermodynamics, the photoelectric effect, atomic physics, etc.,[10] so that the underlying conservation laws become part of their reasoning.

Practicing reasoning in authentic contexts—This is a vital part of the ISLE approach to learning physics. By authentic contexts we mean situations when the students need to employ authentic reasoning similar to that physicists employ when solving problems. This aspect of ISLE is best realized in instructional laboratories where students design their own experiments to answer the questions posed for them or even pose their own questions. ISLE labs are dramatically different from traditional labs where students perform "verification" experiments following step-by-step instructions. To help students learn how to proceed in the "design" situations, we developed

(a) a list of detailed reasoning processes that physicists use and we can help our students develop (and for which we coined the term scientific abilities),[13]
(b) specific scaffolding questions that help students develop scientific abilities, and
(c) a set of self-assessment rubrics that students can use during and after the process of design to help them develop the above abilities and monitor their progress. These rubrics suggest what they should think about *why* and not *what* they should do.

These three items probably represent one of the biggest contributions to the field of PER by the Rutgers PER group under my leadership. As one of the reviewers of this paper pointed out, "They did not claim the development of generic, holistic, mom-and-apple-pie scientific reasoning practices; they have enumerated these practices and labeled each of the student activities with the corresponding practice(s). To my knowledge, this work is the most complete expression currently available in PER of what it means to think like a physicist and how to assess it." To give a reader a taste of this work, in the Appendices I provide the list of scientific abilities that we enumerated, the breaking down of one ability into sub-abilities that can be targeted and assessed, relevant rubrics that students use to self-assess their development of this ability, and the laboratory activity that shows how we engage the students in the development of this ability. The list of scientific abilities, rubrics, and many ISLE labs are posted on line and are free to download.[14]

C. ISLE from the instructor and student perspectives

In summary, one might say that ISLE is a learning system that puts an instructor in the role of a "master" of physics reasoning who is slowly apprenticing her/his students into this craft. An instructor creates conditions for the students to think like a physicist and not to be afraid to throw in ideas that later might be rejected. This "mistake-rich environment"[15] is the heart of ISLE. Therefore, from the point of view of the instructor, teaching students physics through ISLE means:

(1) Asking herself/himself a question: What will students do together to "*come up* with XX" (i.e., the physical quantity of acceleration or a relationship between force and charge separation)?
(2) Recognizing that the *process* in which students engage to construct new ideas is as important as the understanding of these ideas and their application to problem solving. This is a crucial point. It makes ISLE dramatically different from the approaches to learning that focus only on improved conceptual understanding through interactive engagement.
(3) Creating opportunities for students to devise multiple explanations for the same phenomenon and then systematically test them experimentally.
(4) Recognizing that students' ideas play a crucial role in the above process.
(5) Using experiments in three distinct roles: to help students generate models/explanations/hypotheses, to help

students test them, and to help students apply the surviving models.
(6) Recognizing that predictions are not personal stakes, or guesses based on intuition.
(7) Creating situations for students to question their assumptions.
(8) Using representations (including language) as reasoning tools.
(9) Assigning students to read the textbook only after the new ideas are constructed and tested through experiential learning and discussions (this relates to item 2).

From the point of view of a student, learning physics through ISLE means:

(1) Continuously asking myself, "how do I know what I know?"
(2) Cultivating skills of noticing and imagination.
(3) Using intuition, imagination, previous knowledge, and everyday experience to devise explanations of physical phenomena.
(4) Searching for multiple explanations for the same phenomenon.
(5) Testing these explanations (not the intuition) experimentally.
(6) Not being afraid to come up with crazy ideas and making mistakes.
(7) Getting used to working with others: listening to their ideas and communicating my own.

D. What do students learn when they learn physics through ISLE?

Although the main goal of ISLE is to help students learn to think like physicists (which we have instruments to assess), we use traditional PER assessments as well. Those traditional assessments are the Force Concept Inventory[16] and Conceptual Survey of Electricity and Magnetism.[17] On those tests ISLE students (both in high schools and universities) consistently demonstrate Hake gains[18] comparable to the gains typical for interactive engagement curricula. We have collected data on student learning over the past 15 years and of course the results vary by institution and by instructor. Here are some results: Average FCI Hake gains for ISLE students range from 0.3 for university students at risk and "college prep physics" high school students to 0.6–0.7 for honors university courses and honors high school courses.[3] The CSEM average Hake gains range between 0.4–0.5 and post-test scores range from 54% to 71% for different students and instructors. As described in the original CSEM paper, the scores of two-year college instructors averaged 77% on CSEM; the score of 71% for university freshman therefore seems relatively high.

Here are a few specific examples. Students of Danielle Bugge, a high school physics teacher in New Jersey consistently average 0.6 ± 0.2 FCI Hake gains in the last 3 years, and 0.4 ± 0.2 CSEM gains. Students of David Brookes who is using ISLE at Florida International University in a studio format had FCI Hake gains of 0.4 ± 0.2 in 2009 when he started teaching and were 0.6 ± 0.2 in 2013. In 2013 David's male and female students had the same growth in their FCI scores. Students of Alan Van Heuvelen in a large enrollment introductory course for honors engineering students (2001–2003) had Hake gains of 0.6 ± 0.2.

To evaluate ISLE students' development of science reasoning approaches, we conducted several studies at Rutgers in the algebra-based introductory physics courses for science (non-physics) majors that implemented ISLE and found the following:

(a) Between 50% and 80% of ISLE students (depending on the content) spontaneously use multiple representations (in our study these were force diagrams) when solving traditional physics problems while only 10 to 20% of traditionally taught students do so when solving similar problems.[19]
(b) In ISLE labs after 8 weeks of instruction about 80% of students develop such scientific abilities as designing their own experiments, collecting and analyzing data, identifying and evaluating uncertainties, and identifying and evaluating assumptions.[20]
(c) On average, 40% of ISLE students (standard deviation 5%) are able to describe how to test multiple explanations of the same phenomenon compared to an average of 15% (standard deviation 15%) of beginning physics graduate students and 30% (standard deviation 20%) of advanced physics graduate students. Zero percent of undergraduate junior physics majors who had not been exposed to ISLE were successful.[21]
(d) After one semester of ISLE students are able to apply these newly developed abilities to solve experimental problems in novel physics content and in biology.[22]

Let me give an example of how students see knowledge when they learn physics differently. How do students respond to questions asking them to articulate how they know what they know? Table I shows the answers recorded by David Brookes[23] who asked traditionally taught students "How do you know that Newton's third law is true?" and students who learn physics through ISLE "If someone came to you and asked you: &How do you know Newton's third law is true?' how would you answer them?" The students in both groups were successful on all Newton's third law related questions on the FCI. Thus, one can assume that they understand the law and can apply it in different situations. Although the questions asked were slightly different, student answers will give you a flavor of the differences in their approaches.

Although the documents cited above (NGSS, for example) argue that students should not only "acquire" physics knowledge but also actively participate in its construction through science practices, one might question whether it is important for students to be able to explain how they learned something. Our studies indicate that in the courses where students do learn physics by participating in science practices, the students who can adequately describe how they learned something do learn more than those students who think that they learn by reading a book or by watching somebody solve a problem on the board. Specifically, in 2001 May and Etkina[24] published a study of honors engineering students in a calculus-based general physics course at The Ohio State University who reflected on their learning every week. The prompt was: What did you learn this week and how did you learn it? May and Etkina selected the students who started the course with very low knowledge of physics (measured by the FCI) and analyzed their responses. These researchers

Table I. Student responses to the question asking them to explain how they know Newton's third law is true.

How traditionally taught students responded to the question "How do you know that Newton's third law is true?"	How students who learned physics through ISLE responded to the question: "If someone came to you and asked you: & How do you know Newton's third law is true?' How would you answer them?"
001: Because I took physics 140. I don't know, I just know that.	001: I would explain with an example of when a person is pushing against a wall.
002: I guess it's just an established law of physics.	002: Assuming that this person knows of Newton's first and second law. I would use an everyday real life example such as, me pushing a box of books.
003: I remember that from high school.	003: I'd try saying I know it's true experimentally and show them somehow. I could use two of those spring thingies we had in class that measures force, hook them up, and pull.
004:…that law is probably one of the only things I took out of physics 140…	004: I would ask them to punch a wall…The pain caused by punching a wall is a result of the force the wall exerts on the fist. As you increase the force behind your punch, the force the wall exerts on your fist increases proportionally, and therefore the pain you experience increases as well.
005: I think it's one of the laws of physics.	005: By giving them an example…
006: I remember from my physics class…"every action has an equal and opposite reaction."	006: I know Newton's third law is true because my classmates and I assembled an experiment in which we allowed wheeled carts to collide.
007:…just from having a physics class before…forces are always equal when they are opposing each other.	007: I have, along with others, performed many experiments that support the claim and have not found or devised an experiment that disproves it.

found that the six students who achieved the highest learning gains in the course (measured by FCI) wrote in their reflections that they learned by observing experiments, reasoning from them, testing their ideas, and analyzing the consistency of the new ideas and their previous knowledge or the relations of the new knowledge to their every day experiences. The six students who had the lowest gains reflected that they learned mostly by listening to the instructor or directly "observing knowledge" in experiments. This study showed that being able to articulate the path of knowledge construction contributes to knowledge acquisition itself.

III. SUMMARY

The goal of this paper was to describe the evolution and the essence of the ISLE method as a framework for learning and teaching physics. ISLE is more than another teaching method that engages students in active learning. It consistently and purposefully engages them in active learning that mirrors scientific practice.

I showed how the ISLE philosophy provides answers to many questions posed by science education in the 21st century and how it contributes to student learning. Originally, ISLE was born as a learning system for physics in grades 7–11, but slowly, with the contributions of many people, it evolved into a set of principles that can be applied to any physics course. So far the ISLE framework has been used in elementary and middle school science,[25] high school physics,[26] enrichment programs for high school students,[27] college and university introductory physics courses,[3] stand-alone laboratory courses,[28] physics teaching methods courses for future physics teachers,[29] and in professional development programs. Most of the curricular resources created for ISLE users at all levels are free and available for anyone interested at the ISLE website.[30] Recently, we started publishing a series of papers describing how one can use ISLE to learn advanced physics topics, such as the physics of LEDs.[31] Therefore, there is no lack of support for those who wish to implement this learning approach at any level of physics sophistication. The time has come to bridge the doing of physics and the learning of physics so those students who take our courses not only develop the knowledge of fundamental physics principles but also of the way physicists develop, evaluate, and apply this knowledge. Such distinctive learning might produce independent and critical thinkers who do not blindly follow instructions and who can meet the demands of the 21st century.

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APPENDIX A: LIST OF SCIENTIFIC ABILITIES

Below is a list of scientific abilities (each of which has a matching rubric). Each rubric breaks down the ability into smaller sub-abilities, as shown in Table II for one of the abilities.

(A) Ability to represent information in multiple ways.
(B) Ability to design and conduct an experiment to investigate a phenomenon.
(C) Ability to design and conduct a testing experiment (testing an idea/hypothesis/explanation or mathematical relation).
(D) The ability to design and conduct an application experiment.
(E) Ability to communicate scientific ideas
(F) Ability to collect and analyze experimental data.
(G) Ability to evaluate models, equations, solutions, and claims

APPENDIX B: SAMPLE LABORATORY EXERCISES

Examples of two laboratory exercises that help students develop the ability C: the ability to design and conduct a testing experiment.

Table II. Sample rubric for ability C: Ability to design and conduct a testing experiment.

Ability to design and conduct a testing experiment (testing an idea/hypothesis/explanation or mathematical relation) Rubric C

	Scientific ability	Missing	Inadequate	Needs some improvement	Adequate
1	Is able to identify the hypothesis to be tested	No mention is made of a hypothesis.	An attempt is made to identify the hypothesis to be tested but is described in a confusing manner.	The hypothesis to be tested is described but there are minor omissions or vague details.	The hypothesis is clearly stated.
2	Is able to design a reliable experiment that tests the hypothesis	The experiment does not test the hypothesis.	The experiment tests the hypothesis, but due to the nature of the design it is likely the data will lead to an incorrect judgment.	The experiment tests the hypothesis, but due to the nature of the design there is a moderate chance the data will lead to an inconclusive judgment.	The experiment tests the hypothesis and has a high likelihood of producing data that will lead to a conclusive judgment.
3	Is able to distinguish between a hypothesis and a prediction	No prediction is made. The experiment is not treated as a testing experiment.	A prediction is made but it is identical to the hypothesis.	A prediction is made and is distinct from the hypothesis but does not describe the outcome of the designed experiment.	A prediction is made, is distinct from the hypothesis, and describes the outcome of the designed experiment
4	Is able to make a reasonable prediction based on a hypothesis	No attempt to make a prediction is made.	A prediction is made that is distinct from the hypothesis but is not based on it.	A prediction is made that follows from the hypothesis but does not incorporate assumptions	A prediction is made that follows from the hypothesis and incorporates assumptions.
5	Is able to identify the assumptions made in making the prediction	No attempt is made to identify any assumptions.	An attempt is made to identify assumptions, but the assumptions are irrelevant or are confused with the hypothesis.	Relevant assumptions are identified but are not significant for making the prediction.	All significant assumptions are correctly identified.
6	Is able to determine specifically the way in which assumptions might affect the prediction	No attempt is made to determine the effects of assumptions.	The effects of assumptions are mentioned but are described vaguely.	The effects of assumptions are determined, but no attempt is made to validate them.	The effects of the assumptions are determined and the assumptions are validated.
7	Is able to decide whether the prediction and the outcome agree/disagree	No mention of whether the prediction and outcome agree/disagree.	A decision about the agreement/disagreement is made but is not consistent with the outcome of the experiment.	A reasonable decision about the agreement/disagreement is made but experimental uncertainty is not taken into account.	A reasonable decision about the agreement/disagreement is made and experimental uncertainty is taken into account.
8	Is able to make a reasonable judgment about the hypothesis	No judgment is made about the hypothesis.	A judgment is made but is not consistent with the outcome of the experiment.	A judgment is made and is consistent with the outcome of the experiment but assumptions are not taken into account.	A reasonable judgment is made and assumptions are taken into account.
9	Is able to revise the hypothesis when necessary	A revision is necessary but none is made.	A revision is made but the new hypothesis is not consistent with the results of the experiment.	A revision is made and is consistent with the results of the experiment but other relevant evidence is not taken into account.	A revision is made and is consistent with all relevant evidence.

Lab 8: Reflection and Mirrors

Learning goals of the lab:

(1) To learn how to experimentally test a hypothesis.
(2) To understand that each point on a light source radiates light in all directions (sends an infinite number of rays).
(3) To understand that drawing a line perpendicular to the point of incidence on a mirror (known as the "normal line") is crucial for finding the path of a reflected ray.

RUBRICS: A#10 (Ability to represent information in multiple ways, Ray diagrams) and Rubric C: #3 (to distinguish between a hypothesis and a prediction), #4 (to make a reasonable prediction based on a hypothesis), #7 (to decide whether the prediction and the outcome agree/disagree), and #8 (to make a reasonable judgment about the hypothesis.

Testing experiment: where is the image in a plane mirror formed?

Your friend Noelle suggests the following hypothesis: "The image of an object formed by a plane mirror is formed on the surface of the mirror." Design an experiment to test Noelle's hypothesis.

Available equipment: Plane mirror, object, masking tape, paper, meter stick.

Design and describe the experiment that you plan to perform. Make a prediction of the outcome. Remember that your prediction of the outcome of the experiment must follow from the hypothesis you are testing. Then perform the experiment and record the outcome. Explain the outcome using a ray diagram. Discuss whether the outcome agrees or disagrees with the prediction. If it disagrees, how would you convince Noelle that her idea has been disproven?

Testing Experiment: Covering The Image

Your friend Joshua suggests the following hypothesis: "The fraction of the image that is visible in a plane mirror depends on how much of the mirror is covered." Design an experiment to test Joshua's hypothesis.

Available equipment: Plane mirror, object, masking tape, paper, meter stick.

Design and describe the experiment that you plan to perform. Make a prediction of the outcome. Remember that your prediction of the outcome of the experiment must follow from the hypothesis you are testing. Then perform the experiment and record the outcome. Explain the outcome using a ray diagram. Discuss whether the outcome agrees or disagrees with the prediction. If it disagrees, how would you convince Joshua that his idea has been disproven?

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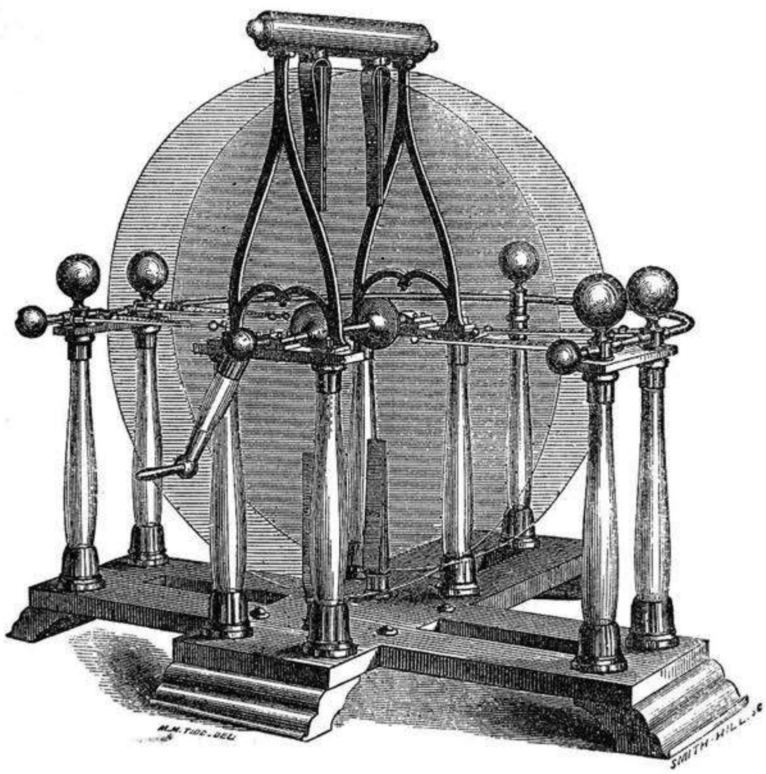

Electrostatic Machine

This huge, double-plate frictional electrostatic machine was made by the Boston firm of E.S. Ritchie for the University of Mississippi. The order was placed by President E. S. Barnard, the second president of the University, in the years before the War Between the States. Each six foot diameter plate was made of glass imported from France. The cost was $3000. The apparatus, one of the largest frictional electrostatic machines ever constructed, stood for many years in the front corner of the Natural Philosophy lecture hall in the Observatory building. The disks have survived and are in the storage room of the University Museum. Ritchie used this woodcut as the frontispiece of his catalogue; this was copied from the frontispiece of Benjamin Silliman, Jr., Principles of Physics or Natural Philosophy (Theodore Bliss & Co., Philadelphia, 1865) (Notes by Thomas B. Greenslade, Jr., Kenyon College)