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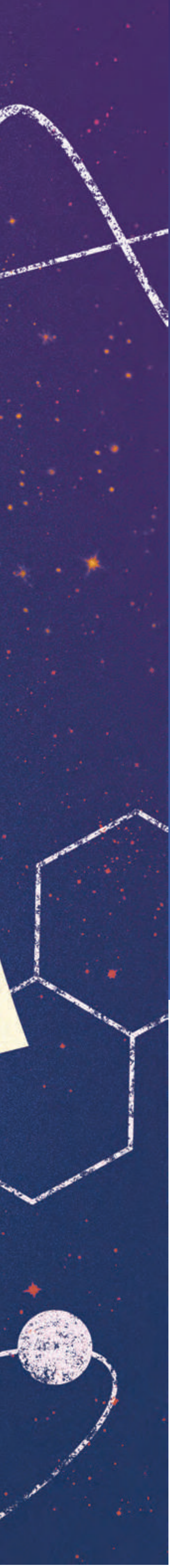

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WHEN LEARNING PHYSICS MIRRORS DOING PHYSICS

Eugenia Etkina

The Investigative Science Learning Environment approach replaces traditional teaching with active-learning methods that emulate scientific processes.

Many years ago, Andrew, one of the best students in my introductory physics course, said to me, "I know how to get a good grade in physics, but I feel like what we do in class can't be what physicists do when they do physics. I wonder what they actually do." That comment got me thinking: Is it possible for a student to experience real physics while learning it? Is it important when you are taking an introductory physics course to know and feel like you are doing what physicists do?

After almost 40 years of grappling with Andrew's comment, I think the answer to both questions is yes. With proper pedagogy, students can experience real physics, and they can benefit tremendously from feeling like actual scientists. As a result, I've helped develop the Investigative Science Learning Environment (ISLE) approach to learning and teaching physics.[1] Below I introduce it and demonstrate how it both deals with Andrew's concerns and addresses what I believe are the major challenges facing physics education in the 21st century.

ISLE in action

Imagine an introductory physics course for physics or science majors. The students have already learned about Newton's laws, momentum and energy, and mechanical waves, and they are now studying geometrical optics. They've learned how to draw ray diagrams and explain shadows, and they are familiar with the law of specular reflection. In the previous class, they used Newton's particle model to explain the relationship between angles of incidence, angles of reflection, and shadows.

In their first encounter with refraction, students in a lab section are split into groups of three or four and tasked with designing an experiment to investigate what happens when a laser beam hits the flat surface of a semicircular piece of plexiglass. Their goal is to find a pattern in the paths of the incident ray and the ray that passes through the plexiglass.

They set up an experiment (see figure 1) and measure the angles with respect to the normal line from the incident surface. The lab handout provides them with hints on how to find a pattern in the data by using trigonometric functions. They do their work on small whiteboards and share their findings with the rest of the class. Some of the groups come up with Snell's law.

The class's next task is to use the particle model of light to explain why the light's path changed in the way it did. After a class discussion and prompts from the instructor, the students come up with the following idea: The surface of the plexiglass slab exerts an attractive force on light particles, which causes the component of velocity along the normal line to increase. Because the velocity component that is parallel to the plexiglass surface does not change, the beam bends toward the normal line (see figure 2).

If that explanation is correct, the speed of light in plastic should be greater than it is in air. To test that hypothesis, students need to design an experiment that measures the speed of light in plexiglass. The instructor shows them a new device: a laser distance meter used in construction to measure distances.[2] Playing with the device, students learn how it determines distance to an object: It uses the value for the speed of light in air to measure the time delay between the emitted and received pulses.

The students design the following experiment: They place the distance meter so that the laser beam passes through the plexiglass slab and reflects off a surface at the slab's end. They record the distance measured by the device. Then they let the beam follow the same distance through the air. If their hypothesis is correct, the distance the beam travels through the plexiglass should be shorter than the distance through the air. They run the experiment and find that the device measures a longer distance in plexiglass (see figure 3). It looks like light travels slower in plexiglass than in air, which means that the particle-based explanation of refraction is not correct.

Is there another way to explain how the beam of light changes direction in the plexiglass? One student suggests that light might behave like a wave. Back in their groups, the students use their knowledge of mechanical waves and Huygens's principle to explain how a wave model of light can account for the outcome of the initial refraction experiment (see figure 4). In the follow-up class, they review their wave model and continue learning the properties of light.

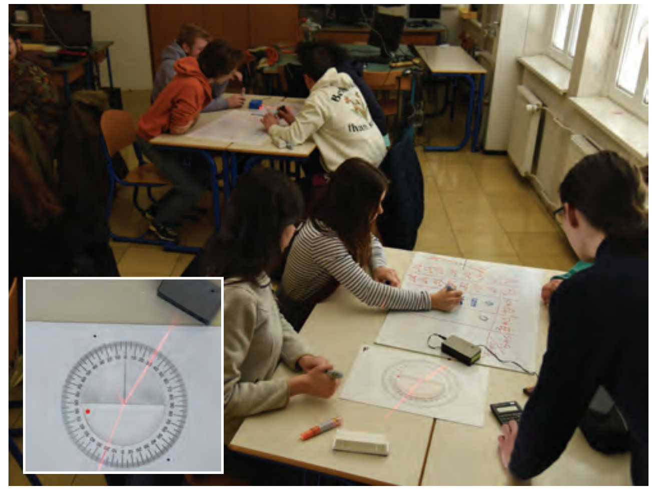


FIGURE 1. STUDENTS LOOK FOR A PATTERN in the paths of incident and refracted light beams. The whiteboard and experiment are both visible on the tables. The inset shows a top-down view of the laser beam hitting the plexiglass.

As you can see, ISLE is very different from traditional pedagogy. Instead of sitting through a lecture—or reading a textbook—about the wave model of light and how it explains refraction, students not only come up with the idea themselves but also learn why the particle model of light does not explain the phenomenon. As they progress through the process, they learn how to design experiments to find qualitative and quantitative patterns in new phenomena, devise hypotheses explaining those phenomena, design experiments to test their hypotheses, use different graphical representations to analyze the phenomena, make predictions about the outcomes of further experiments, rule out hypotheses based on those experimental results, work with their group, and present their findings and procedures to the whole class.[1]

In the ISLE approach, experimental work is an integral part in the development of students' physics knowledge rather than an add-on in which they simply test models presented in lectures. Interconnecting the experimental and theoretical development of models mirrors the process used by physicists to construct knowledge and engages introductory students in authentic physics while they are learning new ideas. Students experience what physicists do when they do physics. That is what Andrew was looking for.

How and what should students learn?

But is that experience important? Class time is brief, and many instructors feel pressure to cover lots of material in a course. If they spend too much time letting students figure out stuff on their own, they might not be able to cover all the material. But the field of physics has imposed that pressure on itself to cover all that information. Thousands of students take introductory physics courses in the US and across the world. Some will become physicists, and for them the experiential part of learning

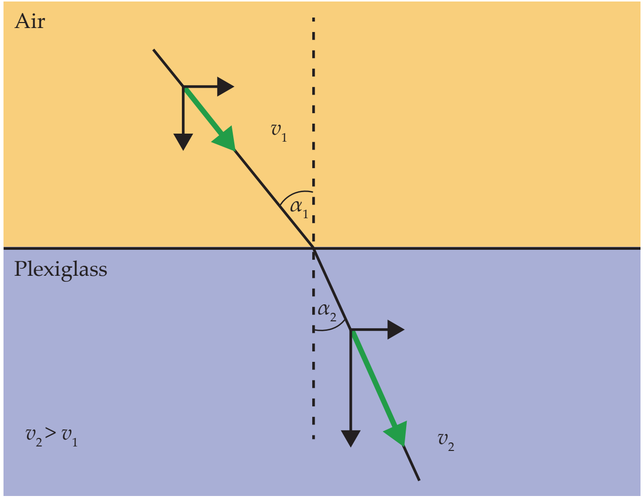


FIGURE 2. EXPLAINING REFRACTION with the particle model of light. Traveling at velocity v_1 in air, a light particle enters a plexiglass slab at an angle of incidence α_1. As the light enters the plexiglass, it refracts at an angle α_2 that is smaller than α_1. To explain that bending using the particle model of light, students hypothesize that when the light particle crosses the air–plexiglass boundary, the glass exerts an attractive force on the particle that causes an increase in the component of velocity perpendicular to the boundary. As a result, the light velocity v_2 in the plexiglass will be faster than the light velocity v_1 in air.

physics through the ISLE approach will be a window into their future profession.

But many will become doctors, ecologists, chemists, politicians, journalists, pharmacists, biologists, and so on. What do those students need to learn in introductory physics courses to be prepared for success in their field in the 21st century? What will they need to remember from their physics course 3, 5, or 10 years down the road? Although some knowledge of physics content might be useful for a pediatrician trying to help a feverish child, they will certainly need to collect data, identify patterns, come up with an explanation for the symptoms, and predict what kind of treatment is appropriate.

The question of what students should learn in our courses is especially timely now that artificial intelligence is becoming increasingly successful at solving traditional physics problems and answering conceptual questions. International agencies debating college educational priorities,[3] domestic organizations like the National Research Council that set goals for K–12 science education,[4] and prominent physicists interested in pedagogy have all looked into the question, and they send the same message: Students need broad and specialized knowledge. Moreover, as a recent report by the Organisation for Economic Co-operation and Development states, “knowledge about the disciplines, such as knowing how to think like a mathematician, historian or scientist, will also be significant, enabling students to extend their disciplinary knowledge” (reference 3, page 5).

In an article in Physics Today (September 2022, page 46), Carl Wieman gives examples of decisions that physics students need to learn how to make so they can think like physicists. The lackluster responses to the COVID-19 pandemic and the

Examples of ISLE problems

Several categories of problems are available in the Investigative Science Learning Environment (ISLE) curriculum resources. Here are example problems for two categories. More can be found in references 1 and 15.

Category: Evaluate reasoning or solution. Students must critically evaluate the reasoning of imaginary people or a suggested solution to the problem, which is given in words, graphs, diagrams, or equations. Students must recognize productive ideas, even when they are embedded in incorrect answers, and differentiate them from unproductive ideas.

Example 1. You are given a loop raceway for Hot Wheels cars. While playing with the cars, you and your friends notice that you need to release a car from a minimum height *H* of at least 1.3 diameters of the loop above the ground to prevent the car from falling off the track at the top of the loop. Two of your friends have different explanations for the observed pattern. Leila argues that the minimum height *H* must be larger than the loop diameter *d*, even if the friction forces are negligible, because otherwise the car would fall off the loop at the top. Jordan, on the other hand, insists that if there were no friction forces exerted on the car, the minimum height *H* would be equal to the loop diameter *d* because the mechanical energy of the car–Earth system is constant.

Analyze each explanation and describe what physics ideas Leila and Jordan used to arrive at their answer, even if you think their answer is incorrect. Then decide which of them is correct. Explain how you made your choice.

Example 2. Some students are given the following problem: “A 5000 cm^3 cylinder is filled with nitrogen gas at 1.0×10^5 Pa and 300 K and closed with a movable piston. The gas is slowly compressed at constant temperature to a final volume of 5 cm^3. Determine the final pressure of the gas.” (a) Explain, with quantitative arguments, why the ideal-gas law cannot be applied to solve this problem. (b) Modify the problem so that it can be solved using the ideal-gas law and give your solution.

Category: Design an experiment or pose a problem. Students must design an experiment, an experimental procedure, or a device that will allow them to measure or determine certain physical quantities or that would meet specific requirements.

Example 1. To develop a touch detector, you connect two force sensors to a computer and a meter stick of known mass. The sensors are used to keep the stick horizontal. (a) How can you use that setup to design an experiment that uses the readings of the two force sensors to determine the magnitude of any pushing force *F* and the location of its application on the stick *x*? (b) How can you use that setup to derive an expression that can be used as a computer algorithm to calculate *x* and *F* using the readings of the force sensors and the parameters?

Example 2. Design two experiments, using different methods, to determine the mass of a ruler. Your available materials are the ruler, a spring, and a set of three objects, one with a standard mass of 50 g, one of 100 g, and one of 200 g. One of the methods should involve your knowledge of static equilibrium. After you design and perform the experiments, decide whether the two methods give you the same or different results.

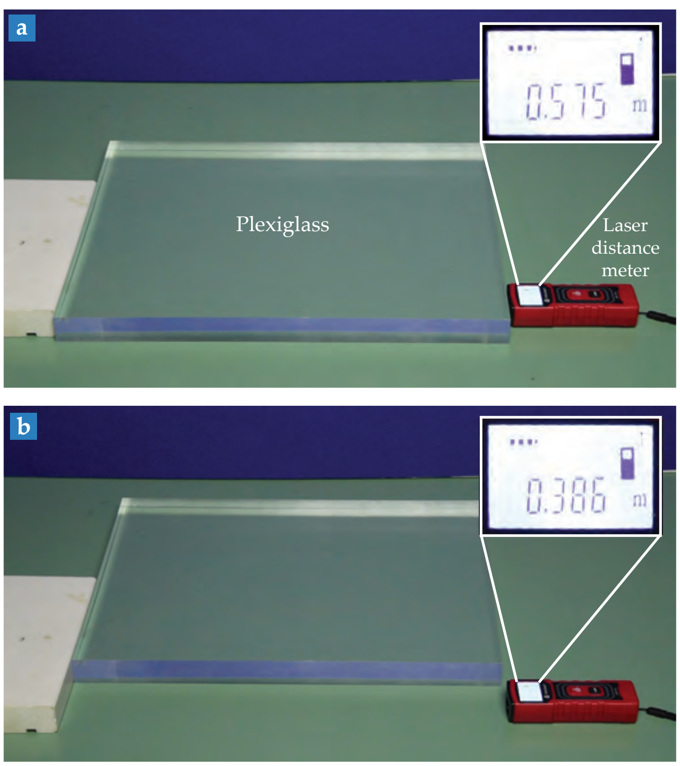
Designing and conducting an observational experiment				
Scientific ability	Missing	Inadequate	Needs improvement	Adequate
Designing a reliable experiment that investigates the phenomenon.	The experiment does not investigate the phenomenon.	The experiment may not yield any interesting patterns.	Some important aspects of the phenomenon will not be observable.	The experiment yields interesting patterns relevant to the investigation of the phenomenon.
Identifying a pattern in the data.	No attempt is made to search for a pattern.	The pattern described is irrelevant or inconsistent with the data.	The pattern has minor errors or omissions, or terms aren't properly defined.	The pattern represents the relevant trend in the data. If possible, the trend is described in words.
If applicable, representing a pattern mathematically.	No attempt is made to represent a pattern mathematically.	The mathematical expression does not represent the trend.	No analysis of how well the mathematical expression agrees with the data is included, or some features of the pattern are not represented in the expression.	The mathematical expression fully represents the trend, and an analysis of how well it agrees with the data is included.

A SELECTION OF RUBRIC CRITERIA used by students to assess themselves when they design and perform observational experiments. The same criteria are also used by instructors to provide feedback.

ongoing climate crisis make it clear that physics educators have not paid enough attention to teaching students those thinking skills. Understanding the nature of scientific knowledge is an essential part of a liberal arts education. Our physics students need to learn how to think like physicists even if they are not planning to enter the field after graduating.

How can students learn physics concepts and models while also learning to think like a physicist? In the past 30 years, the educational community has established that interactive engagement methods lead to better student learning gains than traditional methods.[5] As brain studies have shown, learning involves physical changes in a person's brain and body.[6]

In other words, it is impossible to transmit knowledge by lecturing: The learner must construct it themselves by actively participating in the instructional process and thereby altering their brain connections. But for that to happen, the learner needs to be motivated and feel that they are capable of learning. Although our students have been doing physics all their lives by living and navigating in the physical world, many of them feel that physics is a foreign subject that is detached from their lives. Over the past 20 years, researchers have accumulated evidence that after students take a physics course, their attitudes toward physics and perception of their ability to do physics decline.[7]



Pedagogical challenges

I believe physics educators face three challenges. The first is shifting the focus of learning from the pure outcomes of physics as an intellectual endeavor to the process through which those outcomes are obtained. In other words, instructors need to help students learn by experiencing how physicists construct knowledge. The second is changing the focus of physics pedagogy from simply transmitting physics knowledge to students to creating an environment in which they can self-construct that knowledge. The third is helping students believe that they can do physics and that they belong in physics—

FIGURE 3. IN AN EXPERIMENT, Investigative Science Learning Environment students use a laser distance meter (lower right corner of each panel, with insets of the readouts) to measure the distance traveled by light **(a)** in plexiglass and **(b)** in air. They then compare those speed-of-light measurements to determine in which one light travels faster.

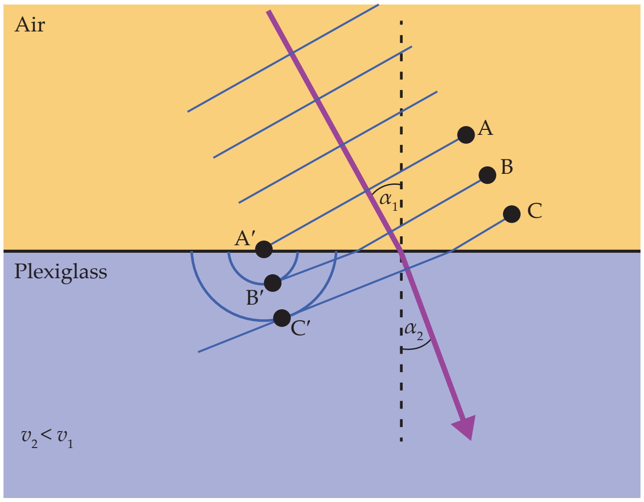


FIGURE 4. EXPLAINING REFRACTION with the wave model of light. Traveling at velocity v_1 in air, a light wave enters a plexiglass slab at an angle of incidence α_1. As it enters the plexiglass, the light refracts at an angle α_2 that is smaller than α_1. To explain that bending using the wave model of light, students hypothesize that once the points on a wavefront reach the air–plexiglass boundary, the radii of the circular wavelets that emerge from those points in plexiglass—according to Huygens's principle—will be smaller than in air. The progression of wavefronts from A–A' to C–C' shows how they bend. That can happen only if the light velocity v_2 in the plexiglass is slower than the light velocity v_1 in air.

namely, helping them see themselves as physicists even though they may take different career paths.

The ISLE approach is only one of many pedagogical tools with interactive engagement methods developed by the physics-education research community over the past 30 years. Others include the SCALE-UP (Student-Centered Active Learning Environment for Undergraduate Programs) project,[8] the physics tutorials pioneered at the University of Washington,[9] peer instruction,[10] paradigms,[11] and modeling instruction.[12] Studies show that they all are more effective at helping students learn physics than transmission modes of instruction.

Although all those approaches have students working in groups to produce answers to the questions posed by the materials developers, only two of them—modeling instruction and ISLE—have students constructing their knowledge through a process based on how physicists do it. And only the ISLE process teaches students to explicitly generate and test alternative hypotheses to explain a phenomenon. It also provides rubrics to help students self-assess and improve their work. My example at the beginning of this article represents the logical flow through which the students construct concepts and relations in an ISLE classroom[1] (see figure 5).

In a typical ISLE class, students work in groups to observe physical phenomena, identify patterns, and devise multiple explanations or hypotheses—qualitative or quantitative—without knowing which one is correct. They use analogical reasoning, graphical representations, and mathematical tools; share their findings with the rest of the class; and come up with a consensus on what hypotheses should be tested experimentally. They then design experiments to test those hypotheses. Before conducting an experiment, they make predictions about its outcome. They compare the results with their predictions and decide which hypotheses they can reject. That process repeats as many times as needed until only one hypothesis is left, which students then apply to solve sample problems. At the end, the instructor summarizes what students have found and shares accepted physics material related to students' findings.

The continuous interplay between the physical world and models is central to the way that physicists generate new knowledge. Research suggests that the ISLE approach to teaching and learning physics is representative of how physicists work. A recent study by the physics-education research group at the University of Washington, for example, observed that experts—both faculty members and graduate students—develop and test hypotheses in a cyclical manner when they model a novel paper-and-pencil problem. We observed similar cycles when faculty are presented with novel experimental problems.[13]

Although the ISLE process may seem long and complicated, it does not take much time and can be easily implemented during a typical class as long as students are familiar with it. More than 20 years ago, our development team at Rutgers University, in an effort to help students engage in the ISLE approach effectively, came up with a list of scientific abilities that represent the processes and activities used by physics practitioners. Each ability was broken down into several smaller subabilities that match many of the decision-making steps physicists undertake that Wieman mentioned in his 2022 Physics Today article. We then devised a set of activities that help students develop those abilities.[14]

We have also developed descriptive rubrics for each subability to help students self-assess and improve their work and to guide instructors in providing feedback to students.[14] The table on the previous page provides several rubric examples that students use when they design an experiment to observe a phenomenon and find patterns. Over the years we have developed a library of curriculum resources for introductory physics courses[1] and a textbook that is designed to accompany a class taught with ISLE pedagogy.[15] Finally, we have developed a library of nontraditional real-life problems that do not have one right solution and that engage students in the decision-making processes identified by Wieman. The box on page 29 illustrates a few examples of such problems, which help students develop traditional problem-solving skills while also teaching them how to think like physicists.

ISLE and belonging

But how does the ISLE approach help address the third challenge I discussed—namely, helping students believe that they can both do and belong in physics? It does so in four ways. First, when students are beginning to learn a new idea and are observing initial experiments, they are not asked to predict the outcome but to say in simple words what they observed. That step removes the feeling of failure that often exists when students are obliged to make a prediction about something they know little to nothing about and quickly see that it is wrong. If students are asked to observe experiments, they all start on the same page, are ultimately successful, and feel that they can do it. As the students work together on the activities, they gain expertise as a community, which makes every student feel that their contributions are valued and that they belong.

Second, when students develop their own hypotheses—we call them wild ideas—to explain the outcomes of observational experiments, those hypotheses do not need to be correct, but they need to be testable. As students work in groups, they share their designs and make predictions based on their wild ideas. If the outcomes of their experiments don't match the predictions, their personal intuition hasn't failed—the wild idea has. So no harm is done to their self-confidence: On the contrary, they often feel that they have accomplished something that is very valuable in science—they ruled out a possible hypothesis! That's not an experience that most physics students get to have. It teaches them that knowing the right answer is not nearly as important as creativity and persistence.

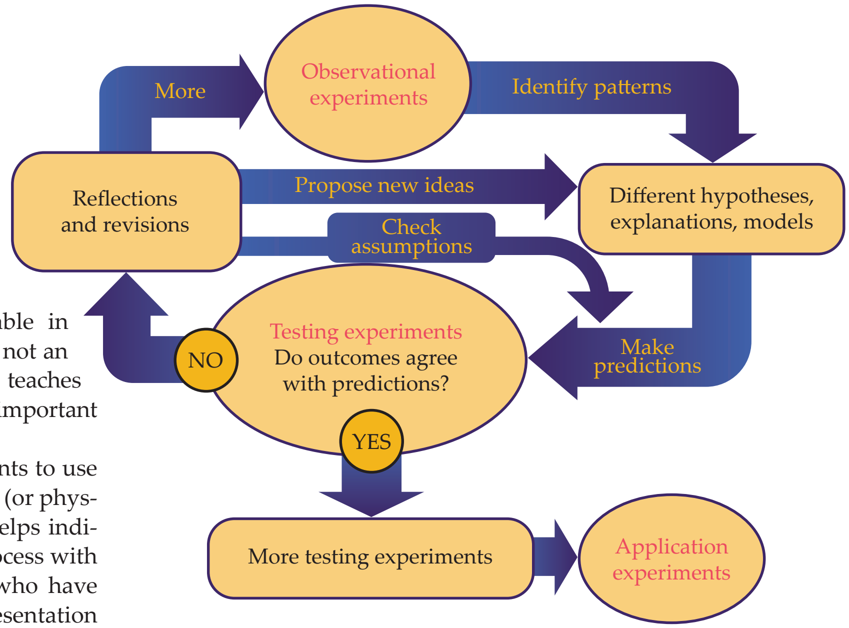


FIGURE 5. A SCHEMATIC MODEL of learning activities employed in the Investigative Science Learning Environment approach.

Third, the ISLE approach consistently asks students to use graphical representations as a bridge between words (or physical phenomena) and algebra (or calculus), which helps individuals who need concrete imagery to describe a process with mathematical symbols. But it's not only students who have trouble with math who benefit from the multiple-representation approach. Recent research in cognitive science shows that it helps all learners. Understanding the interplay between representations is a hallmark of advanced physics thinking, which means that ISLE helps all students reason more like experts and increases their potential for belongingness in physics.

Finally, the ISLE course structure encourages students to resubmit improved lab reports, homework, quizzes, and even exams for a better grade, which helps them feel that their learning is valued. Students thus get accustomed to understanding that they might not succeed on the first try, but if they persevere, they can make it in physics.

In my Millikan Medal (now the McDermott Medal) lecture at the 2014 American Association of Physics Teachers Summer Meeting, I gave an overview of the literature on student experiences in introductory physics courses taught with the ISLE approach.[16] As I described, ISLE students show high learning gains in conceptual understanding, approach problem-solving in an expert-like manner, and develop physical reasoning and experimental abilities that help them when they learn new material. Another recent study shows that ISLE students feel that they can succeed in physics and that what they are learning in ISLE courses is useful for their studies in other classes, for their future in the workplace, and in their lives in general.[17]

Why use the ISLE approach?

Because the ISLE process alters the environment in which students learn physics to better help them succeed, it conforms to what the architect Ronald Mace called universal design: the adaptation of an environment to be accessible by everyone, regardless of their age or ability. It is not surprising that the disability expert Julie Maybee recently argued that the ISLE approach is an example of universal design for physics education.[18]

Evidence shows that the ISLE approach is inclusive[17] and helps students learn.[16] If that doesn't convince you, I encourage you to ask yourself the same question I asked myself: After the dust settles, how do you want your students to be transformed by your teaching? If you'd like them to think more like a physicist and carry those skills with them throughout their lives—regardless of what they do—then I encourage you to consider ISLE.

At the beginning of the COVID-19 pandemic, I created a Facebook group called "Exploring and applying physics" for those who want to implement our approach. In the forum, we post curriculum materials, encourage everyday professional development, run monthly workshops, and discuss student learning and current research. Today the group has more than 2200 members from every continent except Antarctica. You are welcome to join our community!

REFERENCES

1. E. Etkina, D. T. Brookes, G. Planinsic, *Investigative Science Learning Environment: When Learning Physics Mirrors Doing Physics*, Morgan & Claypool (2019).
2. G. Planinsic, E. Etkina, *Eur. J. Phys.* **40**, 065702 (2019).
3. Organisation for Economic Co-operation and Development, *The Future of Education and Skills, Education 2030: The Future We Want* (2018).
4. National Research Council, *A Framework for K–12 Science Education: Practices, Crosscutting Concepts, and Core Ideas*, National Academies Press (2012).
5. S. Freeman et al., *Proc. Natl. Acad. Sci. USA* **111**, 8410 (2014).
6. J. E. Zull, *The Art of Changing the Brain: Enriching the Practice of Teaching by Exploring the Biology of Learning*, Stylus (2002).
7. K. E. Gray et al., *Phys. Rev. Spec. Top. Phys. Educ. Res.* **4**, 020106 (2008).
8. R. J. Beichner et al., in *Research-Based Reform of University Physics*, E. F. Redish, P. J. Cooney, eds., American Association of Physics Teachers (2007).
9. L. C. McDermott, P. S. Shaffer, *Tutorials in Introductory Physics*, Prentice Hall (2002).
10. C. H. Crouch, E. Mazur, *Am. J. Phys.* **69**, 970 (2001).
11. C. A. Manogue et al., *Am. J. Phys.* **69**, 978 (2001).
12. E. Brewe, *Am. J. Phys.* **76**, 1155 (2008).
13. C. Zimmerman et al., https://arxiv.org/abs/2308.01465; M. P. Čančula, G. Planinšič, E. Etkina, *Am. J. Phys.* **83**, 366 (2015).
14. E. Etkina et al., *Phys. Rev. Spec. Top. Phys. Educ. Res.* **2**, 020103 (2006).
15. E. Etkina, G. Planinsic, A. Van Heuvelen, *College Physics: Explore and Apply*, 2nd ed., Pearson (2019).
16. E. Etkina, *Am. J. Phys.* **83**, 669 (2015).
17. D. T. Brookes, E. Etkina, G. Planinsic, *Phys. Rev. Phys. Educ. Res.* **16**, 020148 (2020).
18. J. E. Maybee, *Making and Unmaking Disability: The Three-Body Approach*, Rowman & Littlefield (2019).

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