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Investigative Science Learning Environment

When learning physics mirrors doing physics

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We dedicate this book to all our colleagues who worked with us tirelessly to develop ISLE, to the teachers who adopted it and to our students.

Contents

Preface

This book is for those who are teaching physics at any level. It is for those who are dissatisfied with the current status of physics education and are looking for new ideas. It is for all those who want their students to experience the joy of doing physics while learning it. It is for all those who wish that learning physics would empower their students and give them confidence. This book is for those who wish to prepare their students for success in the future that requires creativity, imagination, collaboration and perseverance. This book is for those who wish to base their teaching on the latest discoveries of cognitive science and the results of physics education research. It is for those who love to try new things and to learn together with their students. This book is for you.

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Author biographies

Eugenia Etkina

Eugenia Etkina is a Distinguished Professor at Rutgers, the State University of New Jersey. She holds a PhD in physics education from Moscow State Pedagogical University and has more than 35 years of experience teaching physics. She is a recipient of the 2014 Millikan Medal, awarded to educators who have made significant contributions to teaching physics, and is a fellow of the AAPT. Professor Etkina designed and now coordinates one of the largest programs in physics teacher preparation in the United States, conducts professional development for high school and university physics instructors, and participates in reforms to the undergraduate physics courses. In 1993 she developed a system in which students learn physics using processes that mirror scientific practice, Investigative Science Learning Environment (ISLE), which is described in this book. She is the lead author of the textbook College Physics: Explore and Apply and the Active Learning Guide. Professor Etkina has conducted over 130 workshops for physics instructors, and published over 100 peer-refereed articles.

David T Brookes

David T Brookes is an Associate Professor of Physics at California State University, Chico. He obtained his PhD in physics, specializing in physics education research, from Rutgers University in 2006. Prof. Brookes has over 20 years of experience teaching physics at college level as both a graduate student teaching assistant, and as a professor. He has contributed extensively to the theoretical development of ISLE, developing ISLE curricular materials, and developing exam questions that assess the *process* of physics reasoning. Prof. Brookes' research is focused on (a) the use of semiotic resources in physics such as how physics teachers and physics students communicate using words and using equations, (b) the social dynamics of small group interactions and how those social dynamics can influence the effectiveness of the group. As a teacher, Prof. Brookes continuously experiments with implementing ISLE in a studio-like setting, reading extensively in educational research and thinking about how to implement those research findings in a practical way in the classroom. Outside of physics, he is an amateur bicycle racer.

Gorazd Planinsic

Gorazd Planinsic is a Professor of Physics at the University of Ljubljana, Slovenia. He has a PhD in physics from the University of Ljubljana. Since 2000 he has led the Physics Education program, which prepares almost all high school physics teachers in the country of Slovenia. He started his career in MRI physics and later switched to physics education research. During the last 10 years, his work has mostly focused on the research of new experiments and how to use them more productively in teaching and learning physics. He is co-founder of the Slovenian hands-on science centre House of Experiments. Professor Planinsic is co-author of more than 80 peer-refereed research articles and more than 20 popular science articles, and a co-author of *College Physics: Explore and Apply and the Active Learning Guide*. He is a recipient of the GIREP medal for his contributions in Physics Education and he is a fellow of IOP.

Chapter 1

Introduction

The goal of this book is to introduce readers to a new philosophy of teaching and learning physics—Investigative Science Learning Environment, or ISLE (pronounced as a small island). ISLE is an example of an 'intentional' approach to curriculum design and learning activities (MacMillan and Garrison 1988). Intentionality means that the process through which the learning occurs is as crucial for learning as the final outcome or learned content. In ISLE, the process through which students learn mirrors the practice of physics. This mirroring involves not only the process of the development of new ideas that are based on systematic patterns of experimentation and reasoning similar to that of physicists, but also the collaborative nature of science and its continuous opportunities to improve one's work.

The authors came to ISLE following different paths. Eugenia Etkina (the founder of the method) was trained as a physics teacher in the Soviet Union, taught there for 13 years and later became a professor in a US Rutgers Graduate School of Education preparing future high school physics teachers. Gorazd Planinsic (the 'experimental expert' of the method) was trained as a condensed matter experimentalist before he was given charge of preparing physics teachers at the University of Ljubljana, Slovenia. David Brookes (the 'theorist' of the method) was trained as a physicist in South Africa and a researcher in the field of PER in the US is now teaching undergraduate students at the California State University Chico. The combined physics teaching experience of the authors exceeds 100 years. They teach in different countries and work with different populations of students. They have been using the ISLE approach to teaching physics with high school students, university students as well as future and practicing teachers. They trained hundreds of other teachers who now use it too. ISLE works. But it is more than just a curriculum. It is a way of thinking about physics and science in general. It is a way of thinking about the students and about the role of a teacher in the classroom. It is a

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way of thinking of the ultimate goals of learning physics, and it is a tool for making intentional changes in your classroom.

In this book, we will provide multiple examples of student activities that follow this new way of thinking about teaching and learning physics, discuss the changes that one can implement in the classroom and provide reasons for our recommendations. ISLE is based on the history and epistemology of physics, analysis of work of practicing physicists, studies in brain and cognitive sciences and the demands of the workplace. In the interludes, David Brookes will share his struggles accepting and implementing ISLE philosophy in the classroom.

1.1 ISLE and interactive teaching methods

In the past 20 years, educators all over the word have accumulated enough data to say with confidence that students learn better through interactive engagement methods than through traditional transmission-mode methods (Hake 1998, Michael 2006, Freeman *et al* 2014, Von Korff *et al* 2016). As Mitchell Waldrop (2015) said 'At this point it is unethical to teach in any other way.' But what is *this* way? In general, a teaching method can be considered interactive when there is interaction between the students and the teacher in the classroom (not just the teacher talking to the students), when the students provide feedback to the teacher in some way, when they hold group discussions (such as brainstorming, 'think-pair-share') or when student questions drive whole class discussions. One popular approach is the 'flipped classroom' (Fulton 2012). In the flipped classroom, students read the textbook (or watch a video with the instructor explaining the material), then come to class and discuss what they read through answering questions posed by the instructor. They often work in pairs and participate in voting for the best answer. One of the flipped classroom examples in physics education is the method of peer instruction (Mazur 1997). Peer instruction has been in place for over 20 years; the students who learn physics through it demonstrate respectable learning gains and thousands of instructors use it. While the students in these classrooms work collaboratively answering questions and the professor limits lecturing to a minimum, the knowledge that students begin with comes from authority. Students' first experiences with physics concepts come from reading the book or watching a video with an authority figure on the screen. While such methods lead to more learning than traditional lecturing, what message about physics are they sending to the students? One answer is that physics is an area of study that can be learned by reading the textbook and discussing what you read in class. The goal of this book is to offer an alternative approach to learning.

Physics is an experimental science. Studying the history of physics (Holton and Brush 2001), the writing of prominent physicists about their work (Born 1943), and observations of this work in real time (Poklinek Cancula *et al* 2015), we find that the origin of every physics idea can be traced to experiments. At some time, at some point, an anomalous or interesting experimental result made scientists wonder what they observed. Then they (or somebody else) tried to figure out how to explain and quantify the observed phenomenon. Multiple hypotheses were tested in multiple experiments and those that were not ruled out remained; they are now in our textbooks. When students start learning a concept by reading the book, they see the final outcome without having any idea of where this knowledge came from. You might argue that they learn where ideas come from by doing experiments in instructional laboratories, but research shows that this is not the case (Holmes *et al* 2017). Traditional labs that provide step-by-step instructions to the students do not engage students in the development of new concepts; they mostly focus on the 'verification of theory' that students have already learned.

But why should our students 'discover' physics ideas on their own if they can quickly learn the right concept from a textbook and practice applying it? The latter approach seems much more efficient and practical. It would be if we lived in the 20th century or earlier. In the 21st century, knowledge is readily available and different skills are valuable. Today, employers seek people who not only have disciplinary knowledge but also epistemic knowledge (how to 'think like a mathematician, historian or scientist') (OECD 2018, p 5). Being able to investigate phenomena, to cope with multiple possible solutions, to evaluate assumptions, to generate different ideas and be able to test them are the skills that will make our students successful in the future, not using the facts explained to them by somebody else. The jobs that require recalling/using/manipulating facts, even reacting based on predetermined set of data/facts, are being replaced by interpretable machine learning systems (Wilson and Daugherty 2018).

Is it possible to create an environment in which students can 'discover' and learn physics for themselves in ways similar to how physicists work within a reasonable time? The method of teaching we describe in this book—Investigative Science Learning Environment (ISLE)—answers this question (Etkina and Van Heuvelen 2001, Etkina and Van Heuvelen 2007, Etkina 2015). There are three key features of this approach, which mirror the features of a scientific inquiry environment while at the same time allowing students to develop traditionally valued physics knowledge (normative concepts).

1. Students develop normative physics concepts as their own ideas by repeatedly going through the following process
   (a) Observing pre-selected phenomena (usually experiments but also could be simulations or previously collected data, photos, videos…) and looking for patterns,
   (b) Developing explanations/models/mathematical relations for these patterns,
   (c) Using these explanations/models/relations to make predictions about the outcomes of testing experiments that they propose,
   (d) Deciding if the outcomes of the testing experiments match the predictions,
   (e) Revising the models/relations if necessary and finally arriving at the normative physics models/relations,
   (f) Applying those for practical purposes (solving problems, building devices, determining the values of physical quantities, etc).

2. While engaged in steps (a)–(f), **students represent physical processes in multiple ways** to help them develop productive tools for qualitative reasoning and for problem solving.
3. While engaged in steps (a)–(f), **students work collaboratively** in groups of 3–4 using whiteboards and then share their findings, designs and solutions in a whole class discussion.

The combination of these features applies to every conceptual unit in the ISLE learning system. However, to make ISLE work in your classroom, more than those three ideas are required. Over the years, we found that helping students develop a growth mindset (Yeager and Dweck 2012) and feel like a member of a learning community (Bielaczyc and Collins 1999) are crucial for the success of ISLE.

1.2 Example of an ISLE process

To give the reader an image of how the ISLE process works in a simplified way, we present the following example. It is an activity that we do on the first day of class (the level of students does not matter) to engage students in the process that they will follow for the rest of the course. The students are grouped in teams of 3–4 and each team has a small white board and dry erase markers.

The activity starts with the instructor pouring ice-cold water into a glass and asking students to say what they observe using only terms that are familiar to them[1]. Student volunteers come closer and touch the outside of the glass and find it wet. They usually say that they see the water drops on the outside of the glass on the part where water fills the glass (figure 1.1) and that this part of the glass is opaque. The instructor then asks the students to work in groups to come up with several possible explanations (we call them 'crazy ideas' to help engage the students in the game) for where this water came from and to write down the explanations on their white-boards. After all groups are done, they lift the boards and share their ideas. Usually

Figure 1.1. Glass filled with ice cold water.

[1] When the air in the room is too dry, we use photos.

the students come up with the following explanations: (1) the water from the glass seeped through the glass wall; (2) the water, which is inside the glass wall, came out on the outside of the glass; (3) the water escaped from the top of the glass and landed on the outside; (4) water on the outside of the glass did not come from the water in the glass, it came from the air outside.

Once all the explanations are listed and shared the next step is to ask—what do we do next? Usually one of the students says: we need to test them. How do we test explanations? The students propose to do more experiments. But what experiments to do? Here, the instructor helps them: let's come up with new experiments whose outcomes we can predict using every explanation and then compare the outcomes with the predictions. The students work in groups designing the experiments and making predictions. They can either perform the experiments themselves, or watch the instructor perform them or watch the photos of the outcomes of the experiments that they proposed which were performed before. Table 1.1 shows the testing experiments that the students usually come up with, predictions based on each explanations, outcomes and final judgment. Outcomes of the testing experiments are

Table 1.1. ISLE process: testing possible explanations for the 'wet glass' experiment.

	Testing exp. 1: Use dry, empty cooled glass (put glass in a fridge)	**Testing exp. 2:** Use different cold liquid (ex. oil) *Assumption:* there is no water in oil	**Testing exp. 3:** Weigh glass filled with ice-cold water	**Testing exp. 4:** Cover the glass filled with ice-cold water *Assumption:* cover does not let water through
Explanation 1: Water from the glass seeped through glass wall	There will be no water outside glass	There will be no water outside glass	$m_f = m_i$	There will be water on outside glass
Explanation 2: Water, which is inside the glass wall, came out on the outside glass	There will be water on outside glass	There will be water on outside glass	$m_f = m_i$	There will be water on outside glass
Explanation 3: Water escaped from the glass and landed on the outside glass	There will be no water outside glass	There will be no water outside glass	$m_f \leqslant m_i$	There will be no water outside glass
Explanation 4: Water from air collected on the wall outside glass	There will be water on outside glass	There will be water on outside glass	$m_f > m_i$	There will be water on outside glass
OUTCOMES	**Water on outside glass**	**Water on outside glass**	$\boldsymbol{m_f > m_i}$	**Water on outside glass**
JUDGMENT	**Reject 1,3**	**Reject 1,3**	**Reject 1,2,3**	**Reject 3**

also shown in figure 1.2. Based on the outcomes, the students reject explanations 1, 2 and 3.

After all ideas except (4) are ruled out by testing experiments, students are asked if they can think of any practical use for this knowledge. The students brainstorm and come up with ideas, such as drying humid places by extracting water from air or collecting drinking water from air in the dessert.

You might wonder what the point of this activity is—don't students in high school or college know that there is water in the air? They might, but this is not important in this case. What is important is that the students learn to create multiple explanations of the same observation (phenomenon) and systematically rule them out. These explanations were hypothetical until tested. Being able to find an experiment whose outcome does not match the prediction based on the hypothesis and subsequently revise the hypothesis are the reasoning steps that are characteristic for science. But unfortunately in most teaching approaches, the students do not have opportunities to rule out ideas as all ideas are presented to them as ideas that have been already accepted in science and all they need to do is to watch the professor 'illustrate' them using lecture demos or they do it themselves conducting 'verification' experiments in traditional labs. Most of their education consists of applying these unquestionable truths to solve well defined problems that have one correct answer. The example of the 'wet glass' shows how one can engage in *authentic scientific reasoning* using very simple equipment and very simple content. But you might be skeptical if such a process is possible for a more complex content. In this book, we present several examples and more are used in the textbook 'College Physics: Explore and Apply' (Etkina *et al* 2019) (we will call it CP:EA) and in 'The Active Learning Guide' (Etkina *et al* 2019) (called ALG), which has exercises for the students that they do in class before they read the textbook. ALG exercises engage students in the activities similar to the 'wet glass' that help them construct all concepts and relations that the students commonly learn in a general physics course.

1.3 Elements of the ISLE process and their logical connections

The 'wet glass' example shows the logical progression of student actions and thoughts that is represented in the diagram below (figure 1.3). Some of the steps in the diagram have not been used yet as the example is very simple, but as the readers progress through the book they will find examples of all steps in the process.

Figure 1.2. Outcomes of the testing experiments (1)–(4) (from left to right). Increase of mass reading in testing experiment (3) was 0.1 g in 5 min on a medium humid summer day.

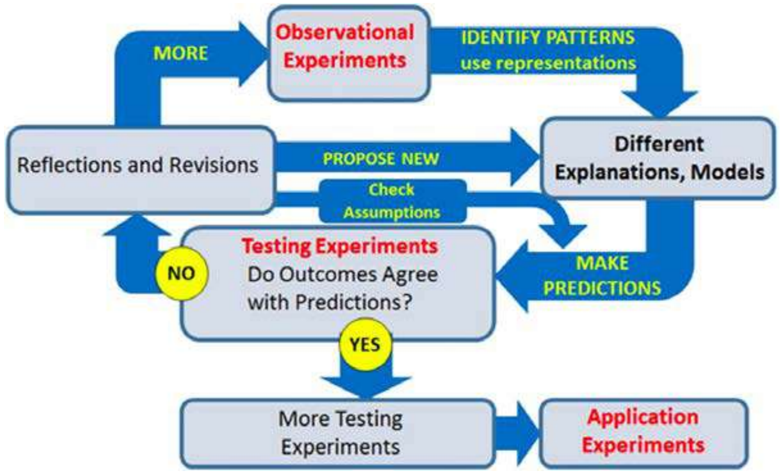

Figure 1.3. ISLE process diagram.

Students who learn physics through ISLE engage and develop two types of reasoning: (1) *inductive* reasoning includes both finding patterns in the data, and *analogical* reasoning when they invent casual or mechanistic explanations/hypotheses for the patterns. (2) *Hypothetico-deductive* reasoning is employed when students use the invented explanations/hypotheses to make predictions about the outcomes of the testing experiments. The hypothetico-deductive reasoning chain is as follows:

If
the explanation (mechanistic or causal explanation/hypothesis/model) is correct
and
I do such and such (description of the testing experiment),
then
so and so should happen (prediction of the outcome of the testing experiment)
because
(the reasoning how the prediction follows from the explanation; this part is optional, depending on the complexity of the problem)
However, it did not happen, *therefore* I need to reject/revise the explanation (check assumptions, collect more data).
Or
It did happen, *therefore* I cannot reject the explanation.

Note that the statement after '*if*' is NOT the description of the experiment (if I do such and such) but the description of the hypothesis under test. It is important that students practice this logical chain when they design experiments to test their ideas.

Although the arrows on the diagram represent a progression of logical steps, at any step one can go back and revisit the previous step or examine the assumptions. The ISLE process is by no means linear or even cyclical. *At every step, the students work collaboratively and share their findings with the class.* The role of the instructor is to facilitate the process and at the end provide a summary of what students found (or what is missing). The summary provided by the instructor after the investigation is called 'time for telling' (Schwartz and Bransford 1998). The most important idea here is that the students invent/design/argue/share first and the instructor confirms/corrects/summarizes afterwards. This idea is the key to understanding ISLE where the product of knowledge (for example, the concept of condensation of water in the air on the surface of the glass) cannot and should not be separated from the means by which it came to be known. Postman and Weingartner (1969) argued that

> '[t]he medium is the message implies that the invention of a dichotomy between content and method is both naive and dangerous. It implies that the critical content of any learning experience is the method or process through which the learning occurs.' (p 19)

Therefore, every medium is a message. In case of ISLE, the process through which the students develop knowledge is the message concerning not only how science works but that they are capable of doing it and that the instructor trusts them to do it from the beginning.

Below we list issues that are important for the above process and simultaneously that distinguish ISLE from other pedagogical approaches (traditional and reformed).

1. *Observational experiments (phenomena):* Starting with observing phenomena is probably the most important element of the ISLE approach. It levels the playing field and allows everyone to be successful. Observational experiments need to be simple and 'clean' enough to help the students infer a pattern easily. It is important that the equipment is familiar and easy to use. If more complex equipment is needed, the instructor needs to make sure that the students have a clear picture of the setup and know how to use it before they begin the experiments. We want to avoid unnecessary frustration before the process of construction of knowledge begins. *We do not require the students to make predictions* before the observation in contrast to the popular approach 'predict, observe, explain' (White and Gunstone 1992) that is used in many reformed curriculum approaches including peer instruction, (Mazur 1997). In fact, the more 'open' the students are to their observations, the better. When the time and topic permit, students do the experiments themselves and collect and analyze data to find patterns. In other cases (dangerous experiments, very expensive experiments, experiments that happen to fast or to slow, experiments with complicated data collection, phenomena that cannot be recreated, such as phenomena in astronomy, meteorology), they might collect data from a video of the experiment or observe the photographs/sketches and work with the table of data collected by somebody else. Historical data can also serve as observational experiments. For example, we can use data for the motion of the Moon that have been already known to Newton to devise the law of universal gravitation (see pp 133–4 in CP:EA).

2. *Explanations/hypotheses/models:* We encourage the students to propose as many possible explanations/hypotheses/models for the patterns as they can. To reduce the pressure of coming up with a correct explanation, we invented the term 'crazy ideas'. This way students know that they are expected to be creative, not correct. The only requirement for these crazy ideas is that they should be falsifiable (aliens did it is an example of a non-falsifiable explanation). The fact that all explanations have equal weight before they are tested allows students to freely express their ideas, often based on everyday experience, without waiting for authority for validation. Students use their prior experiences, prior knowledge and creativity to construct such explanations. Their explanations are analogical or abductive in nature. Sometimes multiple explanations/models are easy to devise (such as in the example with wet glass described above), sometimes only one explanation emerges (especially when students construct quantitative models from collected data, such as in the example of pulled scales described on page 2-3 in this book), but our goal is to encourage as many as possible. In case of one explanation, the students still need to test it. We also separate models into causal and mechanistic. Sometimes students can only devise causal models (for example, a model for acceleration: acceleration of an object is directly proportional to the sum of the forces exerted on it and inversely proportional to its mass); sometimes they can come up with a mechanistic model behind a phenomenon (for example, a model for gas pressure: small ball-like randomly moving elastic particles explain how gases exert pressure in all directions). ISLE instructors do not provide feedback on the explanations/models that students construct before the testing experiments are performed. They are considered to be equally valuable until the testing experiments are performed.
3. *Testing models/explanations*: To test the explanations/models, students design or propose new experiments whose outcomes they can predict using their explanations/models. Before performing them, students make the predictions *using the explanation under test* (not their intuition or gut feeling), not rush to perform the experiments and 'see what happens'. It is important that they not just make the predictions but clearly explain how these predictions are based on the explanations/models/relations that they are testing. This is where the idea of controlling variables may arise as well as experimental uncertainties and axillary assumptions. It is important that the students are cognizant of what they are taking for granted in addition to the model under test (the desk is horizontal; the spring is massless, and so forth). Making predictions based on the idea under test and not the intuition is the most difficult part of the cycle but it helps the students develop hypothetico-deductive reasoning (Lawson 2003). Sometimes we offer ideas that we know students might have on their own to test (for example, the students need to test the following statement: 'the mass of an extended object distributed evenly with respect to the center of mass') and sometimes we offer the testing experiments and ask students to make

predictions using the idea under test (for example, use the idea that when an objects moves in a circle at a constant speed, the sum of the forces exerted on it points towards the center to predict what will happen when a marble rolls inside a circular ring with one segment of the ring removed). 'Testing' provides an opportunity for the students to examine why a particular idea leads to the predictions that do not match the outcomes. However, students do not have a personal stake in these predictions, as they are testing 'somebody else's' ideas. Finally, testing (in particular, the hypothetico-deductive reasoning sequence described earlier) provides an opportunity for the students to use their prior knowledge and connect it with the new topic or apply it in the new context, thus helping students build a coherent knowledge structure.

4. *Judgment:* The outcomes of the testing experiments matching the prediction do not prove the explanations/models. They fail to disprove them. The experiments with the outcomes contradicting the predictions are in a way better, as they allow students (physicists) to think about rejecting of the explanation. Moreover, this is where the assumptions are important. Checking assumptions that went into the prediction in addition to the explanation/model is the step whose value cannot be over-emphasized. After the students tested the explanation/model/relation invented by them and have not ruled out, they gain confidence in it. It is at this moment that the instructor gives a name (if possible) to the invented idea and summarizes student findings using proper scientific language. This is 'time for telling'. As we discussed above, it should come AFTER the students have constructed the idea, not before (see example on page 2-4)
5. *Tools for reasoning:* To construct, test and apply models, students need other tools in addition to mathematical equations. ISLE emphasizes multiple graphical representations at all stages of concept construction (Van Heuvelen 1991, Van Heuvelen and Zou 2001). This process starts with the observational experiments: students learn to draw a picture of the apparatus, record data in a table, then draw a graph and look for patterns. Sometimes the instructor provides hints for a specific physical representation. Among non-traditional physics representations, the ISLE approach uses bar charts (ALG) to represent conservation of momentum and/or energy in mechanics, thermal physics, electrostatics, atomic and nuclear physics. Students learn to convert one type of representation of a process to other types in order to help them identify patterns in phenomena and devise explanations. Then they use concrete representations to help construct accurate mathematical descriptions of processes and later evaluate mathematical solutions (Rosengrant *et al* 2009). They use the mathematical descriptions to make predictions about the outcomes of testing experiments. After the concepts have been constructed and tested, students use the different representations to reason qualitatively and quantitatively about physical processes (solve problems). CP:EA contains multiple worked

examples that show students how to implement a multiple-representations-based problem solving strategy to solve problems.

6. *Applying new ideas:* The final stage of the ISLE process is *application*. This is traditionally what we think of as 'solving problems.' ISLE emphasizes that application problems are based in real life and are relevant to real life. We often have students do application experiments in a lab as well as solving application problems as part of their homework. Typically (but not always) application experiments involve asking students to determine a quantity that they can relate to using two independent experimental methods (Etkina *et al* 2006). For example:
   - Determine the coefficient of static friction between your shoe and the carpet
   - Determine the frequency of vibrations of an electric toothbrush
   - Determine the spring constant of a given spring
   - Determine the rotational inertia of your bicycle wheel (for calculus-based courses)
7. The students are expected to compare their results from the two methods and account for any discrepancy. What is important here is that there is no 'accepted value' to compare their results as different shoes and different tiles have different coefficients and different toothbrushes have different frequencies. Alternatively, an application experiment could be something fun like 'build a pin-hole camera and explain how it works' or 'build a gravity-force car that is powered by the force exerted on an object that is a part of this car.'
8. *Sequencing:* The biggest challenge to creating an epistemologically authentic investigative process is sequencing. In a 'traditional' setting of a large-enrollment course where the course is broken up into lectures (large room meetings where all students come together at the same time) and/or recitations, and labs (smaller groups of students have a class on different days), the instructor following the ISLE method needs to plan whether that initial observational experiment starts in the lecture or in the lab. One of us (DTB) works with his department chair every semester to make sure all weekly lab sections are scheduled between two large room meetings so that everyone in the class has had the same lab experiences coming into the next large room meeting. For ISLE to work, everything that happens in the lab and large room meeting needs to be connected. If ISLE is implemented in a small college class, in a high school setting or in the studio format (Beichner *et al* 2007), it is much easier to coordinate all activities to flow smoothly for all students at the same time.
9. *Role of the textbook:* ISLE differs from some other active engagement approaches concerning textbook reading, especially from the flipped classroom approach. We expect students to read the textbook *after* they have devised ideas in class. We believe that the quality learning time in class should be used for students to engage in a carefully scaffolded inquiry process where they learn to think like physicists. After the process of

exploration is complete, the textbook can be used for the purposes of summarizing ideas, and pulling ideas together. When it comes to problem solving, we suggest following a similar approach: let students first struggle with a problem (invention step), then show them how to solve it using clearly articulated reasoning steps and tools that the students have learned (time for telling step) and then let them study worked examples with the same problem solving strategy in the textbook. This was the students can see the nuts and bolts of practically implementing the ideas they've developed through the ISLE process.

10. *The learning community:* At each stage, the students work collaboratively (in groups), sharing ideas and trying to convince each other (using small whiteboards, whole class symposia, walks-through and so forth). This approach resembles the processes that the scientific community uses to develop and apply knowledge. Sometimes students can feel uncomfortable sharing their ideas in a whole-class setting (called a symposium). In such cases, we use a technique where pairs of groups hold a 'mini-symposium' where they share ideas with each other. Done frequently enough, groups start to do it habitually, getting out of their chairs and taking their whiteboard to another group to compare ideas. The degree of collaborative work depends on the problem. Often the students need first to think/focus on the problem alone and then pair/share ideas.
11. *Assessment:* A process-centered approach to learning requires a new approach to assessment that focuses on the process of the development of knowledge in addition to the physics facts, concepts, relations, etc. In ISLE, students are assessed for conceptual understanding, for problem-solving ability, and, most importantly, for their use of various scientific abilities (skills and processes that they use to answer questions, solve problems, design and carry out experiments, etc) (Etkina *et al* 2006). Students work on activities that help them develop the abilities used by scientists in their work: experiment design, model building, use of multiple-representations, evaluation, etc. Similar tasks are used for formative assessment activities (Black and Wiliam 1998a). A set of rubrics (described below in detail) provides guidance for the students and can be used by instructors for grading—but most importantly by the students for self-assessment. It is important to add that students learning physics through ISLE have an opportunity to revise and improve their work without punishment for resubmissions (see more discussion on this topic in chapter 5), whether it be a quiz, a homework assignment or a lab report. An opportunity to improve mirrors science practice or revisions when feedback is provided (for example, during the peer-referee process).

1.4 Interlude: when inquiry fails: the need for a framework of epistemic practices

One of the first things I encountered on my journey was the ISLE process you've been introduced to in chapter 1, figure 1.3. It took me several years to understand what it meant and why it is so important. I would like to discuss that in this interlude. Presumably you know that lecturing students is not as effective as having students engaged in active inquiry, figuring stuff out for themselves. But inquiry learning can take many different forms, depending on the learning goals of the instructor. The most fundamental objection to inquiry learning is: if we're not going to give students the knowledge they need (direct instruction), how are they doing to discover it on their own (discovery learning) (Klahr and Nigam 2004)? This is a false dichotomy. If knowledge is a process of knowing, our classroom needs to be a place where students can participate in that process (Rogoff *et al* 1996, Sfard 2007). In this view, students are neither receiving knowledge, nor discovering and acquiring knowledge. They are participants in a set of epistemic and representational practices that constitute the activities of practicing physicists. What I needed for a process-focused inquiry classroom is an epistemic framework within which inquiry takes place. That is what the ISLE process represents.

If that is a lot of words, I apologize. Let me give you an example to explain what I mean: before I fully grasped Professor Etkina's ISLE framework, I wrote a tutorial on rolling without slipping for my physics students. I wrote the tutorial because I knew that it would be better if *they* figured it out, rather than me standing at the front of the classroom and telling them. I also wrote that tutorial because I wanted my students to '*get*' rolling without slipping. I knew they didn't understand it. I figured if I take them through the reasoning steps, they'd eventually get it. So I wrote the tutorial with all the steps laid out and the students had to fill in the answers. It went something like this:

Here is a snapshot of a rolling wheel.

a. How fast is the axle moving forward relative to the ground?
b. How fast is the top of the wheel moving forward relative to the ground?
c. How fast is the contact point moving forward relative to the ground?
d. Now imagine you're riding on the axle of the wheel as it is rolling forwards, in this reference frame, how fast and in what direction is the contact point moving relative to you?
e. etc.

Students were expected to work in groups filling in the answers on the worksheet and then continue on to the next step, until they finally got to the point where they combined the translational motion of the wheel in the lab frame with the rotational motion of the wheel in the center of mass frame and *bingo,* it all fits together! I was leading them through a set of steps (based on how I understand rolling without slipping) in order to get them to a point of understanding (my understanding) of rolling without slipping. The epistemic framework behind this approach (if I dare dignify it with that term) is:

> 'I understand rolling without slipping with these deeply connected pieces of knowledge from relative motion, calculus and reference frames; if you understand it like I do, *you'll* understand rolling without slipping.'

This is a messed-up epistemic framework, which has nothing to do with physics or how physicists come to know what they know. This is an example of inquiry with an impoverished epistemic framework which completely misses the key goal of what we're trying to achieve.

My rolling without slipping worksheet missed the point because students need a framework for deciding what constitutes truth. If we are to see students as 'truth-seekers' rather than 'knowledge memorizers', we need to help them to recognize the framework within which the truth is established. This is called 'epistemologically authentic' inquiry (Chinn and Malhotra 2002). It is not just essential for successful inquiry learning, it is the *essence* of why we're here and doing what we do.

To answer why this is so important, I need to make a digression. I only began to fully appreciate the ISLE process diagram after YouTube became ubiquitous. I would spend some hours watching the most terrible 'debates' between (for example) a climate scientist and a climate change denier. For example, the climate scientist might make the case that carbon dioxide levels are rising, and as a consequence, the global average temperature is rising. The denier (and I recall watching some version of this on YouTube) pointed to the last interglacial about 120 000 years ago, when the world was considerably warmer than today and sea levels were higher, and he said that carbon dioxide levels *lagged* behind the temperature increase, therefore the climate scientist must be wrong, because carbon dioxide wasn't the cause of the interglacial warming. Of course, the denier is quite correct in his facts, but the logic is flawed. Just because CO_2 is a feedback mechanism, it doesn't preclude it from being a causal mechanism in a different circumstance. In fact, it can be a cause *and* a feedback. But the climate scientist is left floundering because now he has to explain the subtleties of causality and the distinction between cause and effect in complex systems in a 60 second sound bite. The denier wasn't factually wrong. He broke the rules of scientific reasoning. If he said the same thing in a climate science conference, they'd just laugh at him and ignore the rest of his speech because they all know immediately that he's not playing by their rules of how truth is established.

Here is another example, perhaps simpler to understand. Scientists have established a causal link between smoking and lung cancer. The way in which that causal link was established is not simple. It involves the field of epidemiology with its own set of rules of knowing and truth. It is complicated because you can't do a controlled experiment where you *make* a randomly selected group of people smoke for 30 years while the control group (also randomly assigned) does not. This is clearly unethical. So the rules of truth are subtly different and there is no point in elaborating on them here except to say that it is not easy and you have to study hard for years to become a proficient researcher in this field. Now a tobacco lobbyist might come along and say 'these researchers can't be right because (a) they didn't do a randomized treatment-control experiment and (b) I had a grandmother who smoked like a chimney-pot and lived to the ripe old age of 94.' Has he invalidated the scientists' finding that smoking causes lung cancer? No. Is his evidence factually correct? Yes. Single counter-examples don't constitute sufficient evidence in the epidemiological approach. Epidemiologists establish their truth, taking averages over large data-sets. You can throw all the counter examples you want, but you are not 'allowed' to cherry-pick your data and you need to (randomly) sample a sufficiently large number of people before you can make any claims. To 'play' science, you need to follow the rules of the game.

Now imagine you're a member of the public listening to one of these debates. How do you decide who is correct and who is wrong? Imagine you've even taken a few science courses, but in every one of those courses the teacher lectured you about scientific facts (for example, when two objects collide they exert equal and opposite forces on each other, irrespective of mass and velocity of either object). This doesn't make any sense to you. Neither does the ensuing explanation from the teacher of why this *should* make sense to you. So you decide to take it on trust or faith and accept it must be true because… it's *physics*, and physics is just counter-intuitive. Lin (1983) has provided ample evidence of this effect amongst physics students. As we know, trusting an argument from authority, from a rationalist perspective, is a terrible way to arbitrate truth and, even worse, it renders the argument of the climate scientist and epidemiologist (on the one side) as equally valid as that of the climate-change denier or tobacco lobbyist on the other.

This is where I believe we can make a real difference in the world. I don't know the exact statistics, but I would guess that a small minority of the students in our physics classes will go on to science-focused careers[2]. The majority are probably going to live lives and work in jobs that are either peripherally science-related or completely dissociated from the scientific endeavor. Their time in our classes is one of their few contact points with actual science. The best we can do for them is for them to leave our classes with a deeper appreciation for and understanding of the *process* by which scientists create their knowledge. The two greatest wishes I have for my students are:

1. When confronted with a startling claim in the news or on social media, they would ask questions like 'How do you know that is true?' 'What evidence do you have to back that up?' 'What assumptions are you making in that model, what factors have you excluded?' 'How could we test this idea?'
2. We can't question every claim that is ever made. At some point, we have to place our trust in claims made by another person. So when someone is asked to place trust in a claim, I believe an understanding of science will help people to make better decisions about where to place their trust. For example, I am a physicist. I do not have the content-specific expertise to critically evaluate every claim made by climate scientists. But because I understand the process of science and trust that most climate scientists subject themselves to the same process or 'play by the same rules' (reproducible evidence, testable claims, peer review, etc) that the claims they are

[2] What we do know is that less than 40% of 15–16-year-old school students anticipate being engaged in a science-related career when they are 30 years old (OECD 2016).

> making are generally trustworthy in the sense that they are reproducible, testable, backed up by evidence and so on and so forth. I trust that the process of doing science yields valid claims that explain or account for our experience of the physical world we inhabit, and that are backed up by evidence.

As long as we continue to focus on the end-results of the scientific endeavor in our classrooms and whether our students 'get' that 'knowledge' (in chapter 2, I will explain why knowledge is not an object and we don't acquire or receive it), we are doing a fundamental disservice to our students and to humanity. I realize that is a rather strong opinion, but I hope you will at least see why I believe that a clear articulation of the scientific process is so important for inquiry learning and should be the primary goal of that learning approach.

The way I think about the ISLE process now is that it lays out the 'rules' of an 'epistemic game' (Collins and Ferguson 1993) or a series of epistemic questions that students should be asking over and over again as they do physics. For example, when someone suggests an idea, a student's response should not be 'no that's wrong,' but rather, 'how can we test this idea?' When results don't go as planned, possible questions could be 'how can we explain that?' or 'what assumptions did we make that might have affected the outcome?' When students have gathered data, questions might be 'how can we describe and represent these results?' or 'what is the pattern in these data?' That is what the ISLE process looks like in action. My goal in the classroom is to habituate students into asking those questions. When they do, the class almost runs itself because students are asking the questions they epistemologically *ought* to be asking (MacMillan and Garrison 1983). If students leave my classroom with these questions ingrained into how they think and reason about the world around them, I believe I have made a difference in the world, which is why I got into teaching in the first place.

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Chapter 2

Examples of ISLE-based learning of traditional physics topics and examples of ISLE-based physics problems[1]

In this chapter, we show how students learn traditional physics topics in the ISLE classroom and what types of problems they solve.

2.1 Student learning of traditional topics

2.1.1 Newton's third law

The following example shows an ISLE progression for students learning Newton's third law. The main idea of the law is when two objects interact, they exert forces on each other that are the same in magnitude and opposite in direction (Newton's third law pairs). However, not all equal in magnitude and opposite in direction forces are Newton's third law pairs. These forces need to describe the same interaction and are exerted on two different objects. Newton's third law is a foundational idea of Newtonian mechanics and all concept inventories assess it (e.g. Hestenes *et al* 1992, Thornton and Sokoloff 1998). Research findings show that even after instruction, students often think that a heavier or faster moving object will exert a larger force on a smaller slower object when they collide, that Earth exerts a stronger force on a falling apple than the apple on Earth and that the Sun exerts a stronger force on Earth orbiting the Sun than Earth on the Sun. Or that the weight of an apple and normal force exerted by the table on the apple represent Newton's third law pair. To help students construct correct conceptual understanding, we use the following steps. They can be done in a large lecture hall when students observe and discuss in pairs or

[1] Most of the examples in this chapter are taken from *College Physics: Explore and Apply* 2nd edition by Etkina, Planinsic and Van Heuvelen (2019) (CP:EA). In the textbook, one can find more material and more problems. ©2019. Reprinted by permission of Pearson Education, Inc., New York, New York.

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in a small room setting (instructional lab, high school classroom or a studio classroom) where they interact with equipment in groups of three. Here, we describe the situation when students invent Newton's third law in a studio setting or high school classroom setting. We chose this example to show how students invent a correct physics idea but have difficulty believing that the idea applies to all cases. The students who participate in the activities below have learned kinematics, force and force diagrams and Newton's first and second laws (for the ISLE progression and graphical representations for those topics, see chapters 2 and 3 in CP:EA).

Step 1. *Qualitative observational experiment* (based on the idea proposed by Hewitt (1998, p 36)).

Instructions for the students: Extend your fingers and try to bend them back as much as you can (figure 2.1(a)). Then push with your fingers against the wall and note how far the fingers bend this time (figure 2.1(b)). Try to explain your observations.

The students observe that the fingers bend much more when pressed against the wall (figure 2.1(b)). They discuss in groups possible reasons for this phenomenon. One of the reasons that comes up is that the wall pushes back on the fingers, bending them. Another explanation that students propose is that the wall is 'just in the way'. The students can test these two explanations by designing a new experiment and predicting its outcome using both. One of the experiments involves a compressible spring that replaces the wall (a door spring available in home-improvement stores will work here). If the first explanation is correct, and you press against the spring it should compress and the fingers should bend, if the second explanation is correct, the spring should not compress but the fingers should bend. Once the students reject the second explanation, they can move to the investigation of the magnitudes of the forces.

Step 2. *Quantitative observational experiment:*

After the students are convinced that as the fingers are pushing on the wall, the wall exerts a force on the fingers, we can suggest them to investigate this idea more systematically.

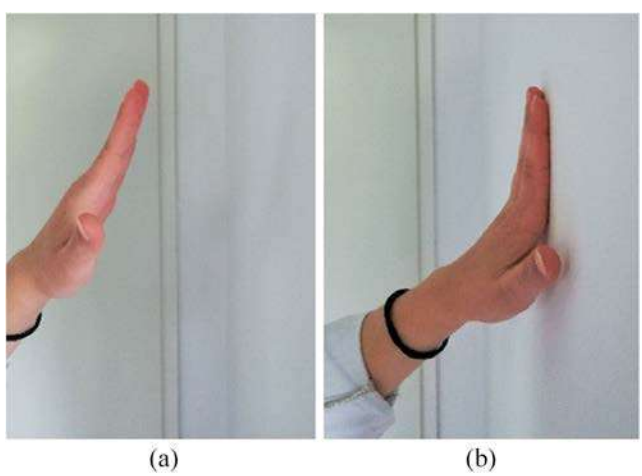


Figure 2.1. Observational experiment that helps students construct the idea that the wall pushes back on the hand when the hand pushes on the wall.

Instructions for the students: You have two different spring scales with hooks. Check that both scales are zeroed. Place the scales on the table and hook them together. Have two people from your group pull on them in as many different ways as possible, as long as the scales are horizontal and aligned so that they measure the forces along the same direction (people holding the scales can move). Record the readings of the scales in each experiment on the whiteboard. Prepare to share the pattern you found with the class and use the pattern to devise a rule about the forces that two interacting objects exert on each other.

Step 2. Patterns and hypotheses:

The students perform the experiments in groups and record the data (see the photo in figure 2.2). After 5–7 min, all groups find out that in each experiment two scales always have the same reading (the readings vary from an experiment to an experiment). If one scale reads 5 N, the other one reads 5 N, if one scale reads 7 N, the other one reads 7 N. Students come up with the pattern that the scales have the same reading when they interact with each other. They also come up with the explanation: the readings are the same because the scales exert the same magnitude forces on each other (we call this a rule). While the students devise this rule with relative ease, they usually believe that it works for static objects but not for moving objects, especially when one of them clearly makes the other move in a particular direction. That is why the next step is to test it.

Step 3. Testing experiments, predictions and outcomes.

Instructions for the students: You have two low friction carts that are equipped with wireless (Bluetooth) force sensors to which rubber bumpers are attached. You also have a dynamic track, a set of objects of different masses and a computer with data-logging software. Use these materials to design experiments to test the rule regarding the forces that two interacting objects exert on each other. Make sure that you describe the set up in words and a sketch, and write the prediction of the outcome based on the hypothesis under test and then compare the outcome to the prediction. The prediction should be based on the rule you are testing.

The students design several experiments—a moving heavy cart hits a light stationary cart, a moving heavy cart hits a light cart that moves towards the heavy cart, a fast-moving cart hits a slow-moving cart, and so forth (https://mediaplayer.pearsoncmg.com/assets/_frames.true/secs-experiment-video-6). They move carts with different speeds, add different masses of the carts and no matter what they do, the

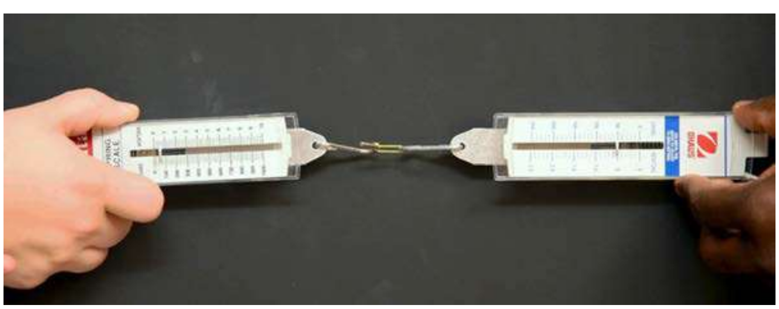


Figure 2.2. Two scales in an observational experiment.

outcome always matches the prediction that they make using the rule—the readings of the force probes are equal every time (see figure 2.3). The graphs from the force probes show that *the carts exert the same magnitude forces on each other* at every instant of time! The students are usually very surprised by this result. They cannot disprove the rule they themselves created! At the end of the class comes 'time for telling'. The instructor tells them that they just discovered what is called Newton's third law: when two objects interact they exert forces on each other that are the same in magnitude and opposite in direction, i.e. $\vec{F}_{\text{A on B}} = -\vec{F}_{\text{B on A}}$ and leads a discussion related to these forces. Specifically, the fact that these two forces are exerted on two different objects and cannot be added to find a net force, and that the forces are of the same nature.

Step 4*. Application experiments.*

Instructions for the students: Examine how you walk. Take one step and carefully analyze force exerted by the floor on your shoe that allow you to begin the step and end the step. Identify Newton's third law pairs and explain how this knowledge accounts for you beginning and finishing each step (see figure 2.4 for the analysis).

Step 5*. Formative assessment:*

Here, we provide some examples of formative assessment questions that we ask our students after they have constructed Newton's third law. The first question is an example of a multiple-choice question that you can ask in a large room setting and the students vote with clickers, the second one is useful for group work and the third one can be used for group work in class or as homework.

***Example* 1:** A book sits on a tabletop. What force is the Newton's third law pair to the force that Earth exerts on the book? Choose the correct answer *with the best explanation*.

(a) The force that the table exerts on the book because it is equal and opposite in direction to the force that Earth exerts on the book
(b) The force that the table exerts on the book because the table and the book are touching each other
(c) The force that the table exerts on the book because it describes the same interaction

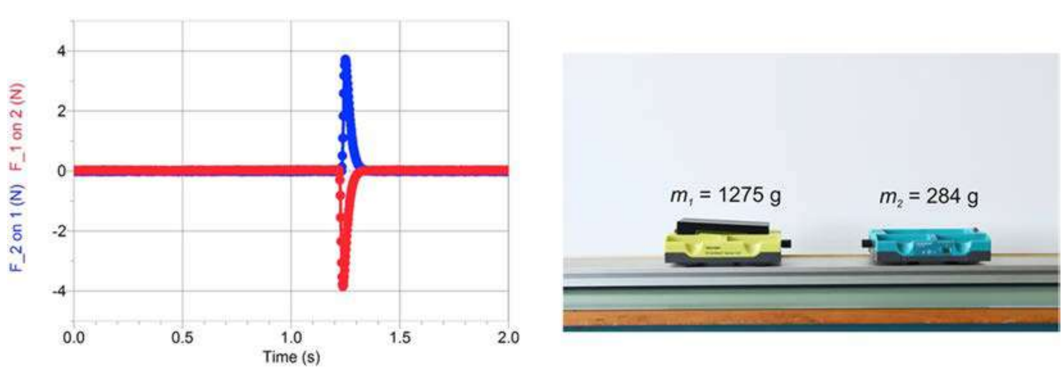


Figure 2.3. Two carts in a testing experiment.

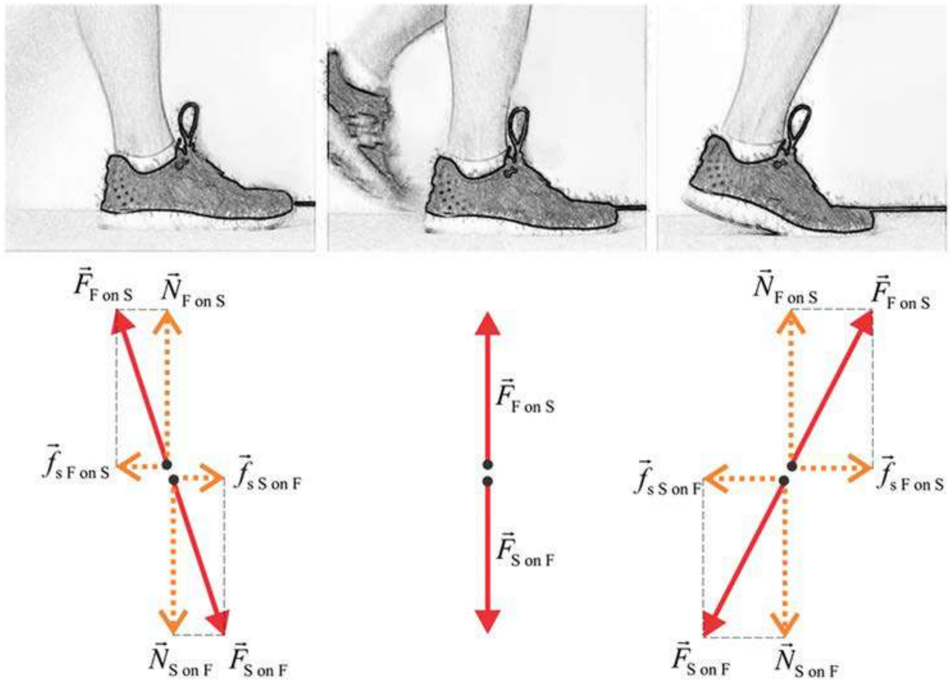


Figure 2.4. Analysis of walking using Newton's third law.

(d) The force that the book exerts on Earth because it describes the same interaction
(e) The force that the book exerts on Earth because it is equal and opposite in direction to the force that Earth exerts on the book

Answer: The correct answer is (d). Students who choose other answers do not understand that the Newton's third law pair forces should describe the same interaction or they think that the sufficient condition for two forces to be Newton's third law pair is that they are equal and opposite in direction.

***Example* 2:** Basketball player LeBron James can jump vertically over 0.9 m. Estimate the force that he exerts on the surface of the basketball court as he jumps. (a) Compare this force with the force that the surface exerts on James. Describe all assumptions used in your estimate and state how each assumption affects the result. (b) Repeat the problem looking at the time interval when he is landing back on the floor.

Answer: (a) Assuming that the jump interval (from his lowered body to his feet taking off) lasts for 0.3 *s and ignoring the air drag we find* $F_{\text{Player on Surface}} = 2 \times 10^3$ N *(in a downward direction).* $\vec{F}_{\text{Surface on Player}} = -\vec{F}_{\text{Player on Surface}}$. *(b) If we ignore air drag and assume that the time interval to stop is the same as jump interval, then the forces are the same as in (a).*

***Example* 3:** Hairdryers contain a small propeller that pushes air away from the dryer through a nozzle. You place a hairdryer on a scale with the nozzle pointing up, and it reads 4.40 N (see the figure). When you turn the hairdryer on, so that the hairdryer is pushing the air upward, the reading of the scale increases to 4.85 N. Explain the change in the reading qualitatively and quantitatively[2].

Answer: When the hairdryer is on, the propeller inside is rotating. It pushes the air up, exerting a force $\vec{F}_{\text{HDON on Air}}$*; therefore, according to Newton's third law, the air should exert a force* $\vec{F}_{\text{Air on HDON}} = -\vec{F}_{\text{HDON on Air}}$ *on the propeller and consequently on the whole hairdryer. Using the 2nd Newton's law, we find* $F_{\text{Air on HDON}} = 0.45$ N.

2.1.2 Electromagnetic induction

Below is an example of how students devise the concept of electromagnetic induction following the ISLE process. Electromagnetic induction is a physical phenomenon when an electric current is created in a coil of wire without any battery. All that is needed is a changing magnetic field in the vicinity of the coil. We chose this example to represent situations when students invent an idea that is only partially correct and they need to improve it when new data arrive. We also show variations in the cycle depending on whether it is a studio classroom, if the students start the cycle in a lab or if the cycle starts in a large room meeting where a large-enrollment course gets together (lecture format). Below are the set of activities that students do in a lab or in a studio format classroom. The students participating in the activities have learned DC circuits and magnetic fields (including the fact that a current carrying coil produces a magnetic field that looks similar to the magnetic field of a bar magnet). Note: it is better when the number of turns of the coil, the strength of the magnet and the galvanometer are such that the typical response of the galvanometer when pulling the magnet from a coil is small (say one tenth of the scale range). This way the students will not 'discover' how to induce the current by accidentally waving the magnet near the coil, but only from movements that give the largest response and are later easiest to interpret. Also, note that digital multimeters are not suitable for this experiment.

[2] These three questions are taken from CP:EA, chapter 3.

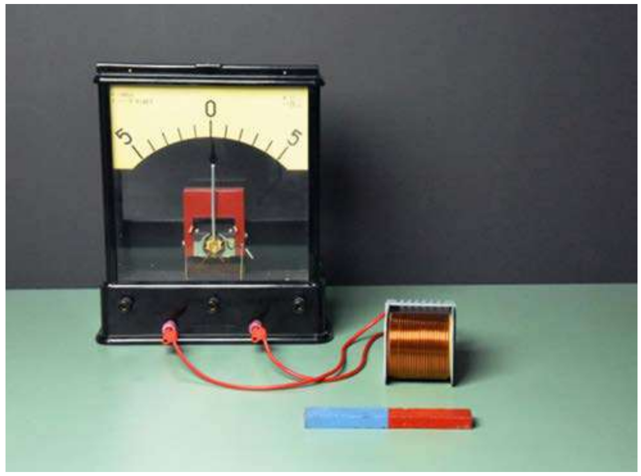


Figure 2.5. Galvanometer, coil and a magnet for observational experiments.

Step 1. *(in a lab or a studio) Observational experiment.*

Instructions for the students: Your group has the following equipment: whiteboard, markers, a coil with several turns, a bar magnet, and an analogue galvanometer.

a. Examine the equipment that you have on your desk (see figure 2.5). The galvanometer registers current through the coil. It needs to be connected directly to the coil (note, there is no battery). Now that you have connected the galvanometer to the coil, work with your group members to find out what you can do to make the galvanometer register current through the coil. Once you have found one way, look for others so that at the end you can formulate a pattern for the cases in which the current is induced. Describe your experiments and findings with words and sketches.
b. Develop a rule: devise a preliminary rule that summarizes the condition(s) needed to induce a current in a coil.

The students have a difficult time making the current in a coil with no guidance. However, in any class, there is always a group that accidentally moves the magnet in such a way that the needle of the galvanometer deflects (see the experiments at https://mediaplayer.pearsoncmg.com/assets/_frames.true/sci-phys-egv2e-alg-21-1-1). After the first 'discovery', the rest of the class gets the idea and students start experimenting—changing the orientation of the moving magnet with respect to the coil, moving the coil instead of the magnet and so forth. They devise the rule that accounts for all observations—the current is induced when the magnet and the coil move with respect to each other and the speed of this motion is sufficiently large. The induced current is largest when the bar magnet is inserted into the coil or pulled out from it. They can even create a mechanistic model for the case when the coil moves with respect to the magnet: when charged particles inside the coil wires move in a magnetic field, there is a force exerted on them and this force can be used to explain the induced current. The next step is to test this rule.

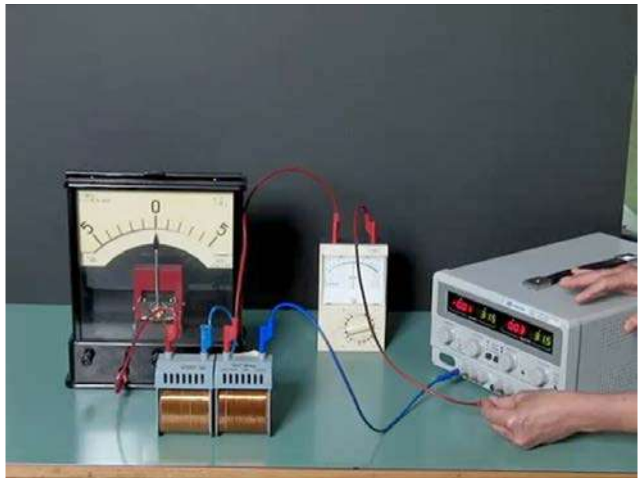


Figure 2.6. Two coils, power supply and a galvanometer for a testing experiment.

Step 2. (in a lab or a studio) Testing experiment.

Instructions for the students: Your group has the following equipment: two coils, a battery or variable power supply, and a galvanometer (see figure 2.6).

You can connect one coil (coil 1) to a battery/power supply and the other coil (coil 2) to the galvanometer. Work with your group members to perform the following experiments to test the rule that you invented in Step 1.

Experiment 1. Use the rule to predict what will happen if you move coil 1 (connected to the power supply) relative to coil 2 (connected to the galvanometer).

a. Describe the experiments in words and sketches and make predictions of their outcomes using the rule you invented in Step 1.
b. Conduct the experiments and record the outcomes.
c. Make a judgment concerning the rule that you're testing. If necessary, revise your rule to incorporate your new findings. Note that your revised rule should be consistent with *all* of the experiments you've conducted up to this point.

Experiment 2. Use your current rule to predict what will happen if you place coil 2 next to coil 1 so that the axes of the coils coincide and (1) connect coil 1 to the power supply without moving either coil, then (2) let the current run for a period of time, and then (3) disconnect coil 1 from the power supply.

a. Describe experiments (1)–(3) with the sketches and use the rule under test to make predictions of their outcomes.
b. Conduct the experiments and record the outcomes.
c. Make a judgment concerning the rule that you're testing. If necessary, revise your rule to incorporate your new findings. Note that your revised rule should be consistent with *all* of the experiments you've conducted up to this point.

When the students work on the activity, their prediction based on their newly invented rule matches the outcome of experiment 1 and they do not need to revise anything (the moving coil with the current in it is equivalent to a moving magnet). However, in experiment 2 nothing is moving, thus no current should be induced according to the rule. And yet, the current appears for a short time when the students connect and disconnect coil 1 from the power supply. To explain it, the students need to revise the original rule and devise the new one—the change in the magnetic field through the coil induces electric current in it. It is a causal explanation, not a mechanistic one. To create a mechanistic explanation, the students need to learn about the relationship between changing magnetic and electric fields, which eventually will be applied to electromagnetic waves. From here, the next steps would be to construct the idea of magnetic flux and Lenz law so that the students can devise Faraday's law of electromagnetic induction and eventually arrive at the mechanism explaining the phenomenon.

Step 3. *Application experiment.*

Instructions for the students: You have a spool of insulated copper wire (diameter 0.2 mm), a neodymium magnet, a plastic tube and a red LED. The LED lights up when the voltage across it increases 1.6 V. Using the equipment listed above, design an experiment that will allow you to make an LED glow.

Here, the students can wrap many turns of wire around the tube, connect the ends to the LED and place the magnet inside the tube. By shaking the tube with the magnet inside back and forth, one can light the LED. In advanced courses, the students can take necessary measurements to estimate the minimum number of turns needed to light the LED. In lower level courses, the instructor can have a discussion about the role of the number of turns and the frequency of hand shaking for the produced emf and suggest that the number of coils that will help light the LED.

Step 4. *Formative assessment.*

Students work on questions and problems (see examples below) in groups or the questions/problems are assigned as homework.

***Example* 1:** Your friend thinks that the relative motion of a coil and a magnet is the only way how to induce current in a coil that is not connected to a battery (assuming you have other equipment too). Support your friend's point of view with a physics argument. Then provide a counterargument and describe an experiment you could perform to disprove your friend's idea.

Answer: When there is relative motion between the coil and the magnet, the magnetic field through the coil is changing, knowing that the magnetic field of the magnet is not uniform. However, even when there is no relative motion, it is possible to induce electric current in a coil if we can change the magnetic field through it using some other means. For example, if, instead of the magnet, we use a coil with the current through it. When we change that current, the magnetic field of the magnet will change and therefore current will be induced in the coil of interest. Students, who know more about the properties of ferromagnetic materials, may suggest heating the magnet above the Curie temperature or hit the fixed magnet with a massive object.

***Example* 2:** Two rectangular loops, A and B, are near each other. Loop A has a battery and a switch. Loop B has no battery. Imagine that the current starts to increase in loop A. Will there be a current in loop B? Samir argues that there will be current. Ariana argues that there will be no current. Describe experiments that support the claims of both students.

Answer: We assume loop B is made of conducting wire. If the mutual orientation of the loops is such that the net magnetic flux through loop B produced by loop A is zero, then there will be no current in loop B. This can happen if the magnetic field produced by loop A is perpendicular to the loop B axis or if the magnetic flux through the loop B have negative and positive parts that add up to zero. In all other cases, there is a nonzero current in loop B.

***Example* 3:** Magnetic field passing through two coils of the same diameter and length decreases from a magnitude of B_{ex} to zero in the time interval Δt. The first coil has twice the number of turns of the second. (a) Compare the emfs induced in the coils. (b) How can you change the experiment so that the emfs produced in them are the same?

Answer: We assume that the coils' axes are initially parallel to the direction of B_{ex}. *(a)* $\varepsilon_{\text{in 1}} = 2\varepsilon_{\text{in 2}}$. *(b) You can turn the first coil to make the angle between its axis and the direction of the magnetic field equal to* 60°.

2.1.3 Light emitting diodes (LEDs)

Here, we show the ISLE progression of steps that students take to learn the basic nature of light emitting diodes. Prior to learning the physics behind the operation of an LED, the students need to be familiar with the basics of DC circuits including Ohm's law ($I = \Delta V/R$). No knowledge of semiconductors is required.

Step 1: Observational experiment.

Instructions for the students: You have two 1.5 V batteries, wires, a small incandescent lightbulb and a green LED. Your task is to make a light bulb glow and then the LED glow (not simultaneously). Represent all possibilities in a table (Etkina and Planinsic 2014).

By working on this task, the students discover that an LED glows only if connected to two batteries in series in a certain way. Specifically the LED's long leg should be connected to a positive terminal of the battery. This finding is in contrast to the light bulb that glows either with one (dimmer) or two batteries connected series (brighter), independently of the voltage polarity (figure 2.7).

Step 2: Explanations.

Instructions for the students: Propose causal explanations for the observed behavior of LEDs.

In our experience, students come up with the following two explanations:

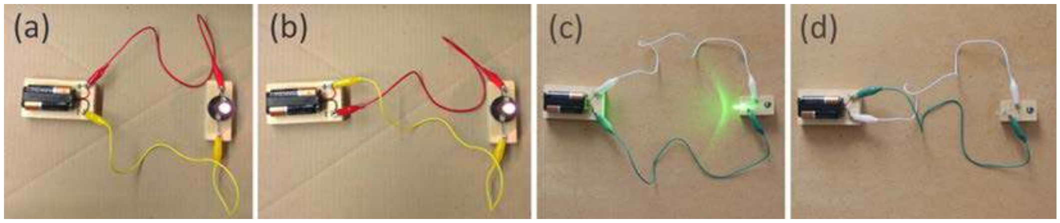


Figure 2.7. Students find out that the lightbulb glows independently of the voltage polarity (a), (b) and that an LED glows only if connected to two batteries in series with its long leg connected to a positive terminal (c), (d).

(A) An LED only lets current through in one direction and when there is a current, an LED glows (assuming enough voltage);
(B) An LED allows current in both directions but only glows when current is in one direction (assuming enough voltage).

Step 3: Testing experiments.

Instructions for the students: Propose experiments to test your explanations. Use the explanations that you proposed in Step 2 to make predictions of the outcomes of these experiments before you perform them. Write them here.

Perform the experiments and record the outcomes.

Compare the outcomes with the predictions and make a judgment about both explanations.

There are usually two experiments that the students propose. Testing experiment 1: put an ammeter in the circuit. The students make the following predictions: if explanation A is correct, then there will be no current registered and no LED glow when the long leg of the LED is connected to the negative terminal of the battery; there will be current and the LED will glow when the long leg is connected to the positive terminal. If explanation B is correct, then the ammeter will register current for both connections of the LED. When the students run the experiment, the outcome matches the predictions based on explanation A (figures 2.8(a) and (b)). This experiment allows them to reject explanation B.

However, some students propose a different experiment. Testing experiment 2: put a light bulb in series with the LED and use it as an indicator of current. Their prediction is that if explanation A is correct, the bulb will only glow when the long leg of the LED is connected to the positive terminal of the battery and if explanation B is correct then the bulb will glow for both connections but the LED will only glow for one correct orientation. To their surprise, the outcome of the testing experiment shows that the LED glows but the bulb does not (figure 2.9(b)). This puzzling outcome leads them to examine the assumption that they made—that the bulb glows when ANY current is through it. They might test this assumption by adding more batteries to make both the bulb and the LED glow (figure 2.9(c)). This modified experiment allows them to use the lightbulb as an indicator of current and to reject explanation B (figure 2.9(d)).

The students then proceed to a quantitative investigation by measuring the current-versus-voltage characteristic $I(\Delta V)$ of an LED and a lightbulb (figure 2.10).

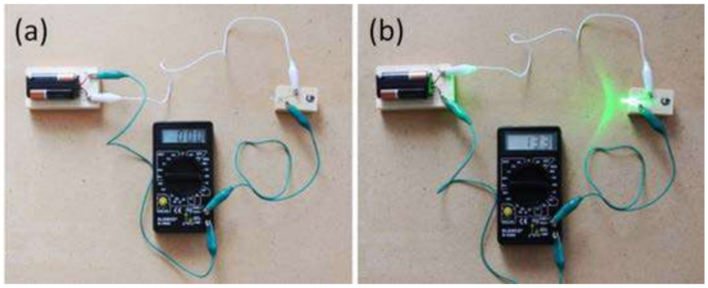


Figure 2.8. Outcome of testing experiment 1: (a) the longer leg of the LED is connected to the negative pole of the battery, ammeter shows 0.0 mA; (b) the longer leg of the LED is connected to the positive pole of the battery, ammeter shows 13.3 mA.

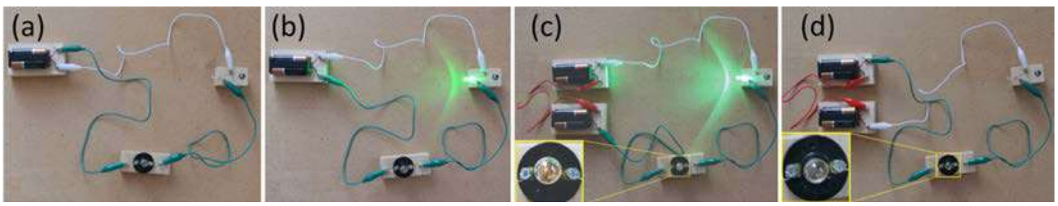


Figure 2.9. Outcome of the testing experiment 2 (a), (b) and the outcome of the improved version (c), (d).

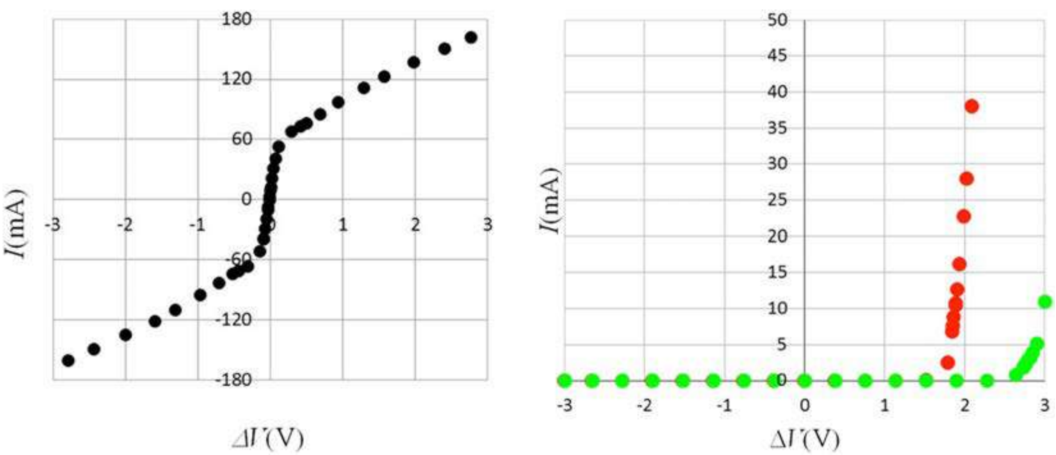


Figure 2.10. $I(\Delta V)$ graph for a lightbulb (left) and for a green and red LED (right).

Analyzing these graphs, the students see that their measurements are consistent with what they found out earlier in qualitative investigation. In addition, they discover that the $I(\Delta V)$ graph for the lightbulb is symmetrical and for the LED is asymmetrical. They also discover that the LED starts glowing at a certain voltage around 2 V (called opening voltage) and that this voltage is different for different color LEDs.

Step 4. *Application experiments:*

Students can compare the electric power of a white LED and small incandescent lightbulb (by measuring voltage across and current through a light source) and find that at approximately the same brightness, a white LED needs about 10 times less electric power than the lightbulb.

As you can see from the above, no knowledge of semiconductors is needed for the students to learn some of the most important features of LEDs that will make this device more familiar to them. However, if you wish that your students learn the mechanism of how LEDs produce light, a few more steps that require abstract thinking are needed. They are described in chapter 27 of CP:EA (pp 872–3). However, before going into these steps, the students need to have an image of the internal structure of an LED. They can get this image by watching a video at https://mediaplayer.pearsoncmg.com/assets/_frames.true/secs-egv2e-inside-an-led. For more information on learning about LEDs, also see the list of resource papers at the end of chapter 7.

2.2 Developing mathematical relations

Another issue deserves attention here. So far, we have been discussing how ISLE students develop qualitative explanations. But we have not yet addressed how students develop operational definitions of physical quantities and cause effect relations and subsequently use these relations in problem solving. As much as possible, students start with performing an observational experiment and analyzing the data that they collected (similar to the example with Newton's third law above). When equipment or time do not permit, the students either collect and analyze data in a video experiment (Brookes and Etkina 2010) or analyze the data that were collected by somebody else in an experiment that students observe. To analyze data, the students use graphs and other representations. The analysis leads them to an operational definition of a quantity (such as $\vec{a} = \frac{\Delta\vec{v}}{\Delta t}$) or a cause-effect relation (such as $\vec{a} = \frac{\Sigma\vec{F}}{m}$).

For example, in an algebra-based physics course, the students invent the operational definition of acceleration through the following steps. They use a ball, a meter stick, and a motion detector.

Instructions for the students:

a. Use the available equipment to design an experiment to record position-versus-time data for a ball falling from the height of about 2 m. It helps to position the motion detector above the falling ball, not below.
b. Perform the experiment and collect data. If you are using a motion detector, the data will be represented as a graph right away. If you are analyzing a video, you will need to figure out how to collect position and time data from it. Repeat the experiment a few times. What can you say about the motion of the ball based on the data you collected?
c. Draw a motion diagram for the ball.
d. Draw a position-versus-time graph for the ball. Discuss whether the graph resembles a position-versus-time graph for an object moving at constant velocity.

e. Determine the scalar component of the average velocity for the ball for each time interval by completing the following table.

Time interval $\Delta t = t_n - t_{n-1}$	Displacement $\Delta x = x_n - x_{n-1}$	Average time $(t_n + t_{n-1})/2$	Average velocity $\frac{\Delta x}{\Delta t}$

f. Plot this average velocity v_x on a velocity-versus-time graph. The time coordinate for each average velocity coordinate should be in the middle of the corresponding time interval (the average time for that time interval). Draw a best-fit line for your graph.
g. Discuss with your group the shape of the graph: how does the speed change as time elapses**? Suggest a name for the slope of the graph.**

The students quickly come up with the ‘speeding up’ quantity or ‘acceleration’ name for the slope of the graph. The above example illustrates how the students develop an operational definition of acceleration. However, this definition does not explain why the acceleration has a specific value (for example, why free fall acceleration is about 9.8 m s^{-1} s^{-1}). The cause effect relation for acceleration is Newton’s second law, which students, again, develop through data analysis. However, in this case, data collection is tedious and we offer them the results of an experiment that somebody else performed. Students observe experiments online: https://mediaplayer.pearsoncmg.com/assets/_frames.true/sci-phys-egv2e-alg-3-5-1a and video experiment 2; https://mediaplayer.pearsoncmg.com/assets/_frames.true/sci-phys-egv2e-alg-3-5-1b to have an image of the set-up

Instructions for the students:

a. On a whiteboard, draw a force diagram for the cart in experiment 1 and another for the cart in experiment 2.

Analysis of video experiment 1		Analysis of video experiment 2	
Acceleration (m s^{-2})	Sum of the forces (N)	Acceleration (m s^{-2})	Mass (kg)
0.38	0.2	0.27	0.56
0.74	0.3	0.20	0.76
1.67	0.5	0.15	0.96
2.8	0.75	0.13	1.16
4.3	12	0.10	1.36

b. Then use the data in the table above to devise a relationship that shows how each cart's acceleration depends on the cart's mass and on the net force exerted on the cart by the string or fan, Earth, and the track. Note: when doing such an analysis, devise a relationship for each independent variable one at a time and for the dependent variable (for example, use some of the data to see how the acceleration depends on the net force exerted and then use other parts of the data to see how the acceleration depends on the mass of the cart). Then combine these relationships to get a final relationship.

From the above two examples, one can see how different representations (real experiments, video experiments, data tables, graphs and algebraic functions) work together to help students see 'where the equations come from'. More examples for the invention of operational definitions of many physical quantities and cause-effect relations among the quantities can be found in CP:EA.

2.3 Problem solving

Research shows that students often start solving problems by searching for an equation that has variables listed in the givens (Van Heuvelen 1991). To help them develop expert solving strategies, we introduce a myriad of nontraditional types of problems that cannot be solved by searching for an equation. These are listed in the table below. The problems develop specific reasoning skills. Research shows that these problems promote higher levels of cognition and improve conceptual understanding and problem-solving skills (Shekoyan 2009, Shekoyan and Etkina 2007, Warren 2010). Table 2.1 below describes the new types of problems and table 2.2 shows examples of every type.

2.4 Role of the textbook

We differ from some other active engagement approaches in that we expect students to read the textbook *after* they devised ideas in class. We believe that the quality learning time in class should be used for students to engage in the inquiry process where they learn to think like physicists instead of reading ready concepts in the book and learning from authority. After the process of exploration is complete, the textbook can be used for the purposes of summarizing ideas, pulling ideas together, or for studying worked examples. One of the useful reading comprehension strategies is elaborative interrogation. This intervention requires the students to 'interrogate' sentences from the text by using information in the text to explain why the given sentences are true (Smith *et al* 2010). Research has suggested that answering elaboration questions can produce semantically deep levels of processing (Levin 2008). When we adopted Smith *et al*'s interrogation approach (Zisk *et al* 2014), we added another dimension to it, specifically when we chose sentences from the text (sometimes we modified those), we ask our students if this sentence is true or false and how they would convince somebody else in their opinion. Below are several examples of such sentences (including the instructions for the student) that we assign as a part of homework.

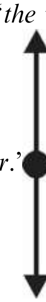
Table 2.1. Types of non-traditional problems.

Type of problem	Keywords	Description
Ranking tasks	Rank, compare	Students have to rank the values of a certain physical quantity for different situations, in descending or ascending order.
Choose answer and explanation		Students have to choose the correct answer *and* the correct matching explanation (cause-effect or mechanistic) in order to get full credit.
Choose measuring procedure	Procedure, method	Students have to choose (or propose) the correct (or the best) experimental procedure that will allow them to measure/determine a certain quantity.
Evaluate reasoning or solution	Evaluate, your friend says…, agree, reconcile, comment on, how will the answer change, discuss, how do we know, compare and contrast	Students have to critically evaluate the reasoning of some (imaginary) people or evaluate the suggested solution to a problem (given either in words, graphs, diagrams, or as an equation). Students have to recognize productive ideas (even when they are embedded in incorrect answers) and differentiate them from unproductive ideas.
Make judgment (based on data)	Decide, reject, do the data…, justify, (in)consistent, hypothesis	Students have to make a judgment about one or more hypotheses, based on data or other forms of evidence that are given in the problem, sometimes taking uncertainties into account.
Linearization		First, students have to write an equation that describes the relevant situation. Then they have to rearrange the equation to obtain a linear function (note that the independent and the dependent variables in this function can be any function of data given in the problem). Students then draw the graph, plot the best-fit line, and determine the unknown quantities using the best-fit line. These problems help students combine knowledge of physics, the ability to 'read and write' with graphs, the ability to manipulate equations, and the ability to recognize linear dependence in non-standard situations.
Multiple possibility problems	Tell all, say everything you can, make a list, as many, give (three) examples, what can you infer, relevant	Students have to list as many quantities as they can that can be determined based on data given in the problem, or tell everything they can about the physical attributes of the objects that appear in the text, or the relations between them. Normally, students are required to determine the values for only few of the quantities that they identify. These problems allow all students to feel successful.

Jeopardy problems	Jeopardy, invent a problem, pose a problem	Students have to convert a representation of a solution into a problem statement. If the solution is given in the form of an equation, they need to understand the meaning of the quantities and their units. Such problems emphasize the value of units.
Design an experiment or pose a problem	Design, invent, write your own, pose, describe experiments, devise	Students have to design an experiment, an experimental procedure, or a device that will allow them to measure/determine certain physical quantities or that would meet specific requirements. Students have to pose a problem that involves certain objects with given characteristics. Often there is an additional requirement that solving the problem should involve the use of a particular physics topic, law, or principle. Students may also need to do an additional literature search.
Problem based on real data		Students have to solve problems that are based on real data, obtained in real-life situations, often using easily available equipment and/or equipment that is typically used in student labs. The types of problems may be traditional or any of the types presented above. Students need to deal with uncertainties, anomalous data and assumptions, and to propose meaningful models.

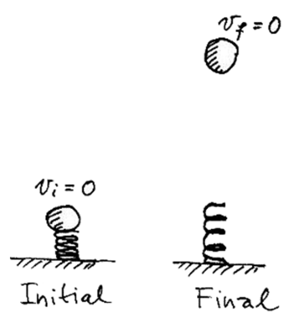
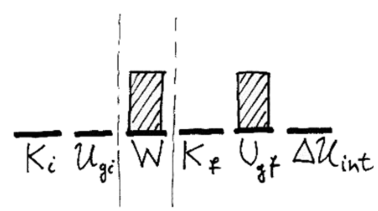
Table 2.2. Examples of non-traditional problems. Image Credit: Etkina E, Planinsic G and Van Heuvelen A 2019 *College Physics: Explore and Apply* 2nd ed ©2019. Reprinted by permission of Pearson Education, Inc., New York, New York.

<table>
<tr><th>Type of problem</th><th>Example</th></tr>
<tr><td>Ranking tasks</td><td>A squirrel jumps off a roof in the horizontal direction. The origin of the coordinate system is at the point where the squirrel leaves the roof. Complete the table below by drawing crosses in the cells that correctly connect the physical quantities in the first column that describe the motion of the squirrel and the descriptions of what is happening to these quantities while the squirrel is in flight. Consider the squirrel as a point-like object and assume that the resistive force exerted by the air is negligible.
<table>
<tr><th>Physical quantity describing motion of the frog</th><th>Remains constant</th><th>Is changing</th><th>Increases only</th><th>Decreases only</th><th>Increases, then decreases</th><th>Decreases, then increases</th></tr>
<tr><td>x coordinate magnitude</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>y coordinate magnitude</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Direction of velocity</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Magnitude of velocity</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Direction of acceleration</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Magnitude of acceleration</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
</table></td></tr>
<tr><td>Choose answer and explanation</td><td>A book sits on a tabletop. What force is the Newton's third law pair to the force that Earth exerts on the book? Choose the correct answer with the best explanation.
(a) The force that the table exerts on the book because it is equal and opposite in direction to the force that Earth exerts on the book.
(b) The force that the table exerts on the book because the table and the book are touching each other
(c) The force that the table exerts on the book because it describes the same interaction
(d) The force that the book exerts on Earth because it describes the same interaction
(e) The force that the book exerts on Earth because it is equal and opposite in direction to the force that Earth exerts on the book</td></tr>
</table>

Choose measuring procedure	You want to determine the temperature in a freezer using the following equipment: an empty plastic bottle with a cap, a graduated measuring cylinder, and a bowl of water. You also know your room temperature T_R. (a) Which of the procedures described below will give data from which you can determine the temperature in the freezer? (b) For the procedure that you have chosen in part (a), derive the expression for the temperature in the freezer as a function of relevant physical quantities. Indicate any assumptions that you made. I. Put the open plastic bottle into the freezer for half an hour. Take the bottle out, turn it upside down into the water, and measure the volume of the water sucked into the bottle. II. Put the open plastic bottle in the freezer for half an hour. Take the bottle out and close it tightly with a cap. Wait until the bottle's shape stops changing. Turn the bottle upside down into the water, open the cap, and measure the volume of the water that entered the bottle. III. Put the closed plastic bottle in the freezer for half an hour. Take the bottle out, turn it upside down into the water, and then open the cap. Measure the volume of the water sucked into the bottle. IV. Put the closed plastic bottle in the freezer for half an hour. Take the bottle out, open the cap, and turn the bottle upside down into the water. Measure the volume of the water sucked into the bottle.
Evaluate reasoning	An elevator is pulled upwards by a cable so that it moves at a constant upward speed. Maria draws the (unlabeled) force diagram for the elevator shown on the right and says, '*if the elevator is moving upwards at a constant rate, the forces exerted on it must be balanced.*' Joe disagrees. Looking at the force diagram, he says '*the way you've drawn the force diagram, the elevator will stop moving because there is no net force exerted on the elevator.*'  (a) Correctly label the force diagram. (b) Who do you agree with and why? For the statement you disagree with, how would you convince him/her that he/she is incorrect?

(*Continued*)

Table 2.2. (*Continued*)

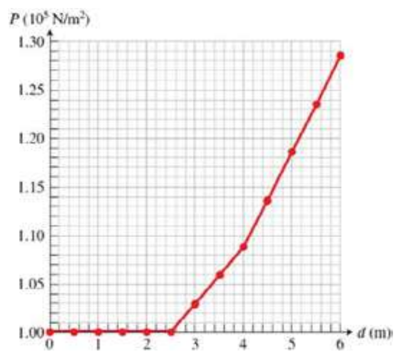
Type of problem	Example
Evaluate solution	Your friend Devin has to solve the following problem: 'You have a spring with spring constant k. You compress it by distance x and use it to shoot a steel ball of mass m into a sponge of mass M. After the collision, the ball and the sponge move a distance s along a rough surface and stop (see figure below). The coefficient of friction between the sponge and the surface is μ. Derive an expression that shows how the distance s depends on relevant physical quantities.' Devin derived the following equation: $$s = \frac{kmx^2}{2(m+M)^2\mu g}.$$ Without deriving it, evaluate the equation that Devin came up with. Is it reasonable? How do you know? 
Evaluate assumptions	Students were using a small spring to launch a marble vertically up from a table. Brian presents the following analysis of the experiment: *the system consists of the marble and Earth. The spring is external to the system and does work on it. The initial state is when the marble rests on a compressed spring. The final state is when the marble reaches the highest point above the table (see sketch on the left). The work-energy bar chart for this process is shown on the right.*  

In the analysis I assumed the following: (1) I ignored air resistance, (2) I assumed the mass of the spring is negligible and (3) I assumed the table is very hard so that it does not deform.

(a) Which of the assumptions are relevant for Brian's analysis and which are irrelevant? Explain why.
(b) Is Brian's work-energy bar chart consistent with the relevant assumptions? Explain.
(c) Describe how Brian can validate the relevant assumptions.

Make judgment (based on data)

A truck transporting chemicals has crashed, and some dangerous liquid has spilled onto the ground and possibly entered a water well. An inspector fixes a pressure sensor to the end of a long string and lets the sensor slowly descend from the top of the well to the bottom. Using this device, he obtains the graph on the right that shows how the pressure P in the well changes with distance d measured from the top of the well. (a) Explain what features of the graph support the idea that there is another liquid in the well in addition to water. (b) Determine the density of the unknown liquid. Is the liquid above the water or below the water? (c) Determine the depth of the water, the depth of the unknown liquid, and the depth of the well.

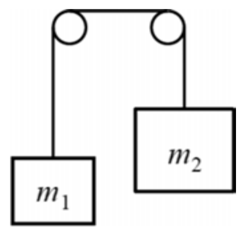


Make judgment (based on data)

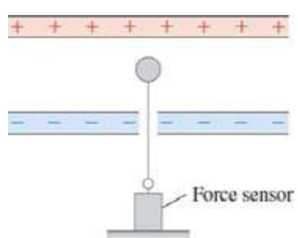
Your friend Juan is presented with the following problem. Two blocks, masses $m_1 = 3$ kg and $m_2 = 5$ kg, hang over light frictionless pulleys from a string of negligible mass (see the figure). Find the acceleration of the system. After some

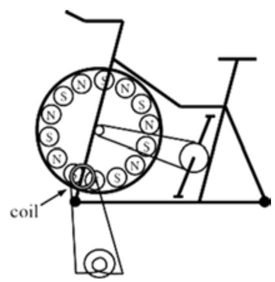
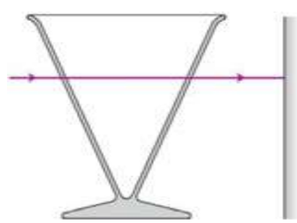
(*Continued*)

Table 2.2. (*Continued*)

Type of problem	Example
	calculating, Juan comes up an acceleration of 16 m s^{-2} for the system. *Without* solving the problem from scratch, is Juan's solution reasonable or not? Use your knowledge of physics to construct a clear argument why his solution is reasonable or not reasonable. 
Linearization	A small object of unknown mass and charge is tied to an insulating string that is connected to a sensitive force sensor. The object is placed between two large conducting plates, and the string is kept taut by charging the plates as shown in figure below. The mass of the string is 0.030 g, and the distance between the plates is 15.0 cm. As the potential difference between the plates increases, the force exerted by the force sensor on the string changes as shown in the table. Determine the mass and charge of the particle (note: this is a problem that requires linearization of data).

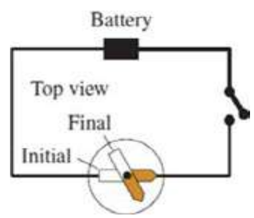
ΔV (V)	$F_{\text{FS on S}}$ (10^{-3} N)
5000	52
5500	67
6000	82
6500	97
7000	110



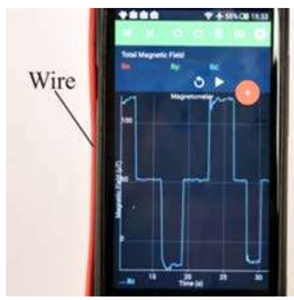
Multiple possibility problem	As we worry about a looming energy crisis, designers have come up with a way to do something useful with those stationary exercise bicycles at the gym. They are going to use the exercise bike to generate electricity! The spinning wheel has a ring of magnets attached that pass by a fixed coil. A light bulb is attached to the coil. The current induced in the coil as the magnets pass by causes the light bulb to light up, thus converting the exerciser's energy into useful lighting for the gym. There is however one key problem with this design. There is only one 'load.' Come up with a modified design that would allow the exerciser to switch between different loadings at the touch of a button or the flip of a switch. You are free to modify the actual machine and/or the external circuit in any way you want except for one restriction: the variable loading should convert more or less energy to power the gym. In other words, adding a friction belt to the wheel would be considered 'cheating.' Describe and explain how your design would work using words and pictures. 
Multiple possibility problem	You have a V-shaped transparent empty container such as shown in figure on the right. When you shine a laser pointer horizontally through the empty container, the beam goes straight through and makes a spot on the wall. (a) What happens to this spot if you fill the container with water just a little above the level at which the laser beam passes through the container? (b) What happens if you fill the container to the very top? Indicate any assumptions used and draw a ray diagram for each situation. Note: this is a multiple-possibility problem. 

(*Continued*)

Table 2.2. (*Continued*)

Type of problem	Example
Multiple possibility problem (Tell all problem)	When a switch is closed, a compass needle deflects from the initial to final direction, as shown in figure. Say everything you can about this experimental setup. 
Equation Jeopardy problem	Describe in words a problem for which the following equation is a solution and draw a force diagram that is consistent with the equation (specify the direction of the axis): $$2.0\ m/s^2 = \frac{196\ \mathrm{N} - F_{\mathrm{P\ on\ O}}}{20\ \mathrm{kg}}$$
Image Jeopardy problem	The figure shows the primary axis of a lens; the path of ray A, as it approaches the lens, gets refracted, and continues to travel; and the path of ray B before it hits the lens. (a) Determine the type of lens (concave or convex) and its location, (b) determine the location of both focal points of the lens, and (c) draw the path of ray B after it passes through the lens. 
Design an experiment	Describe an experiment that you will design to find out whether the resistance of a particular circuit element is independent of the voltage across it. Make sure that you describe the experiment and how you will make a judgment clearly enough so some other person can repeat the experiment and understand the judgment.

Design an experiment	Describe two experiments to determine the speed of propagation of a transverse wave on a rope. You have the following tools to use: a stopwatch, a meter stick, a mass-measuring scale, and a force-measuring device. Use whatever other items you need for your experiments.
Pose a problem	Write and solve a problem that requires using the law of conservation of momentum in which it is important to know that momentum is a vector quantity.
Problem based on real data	You place a long wire next to your mobile phone on a table as shown in figure. You run an application that allows you to measure the time dependence of the component of the *B* field that is perpendicular to the screen of the phone (let's call it B_z). While recording the magnetic field, you repeat the following steps: connect the wire to an AA battery, disconnect the battery, flip the battery (to swap + and − terminals), again connect the wire to the battery… and so on. Using an ammeter, you also determine the current through the wire. Average values of your measurements are summarized in the table. (a) Estimate the distance between the magnetic field sensor in your phone and the wire. (b) If the experiment was performed in New Jersey, determine the direction of the current in the wire (up or down with respect to the phone) when the magnetic field reading is -19×10^{-6} T. Explain your reasoning. Indicate any assumptions that you made.



Connection	I(A)	B_z(T)
Battery (+,−)	4.9	122×10^{-6}
No battery	0	52×10^{-6}
Battery (−,+)	4.9	-19×10^{-6}

Instructions for the student: As you read the text, you will encounter the following sentences (or similar sentences). After reading, if you think the sentence is true, write a response that would convince a classmate that the sentence is indeed true using information from the text. If you think the sentence is not true, write a sentence that would convince a classmate that the sentence is not true.

1. A moving ball's velocity always points in the direction of the sum of the forces that other objects exert on it (incorrect statement).
2. It is possible for a car to have simultaneously a zero velocity and a non-zero acceleration or a non-zero velocity and zero acceleration (both are correct).
3. The impulse-momentum equation is sometimes more useful than the work-energy equation for analyzing certain kinds of collisions (correct statement).

2.5 Interlude: the tyranny of coverage

'By concentrating on *what*, and leaving out *why*, mathematics is reduced to an empty shell. The art is not in the 'truth' but in the explanation, the argument. It is the argument itself which gives the truth its context, and determines what is really being said and meant. Mathematics is *the art of explanation*. If you deny students the opportunity to engage in this activity—to pose their own problems, make their own conjectures and discoveries, to be wrong, to be creatively frustrated, to have an inspiration, and to cobble together their own explanations and proofs—you deny them mathematics itself. So no, I'm not complaining about the presence of facts and formulas in our mathematics classes, I'm complaining about the lack of *mathematics* in our mathematics classes.' (p 5)

The Mathematician's Lament by Paul Lockhart:
https://www.maa.org/external_archive/devlin/LockhartsLament.pdf

I am not sure who first coined the phrase 'tyranny of coverage' but it is a fairly common phrase in the 'scholarship of teaching and learning' (SoTL) literature. This is how I see it: one of the most common comments or questions I get when I tell people about ISLE goes something like this:

> 'I like your ideas about promoting critical thinking by having the students engage in inquiry learning instead of telling them what they need to know. But how am I going to cover all the topics my students need to know so that they can (for example) pass the physical science portion of the MCAT®?

The Medical College Admission Test® (MCAT) is a significant entrance exam that students in the United States need to do well in to be admitted to medical school. The test has some physics questions in it and almost all students who go to medical school must take two semesters of physics before they take the MCAT and enter medical school.

In summary, this is the tyranny of coverage:

> 'Inquiry learning is cool, but it can't stand in the way of what I really need to do, which is cover topics X, Y, and Z by the end of the semester.'

Maybe you've been thinking the same thing yourself after reading the last chapter? So let me get one thing out of the way first. If you do ISLE, you will not cover as many physics topics as you used to when you were doing a significant amount of talking in your classroom while your students listened to you and took notes. You cannot have students actively engaged in the process of doing physics and cover the same quantity of material.

The tyranny of coverage is ubiquitous and pervasive. Not for the first time, I observe that I have been using ISLE for almost 20 years and the conversation with other professors and teachers hasn't changed much from 20 years ago.

For example, I was once on the receiving end of an aggressive phone call from one of my colleagues in biology who told me in no uncertain terms that I was ethically and morally failing my students by not covering every physics topic in the MCAT.

I was under sustained pressure from my department head for over a year to cover 'just a few more topics' than I currently did in my introductory physics course. This was coming from someone who appeared to hold fairly 'progressive' views about education in the sense that they claimed they really saw the value of students learning scientific reasoning abilities; what we could term the 'critical thinking skills' of physics.

The next point I want to make is that 20 years after meeting Professor Etkina, I find that I am still struggling with the 'tyranny of coverage.' I have two ideas why that is, but I will discuss that later since they are the key points of this chapter. I don't want anyone to get the impression that I have somehow conquered this problem of coverage and that I'm going to offer you a solution to it. Just last semester, I was still worrying about whether I was covering enough topics in my physics class and as a direct consequence of that, I neglected the centrality of the process of doing science. In trying to keep up with a schedule of topics that I had laid out at the beginning of the semester, I neglected many of the aspects I will talk about in subsequent chapters. Things like fostering a strong learning community and helping students develop a sense of science identity. The result was not pretty. A good fraction of my students hated the class and I did not enjoy teaching it. Even though I intellectually understand the arguments that I will lay out in this interlude, I still find myself falling back into old habits of thinking. For me, the struggle between coverage and scientific process continues.

For the rest of this interlude, I am going to discuss two reasons why I believe the tyranny of coverage is so difficult to break free from. They are:

a. We treat knowledge as a physical object and we fundamentally lack the language to describe knowledge and knowing more accurately in terms of a process.
b. Our educational and social systems are built around the concept of objectifying knowledge.

I will conclude by suggesting that to break free of the tyranny of coverage, we need to undergo radical conceptual change of the type where we recategorize knowledge as an ontological process rather than an ontological object.

Knowledge is a process, not an object

The realization that knowledge is a process, not an object, happened for me in the space of one afternoon while I was doing my laundry. It was the single most significant transformative experience of my life and I remember that afternoon as clearly as if it happened yesterday. It was probably some time in October 2001. I was a physics graduate student, roughly 2 years into my PhD. I had made the decision to study physics education research and I was struggling with the fundamental philosophical conflicts between the positivist and constructivist views of science and reality. While this may seem pointless or abstruse, much of science education has firmly placed its eggs in the constructivist basket and these were totally new ideas to me. As a practicing scientist, I believed that there was an underlying physical reality and it was the job of scientists to uncover and objectively describe that reality (the positivist view). The constructivist view, on the other hand, claims that our view of the world is inherently subjective, and biased by the observer. In short, we *make* our reality, irrespective of whether an objective reality exists or not.

Anyway, there I was in the laundromat with a photocopy of a book chapter I had acquired from the university library entitled 'The Conduit Metaphor: A Case of Frame Conflict in our Language about Language' by Michael Reddy (Reddy 1993). It is a rather 'dense' paper and so I'd been procrastinating about reading it, but I had finally decided to conquer it, ready with my pen, planning to add a lot of notes in the margins. In his paper, Reddy argues that there is a problem (a frame conflict or 'semantic pathology') with how we talk about and conceive of information and knowledge. We talk about information as being 'contained *in* a book,' or the 'meaning is *in* the words.' We think of knowledge as an object that can be transmitted *to* students or acquired *by* students. Our entire system is built around knowledge categorized as an object, contained within words, the book, or the library being conveyed from one location to another. This is what he called the 'conduit metaphor' and it is ubiquitous. He then described a thought experiment in which a set of individuals are isolated from each other in different environments and can only communicate through drawings. In this thought experiment, one person (person A) invents a rake to rake leaves since his environment is full of trees. He draws a picture of his rake and sends it to person B. But person B lives in a rocky environment with no trees and reinterprets it as a rock-pick, useful for digging up large rocks. He draws his two-pronged, long-tined rock-pick and sends the diagram back to A. A realizes that his rake design has been misinterpreted and sends back a more detailed diagram of his rake. This communication goes back and forth over numerous iterations until each has come to the realization that their physical environments are different from each other and so a mutually shared understanding is built. The other important point is that it took persistence and time for this shared understanding to be established.

While this example may appear contrived, it is true of all human communication. As I was reading it, I realized that when I say 'force' to my physics students, they hear a word that activates a set of associations that are fundamentally different from my 'expert physicist's' associations. When I say force, my students hear 'power' or 'energy,' or what big, heavy objects have that makes them hurt when they hit us. And when I ask my students 'what happens to an object when there's no force exerted on it,' they say 'it stops moving.' And I mistakenly interpret this as an impetus misconception because I'm looking at their reasoning from the perspective of physics. The problem we're having is one of miscommunication and it is coming from both sides. The problem isn't that students have an impetus misconception; it is that I and they are talking past each other, using a word drawn from two totally different contexts and failing the *negotiate* meaning with each other.

Our understanding of our world is fundamentally constructed and negotiated. Whether 'force' is a thing that objectively exists in nature is no longer relevant because all that we have access to is our representational constructs (words, drawings, etc) which are inherently subjective and context-dependent. Consequently, learning *cannot* be an act of conveying information or knowledge, it is an act of co-constructing shared meaning through multiple iterations, (potential) frustration, and persistence over time. What I've described is a process. There is no knowledge 'object' that is conveyed, only a process of coming to know. That is all that there is.

By this time, the Sun was setting. My clothes had long-since finished their cycle in the dryer, but I was still sitting there, furiously scribbling these ideas down in the margins of the photocopy. My world was utterly transformed and there was simply no way of going back.

Why am I writing this story that sounds like a quasi-religious conversion experience? I believe it is impossible to surpass the tyranny of coverage without a new conception of knowledge. If you read almost any course catalog, you will see that we describe our physics courses by a list of topics that are covered (quantity of knowledge). When writing tests, we worry about whether we have asked enough questions that cover enough of the topics that have been learned. Everything we're doing is based on a model of knowledge as an object. For change to happen, I believe we need to start by reconceptualizing knowledge as a *process*. Physics is a way or a *process* of knowing about the world.

I am frustrated with the glacial pace at which educational change seems to happen. It seems that the 'old way' of doing things is stubbornly entrenched in people's minds, even in those who know there is a problem and want to change. The hope is that by writing a first-person account of that change, it might provide at least myself, and maybe even some readers, a bit of perspective on the difficulties, the challenges, and the possibility of change.

Systemic change

The pathology of knowledge as an object is embedded everywhere in our culture. It is epitomized by the American TV game show 'Are you Smarter than a 5th Grader?' In it, adult contestants are pitted against a 'class' of 5th graders, answering questions purportedly taken from 5th grade textbooks. If the adult contestant drops out or cannot answer a question, they have to address the camera and say 'My name is…, and I am not smarter than a 5th grader.' According to Wikipedia, only two contestants in the history of four seasons have made it to the million dollar prize and not had to utter the words of shame.

Here is what is interesting: all questions on the show are factual. For example, 'what US state is home to Acadia National Park?' You either remember it or you don't. Or if you've never heard of Acadia National Park, you simply have no way of getting to an answer.

This is the cultural baggage we're struggling against: for too long the purpose of education has been to teach conformity, to segregate society; to teach passive acceptance of authority and dissuade active criticism (Postman and Weingartner, 1969). If knowledge is an object, you either 'get' it or you don't. If you don't, it is your fault since that piece of knowledge should be objectively clear. It is easy to write a test that measures how *much* knowledge each student possesses by having them recite *what* they know, thus separating the worthy from the unworthy. In short, it is much easier to measure the end product ('knowledge') than the process of knowing. It is easier to ask what you know than *how* you know it. And if everyone could adequately answer *how* they know something it would subvert everything because those in power could no longer hide behind logical fallacies and weak or unsubstantiated claims.

But now, the power structures of old are changing and the world we are preparing our children for requires less conformity and more innovation and independent thinking. We are preparing our children for jobs whose existence we can't even conceptualize yet. Our children will need to tackle crises that represent an existential threat to life as we know it. Today's companies no longer want factory workers, they want people who can think dynamically and learn on the job (Duggan and Gott 2002).

The other day, I was on a training ride on my bicycle, riding with a retired CEO of a tech start-up. Our conversation drifted to the nuts and bolts of the electrical engineering problems they had to overcome in building certain products. In particular they were pushing the size limits of micro to nano-scale electronics and he commented that at that level, every connecting wire not only has a resistance, but also has a capacitance and self-inductance that needed to be taken into account. More pointedly, he commented to me how hard it was to find good electrical engineering graduates to employ. He said that he would give an arm and a leg to be able to hire someone who understood from the get-go without extra on-the-job training, that a resistor as we learn about it in physics class is just a *model* of real life and has implicit assumptions (like we normally ignore the self-inductance of a resistor or the capacitance of a resistor until we get to certain size-scales). He (rightly) saw this as a problem of how we teach physics as factual knowledge rather than a process of thinking.

Freedom from the tyranny of coverage

Let me conclude by describing the best class I ever taught: my students were working on understanding friction. We had progressed to the point where they had established a model for static friction: $f \leqslant \mu N$, when one student asked me a question: 'In American football, the players are taught to get down low and push upwards to push the other guy backwards. Does that have something to do with friction?' For a moment, I froze like a deer in the headlights because I had no idea if I could adequately answer his question. Then I thought, 'We won't get through all the stuff I planned to cover today.' Then I thought, 'who cares?' I mentally ripped up my lesson plan and sent all the students to their desks with instructions to draw force diagrams for two football players pushing each other, but with an angle to the push. 'See if you can explain why it would be advantageous to get down low and push upwards,' I said. They worked together on whiteboards in their groups of three as we always do. It was the best lesson of my life because, for the next hour, I *did* physics *with* them. At the time I had no idea if even I could come up with an adequate explanation, but I decided to take a chance. The diagrams and explanations we created involved everything my students and I understood (Newton's second law, Newton's third law and our basic friction model), and required them to extend those models beyond their current understanding. (The direction of static friction exerted by the surface on the player was particularly challenging for them because as the player pushes back and downwards against the surface, the surface pushes up and *forwards* on the player.) After about 1 h, we held a final class meeting with groups presenting their work to each other and we were able to conclude *why* it would make sense to 'get down low and push upwards' to reduce the frictional force that the ground exerted on your opponent, while simultaneously increasing the frictional force that the ground exerts on you. That is an example of what it is like to be temporarily free of the tyranny of coverage and what is possible when I had the courage to discard my lesson plan and *do* physics with my students.

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Chapter 3

Justifying elements of the ISLE learning system

ISLE rests on four foundational principles of learning. These foundational principles are as follows:

1. **Learning is a physical process** that involves changes in the brain and body of the learner. It happens when the learner establishes new neuronal connections to the existing ones. The corollary of this principle is that no one can learn by only observing somebody else or listening to somebody else without a purposeful effort to connect these sensory experiences to what they already know and to actively test new ideas. This corollary is known as *active learning*.
2. **Learning is a social process** that involves people sharing, debating and testing their ideas in interactions with others. The corollary of this principle is that it is very difficult to learn and improve something in solitude without being socially engaged with other people. This corollary is known as *collaborative work*.
3. **Learning is also an individual process** of the changes in the brain of the learner (Zull 2002). This process also depends on the access to resources and on the level of confidence in one's abilities, which involves developing a 'growth mindset' (Yeager and Dweck 2012). People who believe that their intelligence can change will overcome obstacles in learning and seek harder challenges. The corollary of this principle is that students need to have an opportunity to learn at their own pace, to have access to the relevant resources and to improve their work without punishment. This corollary is known as *universal design* (Scott *et al* 2003).
4. **Learning is a process that needs to prepare an individual for a productive life in the society**. The corollary of this principle is that physics is uniquely positioned to prepare our students for life in the 21st century, which values creativity, innovation and collaboration above factual knowledge and simple skills.

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Below, we elaborate on these principles and show how ISLE adheres to them.

3.1 How people learn?

It has been established for quite some time that for learning to occur individuals need to construct their own knowledge (APA 1997). The knowledge that the learners have developed prior to instruction affects their ability to learn new ideas. As Chinn and Brewer argued, people tend to recast new data into their preexisting views/models of the world, rather than revising their explanations/views of the world (Chinn and Brewer 1993). These ideas are consistent with the research on brain function and development (Zull 2002). Thus, prior knowledge is a foundation for the construction of new knowledge and is simultaneously an impediment to it.

In the early 1980s, Posner *et al* (1982) suggested a *conceptual change* science-learning model that addressed the benefits and difficulties of prior knowledge for learning. They proposed that when learners are confronted with an experience that contradicts their prior ideas, and are dissatisfied with them, then they would be willing to adopt new ideas. This change would occur if the students have to use their prior knowledge to predict what will happen in a particular experiment. Then they observe the experiment, see that their prediction did not match the outcome and experience a so-called 'cognitive conflict'. The existence of the conflict creates the motivation to learn a new concept that explains the experiment. This is where the teacher comes in to propose this concept or help students develop it under his/her guidance. The conceptual change theory was modeled after how scientists change their theories based on their falsification (Popper 1980). It also turned students into active participants in the learning process, thus addressing recommendations of cognitive science.

While this approach seems reasonable, it does not take into account many other issues that are necessary for learning, such as motivation (Pintrich 1999), affective resistance (Linnenbrink and Pintrich 2002), and beliefs about learning (Sinatra *et al* 2001). Researchers found that cognitive conflict and deep engagement were often insufficient to induce change (Dole and Sinatra 1998; Pintrich *et al* 1993).

In addition, studies showed that asking students to make predictions about the outcomes of experiments that later turned out to be unsuccessful had little effect on their ability to see what actually happens in the experiment (Chinn and Malhotra 2001). We argue that repetitive cognitive conflict may even be hindering students' learning of science. Indirect evidence that this method might have a negative effect comes from qualitative research of physics students' attitudes towards physics (Lin 1983) and from the use of the Maryland Physics Expectations Survey (MPEX) (Redish *et al* 1998) and CLASS (Adams *et al* 2006) in reformed courses (all of which use the cognitive conflict approach and in all of them students showed a drop in attitudes). Additional indirect evidence comes from studies of attempts to correct people's misperceptions about political 'hot topics' such as climate change. Attempts to correct people's beliefs with factual evidence actually leads to a 'backfire effect' where they ‘double down’ on their beliefs when evidence conflicts with those beliefs (Lewandowsky *et al* 2012).

We believe that by asking students to make predictions based on hypotheses that they are testing and not their intuition, the ISLE method naturally creates a safe and positive environment for students to express and explore their own ideas. This learning method explicitly avoids creating negative emotions in students’ minds that may occur when they are asked to make predictions based on their gut intuition. As we know from brain studies (Zull 2002), negative emotions can be detrimental to learning through activation of an important part of the cortex, the *amygdala*, the evaluator of the affective and motivational values of stimuli. Some of the studies suggest that when a student is scared in class, activation of amygdala might lead to the slowing down of mental processes.

Zull (2002) in his book relating the results of brain studies to student learning borrows Kolb’s learning cycle to explain how the brain processes new information. Kolb (1984) suggested that when meeting a new situation, our brain progresses through a cycle of concrete experience, reflective observation, abstract hypothesis, and active testing. Concrete experience involves the sensory cortex (reflective observation involves the integrative cortex in the back), creating new abstract concepts (and later making judgements) occurs in the frontal integrative cortex, and active testing involves the motor brain. We can see how Kolb’s learning cycle is similar to the ISLE process diagram shown on page 1-7.

In the second chapter of this book, we gave examples of activities that help students invent operational definitions of physical quantities and cause-effect relations. In the above examples, the students coordinated multiple representations—real experiments, data tables, motion and force diagrams (specific physics representations, which we will discuss more in the chapter Scientific Abilities) and algebraic equations. All of the above are called semiotic resources—tools used in communication in a particular discipline (Airey and Linder 2017). We can see the act of ‘doing physics’ as a process of coordinating multiple representations (Van Heuvelen 1991, Lemke 2004). These are diagrams and pictures (Rosengrant *et al* 2009), equations (Rotman 1988), words (Brookes and Etkina 2007), even kinesthetic actions and experiences (Schwartz 1999, Richards and Etkina 2013, Daane *et al* 2014), and physical equipment (Norman 1993, Hutchins 1995). All of those semiotic resources can be coordinated in various ways to make sense of the physical world. Requiring students to coordinate multiple representations has been shown experimentally to improve understanding, compared to students who only use a single representation (Schwartz *et al* 2005).

The above discussion explains the presence of the following elements of the ISLE learning system:

- **Students suggest their own explanations for observed phenomena**. Their explanations are based on their prior experiences.
- **When students devise explanations, they use their own languag**e, which allows them to connect ideas to their old memory networks. Thus, new concepts become associated with the old reactivated network.

- **Students do not predict the outcomes of observational experiments**. They start with concrete experiences. Then, they activate relevant ideas and memories that they already have in their brains to explain the observations. Some of the old ideas might not be applicable, and students need to modify or adjust them to explain a new situation. Students do not need to 'delete' or 'erase' old ideas. Instead, they examine their applicability through testing experiments.
- **Students use representational tools** to make bridges between phenomena and mathematical equations. These are sketches, graphs, motion and force diagrams, momentum and energy barcharts, ray diagrams and many others. The students also use them to evaluate solutions to the problems (Rosengrant *et al* 2009).

3.2 Learning is a social process

In order to understand the social aspect of the process of learning physics, we first need to ask ourselves how physicists construct knowledge. Analysis of the history of physics (Holton and Brush 2001), the philosophy of science (Kuhn 1970), and work of educators studying the nature of science (Lederman *et al* 2002) shows that there is no generic 'scientific method.' However, we can discern common elements of scientific processes on which most of the scientists and philosophers of science agree. These are:

(a) scientists build knowledge using empirical, reproducible evidence (Open Science Collaboration 2015),
(b) they use *both* inductive (Allchin 2003) *and* hypothetico-deductive (Lawson 2002) reasoning (Born 1943),
(c) they value coherent and testable ideas (Popper 1980), and
(d) scientists work collaboratively and collegially (Latour 1987, Holton and Brush 2001).

So far, we have discussed how points (a)–(c) are addressed in the ISLE process. However, we have not yet addressed the last point—the collegiality of science. Why don't we observe 'lone wolf' scientists who work individually in seclusion? Possibly, the answer lies in the finding that under the right conditions, the collective intelligence of a group can out-strip the combined intelligences of the individual participants (Elliot 2007, Williams Woolley *et al* 2010). If this is true, then creating a real collaborative environment should be very helpful for the students. But how do we create a real learning community that enhances learning capabilities of every student? From research on successful learning communities, we can make a list of important attributes.

1. Sharing of resources—not only material but intellectual. The physical environment in the classroom should be conducive to sharing (for example, round tables are better suited for group discussions than rectangular ones). Small whiteboards for each group help students working in the group to put their ideas to the board to be heard. The intellectual environment should be conducive too—students who come to class with more physics knowledge

should not suppress the expression of thoughts of those who know less or in a different way. Therefore, it is the role of the instructor to listen to and hear good ideas in unexpected places and bring those to the foreground in the learning community.

2. While the role of the instructor is to help lead the community, the students need to have an opportunity for self-direction. The students need to have a feeling of control in the community and a sense of autonomy (Ames 1992, Tobin 2008, Wilson *et al* 2013).

The above discussion explains the presence of the following elements of the ISLE learning system:

- **Students work in small groups** while engaged in the processes described in figure 1.3, page 1-7 to construct their own ideas using inductive and hypothetico-deductive reasoning. Groups are equipped with small whiteboards so that the work of each students is visible and each student has a marker of a different color. This way everyone can make a contribution.
- **The instructor carefully monitors group work** making sure that everyone has a voice but **without imposing on the students his/her own ideas**.
- **The students design their own experiments** (when possible) **and make their own judgments** about the success of those experiments (the details of how they learn to do it are described in the chapter on scientific abilities).

3.3 Developing confidence and growth mindset

No learning system is going to be successful if the students are not motivated to learn (Brophy 1983). Motivation becomes even more important in an inquiry-based environment, like an ISLE classroom, as the students are being challenged to figure out things for themselves rather than being given the answer. Research shows that motivation to overcome difficulties and solve challenging problems is related to the person's mindset. If a person believes that intellectual abilities are fixed, then he/she avoids a difficult problem. If a person believes that intellectual abilities can grow with time, then she/he sees difficult problems as a challenge and an opportunity. Having a growth mindset is one of the main motivational factors (Dweck and Leggett 1988, Yeager and Dweck 2012). Studies show that motivation is a complex interaction of personal goals (performance versus mastery), orientation towards learning (ego-involvement versus task-involvement), and source of motivation (intrinsic versus extrinsic) (Ames 1992). Cordova and Lepper (1996) connected motivational manipulations, such as embedding learning tasks in a meaningful context and offering some freedom of choice, with more intrinsic motivation, deeper task involvement, and better performance on a post-test. Covington and Omelich (1984) demonstrated that giving students the opportunity to improve a grade (take a retest) helped them to disconnect their test performance from their beliefs about their abilities. Students do better on motivational measures when they are focused on self-improvement rather than social comparison.

The above discussion explains the presence of the following elements of the ISLE learning system:

- **Each unit starts with a motivational experiment, video, story, etc.** The students observe and listen but do not try to give an explanation. We call this beginning 'creating the need to know'. As the unit progresses, the students slowly begin to construct the knowledge needed to answer the questions posed in the 'need to know' segment. For example, when students start learning kinematics, we show them a GSP and tell them that by the end of this unit, they will be able to determine what data the GPS needs to collect to give you an estimate of the arrival time and how this is done; when the students start learning circular motion, they observe a YouTube video of Damien Walters running a loop-the-loop (https://www.youtube.com/watch?v=OTcdutIcEJ4); when the students start learning wave optics, they observe the video of a soap bubble (https://mediaplayer.pearsoncmg.com/assets/_frames.true/secs-egv2e-soap-bubble). Throughout the unit, we explicitly connect the physics content to students everyday experiences and we make sure that most observational experiments that they conduct relate to something with which they are familiar.
- To improve motivation and develop growth mindset **ISLE students are encouraged to resubmit their assignments multiple times** until they develop mastery. Multiple trials do not result in lower grades, only mastery counts. The details of achieving this goal are described in the chapters on scientific abilities (chapter 4) and assessment (chapter 5). This reflects our deep belief that every student should be given an opportunity to succeed.
- The **ISLE system specifically focuses on the steps where students can be successful;** describing their observations in simple words, suggesting possible explanations, and making predictions (i.e. describing the results of testing experiments).
- **A student's individual grade does not depend on the grades of others**; course grades are based on point-accumulation system.

3.4 What do students need for success in their future lives and for success in the science workplace?

We all want our students to be successful in the future. But what does it mean for those living in the 21st century? Long gone are the times when one could succeed by knowing facts and following directions. In the 21st century, the majority of jobs involve creative decisions based on data (Marshall and Tucker 1992). Studies conducted by science-based industries show that procedural knowledge rather than declarative knowledge is needed (Chin *et al* 2004, Lottero-Perdue and Brickhouse 2002, Duggan and Gott 2002, Aikenhead 2005). Being able to think on the job, reason with evidence and make difficult judgments in novel situations is more valuable than scientific facts remembered from schooling. European documents (Gonzalez and Wagenaar 2003, OECD 2018) are in agreement with these recommendations, as well as NGSS Lead States (2013). The latter indicate that learning through inquiry is crucial and includes the abilities to: (a) identify questions and concepts that guide scientific investigation; (b) design and conduct scientific investigations; (c) use technology and mathematics to improve investigations and communications; (d) formulate and revise scientific explanations and models using logic and evidence; (e) recognize and analyze alternative explanations and models; and last, but not least, (f) communicate and construct a scientific argument.

All of the above documents indicate that there is a world-wide need for graduates who have learned the practices of science in addition to learning scientific facts and laws.

The above discussion explains the presence of the following elements of the ISLE learning system:

- The process through which knowledge is constructed is central to student learning.
- The students work in groups and communicate their ideas with each other.
- Students collect, analyze and interpret data and design their own experiments to test ideas and to solve problems.
- Students solve both traditional back-of-the-chapter problems and real-world problems that do not have one right answer.
- Students have an opportunity to revise and improve their work.

3.5 Interlude: learning is hard, you're going to be uncomfortable in here

'At first, I was terrified by the idea that if education is going to be transformative, it's going to be uncomfortable and unpredictable. Now, as I begin my fifteenth year of teaching at the University of Houston, I always tell my students, "If you're comfortable, I'm not teaching and you're not learning. It's going to get uncomfortable in here and that's okay. It's normal and it's part of the process." The simple and honest process of letting people know that discomfort is normal, it's going to happen, why it happens, and why it's important, reduces anxiety, fear, and shame. Periods of discomfort become an expectation and a norm.' (Brown 2012, p 197)

Ideally, learning should be a transformative experience. Imagine the classroom as a black box for a moment. Students enter the classroom in August, and re-emerge in (say) December looking much the same as when they came in. There is no physical manifestation of what has happened in that room, and the world is running pretty much as it was four months previously. So what has changed? If you undergo a transformative experience, the way you *see* that world has subtly shifted. To the learner, it isn't the same world anymore: the angle of the light has moved, the color has changed, it *looks* different. When I see a student who has undergone that transformative experience as a direct result of the learning environment I've tried to create, that is the most rewarding feeling I have ever experienced.

There is, however, a problem. Many of our students are not expecting or even desiring a transformative experience. For many students, their expectations of what should happen in their physics class are rudely violated when they enter my classroom. Over the last 10 years, I have come to see that, if students are to have a positive experience in my classroom, I need to actively strive to bridge the divide. I want to start by describing the gap as accurately as I can.

The gap between school and real-life learning

Schooling, or learning in a school setting has become (maybe it was always this way?) far, far removed from real-life learning. What do I mean by real-life learning? Think about something you're good at; a hobby, like cooking or computer gaming. For example, I'm a good musician; I play the bassoon with a fair amount of competence that at one point allowed me to play in a professional orchestra. Think about how you became good at your hobby. Were you good at it from the beginning? I was terrible at the bassoon for about three years straight until I had the good fortune to find a teacher who focused on teaching me how to develop the skill of deliberate practice (Ericsson *et al* 1993). Even then, it took me another three years of 3-hours-a-day deliberate practice to become competent. Think about how many hours you spent working at your hobby. Think about how many times you sucked and wanted to quit, but you didn't, you persisted. This is what real learning looks like. It is hard, it's messy, it requires persistence, motivation, and tolerance of failure. I highly recommend watching Yung Tae Kim's TED talk on YouTube: https://youtu.be/lHfo17ikSpY. In real-life learning, such as learning to skateboard, failure is normal. You start out as a novice, and as a novice you don't know what you're doing. You are going to stumble and fall a lot. Learning from one's mistakes is critical to success. Persistence and reevaluating one's performance based on feedback crucial if you are going to improve. Skateboarders keep practicing until they master a trick. There is no time limit on this process. As Dr Tae points out in his talk, learning isn't *fun*; it is more like *flow* (Csikszentmihalyi 1990).

Students' most common or familiar experience of school learning is totally at odds with what I've described above. Students mostly sit passively listening to the teacher. Facts and procedures are memorized and regurgitated on the test. The teacher is always rushing from one topic to the next, making sure they 'cover' the material. The teacher is the final arbiter of correctness and failure is bad. That is their expectation and experience of what school learning is and should be. Students' expectations are violated when they enter an authentic inquiry-learning environment, such as ISLE, because, if properly designed, that learning environment looks more like learning to skateboard or play the bassoon, and less like 'traditional' school learning. ISLE is structured around having students *investigating* physical phenomena using authentic scientific practices. They are not told what to do; *they* are the authors of their knowledge! Students get multiple opportunities to improve and resubmit their work. For some students (those who have been struggling in the traditional school setting), taking my physics class is the first time they have been free to ask questions, challenge authority, and be masters of their own learning. They take to the class like a duck to water, but they are only a minority. For most students, they have become good at and successful in 'traditional' schooling. The ISLE physics class has not only switched the game on them, but represents a threat to their ability to be successful in school. Even more importantly, it threatens their identity as a good student (Carlone 2004). It is no surprise that students' reactions are often extremely emotional.

Fostering the transformation

The reason I have described the contrast between school learning and real-life learning in such detail is because students do **NOT** have a deficient understanding of what learning is. Many of my students (and presumably yours) have an extra-curricular hobby that they are extremely accomplished at. Some are good at sports or music. Some are great computer gamers. They understand what real-life learning looks and feels like in all its messiness and frustration. That is why an ISLE implementer (Yuhfen Lin) created what we call the 'expertise activity' (Brookes and Lin 2012). In this activity, we ask students to identify a hobby they are accomplished at and divide them into thematic groups based on their responses. For example, there is often a cooking group, a sports group, a board and computer games group, etc. We task each group with drawing up a *learning cycle* on their whiteboard that explains to the rest of the class how one can move from becoming a novice to an expert in their chosen field of expertise. The important point is that they must draw a repeatable cycle, *not* a list of 'what does it take to become good at something.' Having them construct a learning cycle draws out all the keys features of real life learning: the need for motivation and persistence, the role of critical self-evaluation and seeking feedback from others, etc. These are all features of the ISLE classroom. At the end, students present their learning cycles to each other and I draw the discussion together at the end, highlighting common features, connecting those features to how the ISLE class is set up, and sometimes have them watch Dr Tae's TED talk.

We use a number of activities like this one, throughout the semester, to encourage students to think more deeply about learning, and how they approach learning in the unfamiliar learning environment of the ISLE physics class. For example, I have students read articles about fixed and growth mindset and discuss their reactions, either in class time or through journaling. I talk to students and show them articles that clearly argue that the 21st century workplace that they are going to be a part of needs people who can think *with* their knowledge and who are life-long learners. My goal as an instructor is to help students become more comfortable with the discomfort of learning and to support their epistemic struggles (Jaber 2015) because ultimately, it is *they* (not me) who have to make sense of physics and see how it is connected to the world around them.

I bet you're thinking: 'how can I possibly implement ISLE, *and* do extra activities with my students, *and* cover the topics I need to cover during the semester?' All I have to say in response is that I often think the same thing and skip some of these activities. Every time I do that, the class goes worse than the occasions when I choose to set time aside to really engage in these activities and 'cover' fewer physics topics.

It is difficult to document that a transformative experience really happened, but in an interview study of students in an ISLE physics class conducted in 2010 (Brookes *et al* 2019), this one quotation from a student still stands out to this day. It is particularly special because the interviewee was what I would describe as a 'traditionally good student.' She worked hard, did her homework, everything was scheduled and done one time. But she was one of the most nervous test-takers I'd ever seen, presumably because she felt under such pressure to be successful. I'll let her words speak for themselves:

> 'And I know this class is challenging because of the exam… If there's anything that requires you to reason beyond any human possibility is the exam… But you know it and the best example was the last exam, Exam 2, with the barber shop thing. I didn't know that I knew that question and I literally reasoned it out and I got full points on that question. I got full points on that question. I never—I even left it. I was like, 'I think that's right but I'm not even sure because I just reasoned it out but I hope that that's right. And when I found I got full points I was like, 'Wow.' Because I remember I even told during the exam, I was like, 'You threw this out of nowhere. I don't know where this came from but this is weird.' And I realized that I was able to reason it out. That to me was the biggest accomplishment I've had in this class. Because I actually beat—like I stared at that question and I was like, 'What is going on?' And I skipped it and I would go back to it, 'What is going on?' And I'd go back to the other question and keep on going, come back, 'Oh my God, I'm never gonna get this question.' And then to have that moment that you're just like, 'You know what? I'm gonna take it step by step. I'm gonna do the analyzing we normally did with the mirrors and just figure it out and work through it.' And it worked. And to see that it worked, it completely—it made everything worthwhile.'

Every time I read this, I feel my eyes getting a little moist.

Inquiry learning is transformative for the instructor as well

This is what I love about education, teaching, and learning: it is not only a potentially transformative experience for my students, but also for me. Both my students and I are served with an opportunity for personal growth. In my case, it is a life-long process that is *always* taking me out of my comfort zone.

Some teachers are outgoing and charismatic. In an ISLE classroom, they are challenged to relinquish control. They are no longer the center of attention. They need to let their students be wrong and be comfortable to *not* jump up to the front of the classroom and tell everyone the right answer. Others (and I am more in this camp) are painfully shy and reserved. Our challenge is to be more vulnerable, to coach and nurture students when they are struggling rather than hiding from the intense emotional struggle that often occurs in an ISLE classroom. To create a rich classroom learning culture without the resource of charisma is incredibly difficult.

Did I mention I'm always uncomfortable when I'm teaching? That is why I think I am the luckiest person in the world: I get to do the hardest, most challenging job in the world. Harder than being a neurosurgeon, harder than being a rocket scientist. Real, authentic inquiry learning challenges us to reexamine our deepest selves as human beings.

I'm writing this because, if you've read to this point, you're probably interested in ISLE and inquiry learning and are of firm conviction that standing at the front and lecturing is not a good way for students to learn. You might even have tried inquiry learning and received strong negative reactions from some of your students. It really hurts when a student writes on their student evaluations of the instructor:

> 'He did nothing to make [the class] a good learning experience. I always felt discouraged to learn. I work my hardest and put in time for office hours and supplemental instruction and still always receive [an F].'

This is transcribed verbatim from my end-of-semester evaluations. The student's comment shows I have failed to nurture and support their struggle (despite my desire and willingness to do so). I feel like a complete failure even though there are comments like this one from the same class:

> 'He taught us in a unique way with the growth method. One of my favorite classes I've taking in college. I think that he genuinely wants us to learn the material and gives us ample opportunity to do so.'

What I'm trying to say is, don't be discouraged. It is easy to give up in the face of both student and institutional resistance. Being vulnerable and open to growth means reading your students' evaluations and, as dispassionately as possible, trying to evaluate what is lying underneath what they have written. Sometimes this is easy. The following student is completely honest about why they hated my class and it has little to do with me and everything to do with our conflicting expectations of the class:

> 'Worst teacher I have ever had. Don't care to learn physics and I know it doesn't relate to my major so I have no need to learn it either but it's mandatory.'

In short, this student never wanted to be there and hated that I required him/her to work hard for their grade. But other reactions are harder to evaluate like the student who said I did nothing to make the class a good learning experience. It is possible that this student also didn't get the point of the class, but I clearly let someone 'fall through the cracks' so to speak. I can pretty much identify every student who was a regular at my office hours, which means I clearly didn't respond to someone's needs adequately. I need to improve. Teaching in this unconventional way is always an opportunity to learn and to grow. It is easy to hide from the pain and go back to the safe place of lecturing where nobody can hurt you. It is harder to really read, then re-read, and re-read again, all the comments your students leave and critically evaluate which ones are valid criticisms of what you were doing, which ones were maybe a failure of messaging on your part, and which ones are simply students who you would have never have 'won over' no matter how hard you tried. As I keep trying to remind myself: 'learning can be uncomfortable, get comfortable with the discomfort.' Implementing ISLE has, for me, been the most significant transformative experience of my life.

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Chapter 4

Scientific abilities

Practicing reasoning in authentic contexts is a vital part of the ISLE approach. 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 when students design their own experiments to answer the questions posed for them or even pose their own questions. Student experimentation in ISLE is drastically different from traditional approaches where students observe demonstrations performed by a teacher or labs where students perform 'verification' experiments following step-by-step instructions. To help students learn how to solve problems and how to proceed in the 'design' situations, we developed:

(a) **a list of reasoning processes** that physicists use and that we can help our students develop (we coined the name of 'scientific abilities' for those);
(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 scientific abilities. These rubrics suggest what they should *think about* and not what they should do.

4.1 Defining scientific abilities

The work on scientific abilities was carried out by a large group of people and is described in several publications (Etkina *et al* 2006, 2008). The list of scientific abilities, rubrics and many ISLE-based resources including instructional labs are posted online and are free to download at https://sites.google.com/site/scientific-abilities/.

We use the term 'scientific abilities' to describe some of the most important procedures, processes and methods that scientists use when constructing knowledge and when solving experimental problems. We use the term 'scientific abilities'

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instead of 'science process skills' to underscore that these are not automatic skills, but are instead processes that students need to use reflectively and critically (Salomon and Perkins 1989). The list of scientific abilities developed by our physics education research group is as follows:

(a) the ability to represent information in multiple ways;
(b) the ability to use scientific equipment to conduct experimental investigations and to gather pertinent data to investigate phenomena, to test hypotheses, or to solve practical problems;
(c) the ability to collect and represent data in order to find patterns, and to ask questions;
(d) the ability to devise multiple explanations for the patterns and to modify them in light of new data;
(e) the ability to evaluate the design and the results of an experiment or a solution to a problem;
(f) the ability to communicate.

This list is based on the analysis of the history of practice of physics (Holton and Brush 2001, Lawson 2000, Lawson 2003), the taxonomy of cognitive skills (Bloom 1956, Krathwohl 2002), and recommendations of science educators (Schunn and Anderson 2001).

To help students develop these abilities, one needs to engage students in appropriate activities, and to find ways to assess students' performance on these tasks, to provide timely feedback and to revise planned instruction based on student work. Activities that incorporate feedback to the students and to the instructor are called formative assessment activities. As defined by Black and Wiliam, formative assessment activities are 'all those activities undertaken by teachers, and by their students in assessing themselves, that provide information to be used as feedback to modify the teaching and learning activities' in which they are engaged. (Black and Wiliam 1998b). Black and Wiliam also found that self-assessment during formative assessment is more powerful than instructor-provided feedback; meaning the individual, small-group, and large-group feedback system enhances learning more than instructor guided feedback. Sadler (1989) suggested three guiding principles, stated in the form of questions, that students and instructors need to address in order to make formative assessment successful.

1. Where are you trying to go? (Identify and communicate the learning and performance goals.)
2. Where are you now? (Assess, or help the student to self-assess, current levels of understanding.)
3. How can you get there? (Help the student with strategies and skills to reach the goal.)

As noted above, students need to understand the target concept or ability that they are expected to develop and the criteria for good work relative to that concept or ability. They need to assess their own efforts in light of the criteria. Finally, they need to share responsibility for taking action in light of the feedback. The quality of the feedback rather than its existence or absence is a central point. The feedback should be descriptive and criterion-based, as opposed to numerical scoring or letter grades without clear criteria.

With all the constraints of modern teaching, including large-enrollment classes and untrained teaching assistants (TAs), how can one make formative assessment and self-assessment possible? One way to achieve this goal is to use scoring rubrics. A scoring rubric is one of the ways to help students see the learning and performance goals, self-assess their work, and modify it to achieve the goals (three guiding principles as defined by Sadler above). The rubrics contain descriptions of different levels of performance, including the target level. A student or a group of students can use the rubric to self-assess their own work. An instructor can use the rubric to evaluate students' responses and to provide feedback.

4.2 Fine-tuning scientific abilities and devising rubrics to assess them

After making the list of scientific abilities that we wanted our students to develop, we started devising assessment rubrics to guide their work. Rubrics are descriptive scoring schemes that are developed by teachers or other evaluators to guide students' efforts (Brookhart 1999). This activity led to a fine-tuning of the abilities, that is, to break each ability into smaller sub-abilities that could be assessed. For example, for the ability to *collect and analyze data*, we identified the following sub-abilities:

- the ability to identify sources of experimental uncertainty,
- the ability to evaluate how experimental uncertainties might affect the data,
- the ability to minimize experimental uncertainty,
- the ability to record and represent data in a meaningful way, and
- the ability to analyze data appropriately.

Each item in the rubrics that we developed corresponded to one of the sub-abilities. We agreed on a scale of 0–3 in the scoring rubrics to describe student work (0—missing, 1—inadequate, 2—needs some improvement, 3—adequate) and devised descriptions of student work that could merit a particular score. For example, for the sub-ability 'to record and represent data in a meaningful way' a score of 0 means that the data are either missing or incomprehensible, a score of 1 means that some important data are missing, a score of 2 means that all important data are recorded but presented in a way that requires some effort to comprehend, and a score of 3 means that all important data are present, organized, and recorded clearly.

Simultaneously, while refining the list of abilities, we started devising activities that students could perform in problem solving sessions and labs. Defining sub-abilities and developing scoring rubrics to assess them informed the writing of these activities. After we developed the rubrics, we started using them to score samples of student work. Each person in a nine-person group assigned a score to a given sample using a particular rubric; we then assembled all the scores in a table and discussed the items in the rubrics where the discrepancy was large.

Based on these discussions, we revised the wording of the rubrics and tested them by scoring another sample of student work. This process was iterated until we achieved a nearly 100% agreement among our scores.

In the sections below, we list scientific abilities and corresponding sub-abilities that we identified, provide examples of scoring rubrics that we devised and discuss where in the instructional process we use the rubrics. For each scientific ability, we provide examples of the tasks written for the students. In subsequent sections, we will report how we used the rubrics to study students' development of some of the suggested abilities.

1. Ability to represent information in multiple ways

In introductory physics courses, students are often given a verbal description of a physical process and a problem to solve relative to that process. They can start their analysis by constructing a sketch to represent the process and include in the sketch the known information provided in the problem statement. They construct more physical representations that are still relatively easy to understand—for example, motion diagrams, free-body diagrams, graphs, qualitative work-energy and impulse-momentum bar charts, circuit diagrams, ray diagrams, field lines and more (see table 4.1). Finally, they use these physical representations to help construct a mathematical representation of the process.

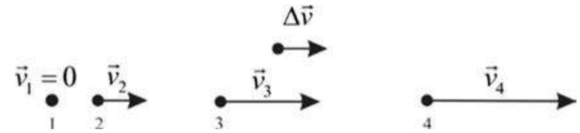
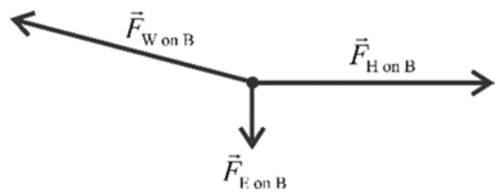
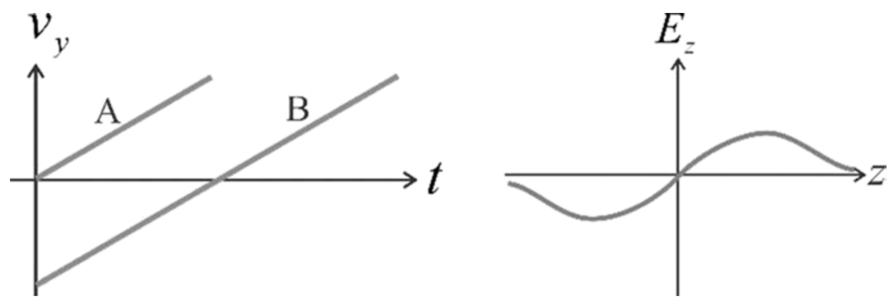
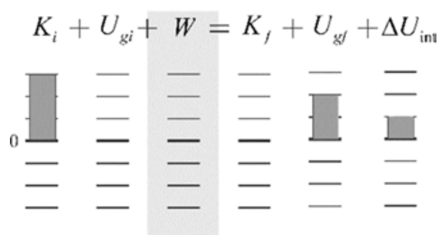
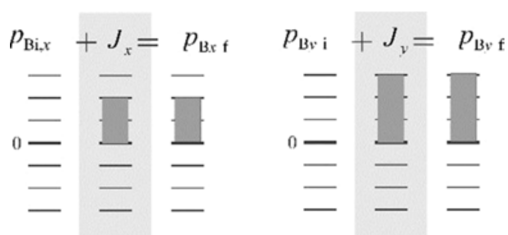
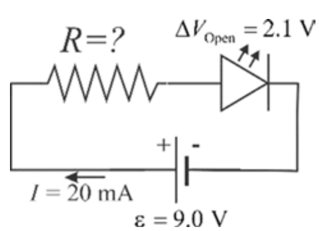
What sub-abilities help to make this multiple representation strategy productive for reasoning and problem solving?

- The ability to correctly extract information from a representation;
- The ability to construct a new representation from another type of representation;
- The ability to evaluate the consistency of different representations and modify them when necessary.

In addition to such sub-abilities that students need to master while using multiple representations, there are specific sub-abilities needed for each type of representation. For example, to use force diagrams (or free-body diagrams FBDs) productively for problem solving, students must learn to:

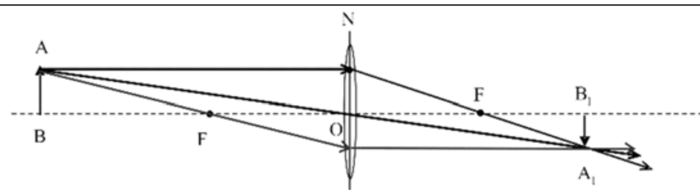
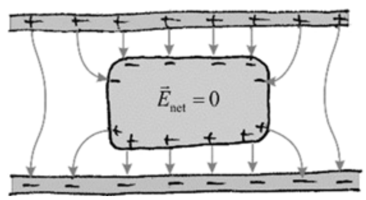
- Choose a system of interest before drawing the diagram.
- Use force arrows to represent the interactions of the external world (environment) with the system.
- Label the force arrows with two subscripts (for example, the force that Earth exerts on the object is labeled as $\vec{F}_{\mathrm{E\ on\ O}}$).
- Try to make the relative lengths of force arrows consistent with the problem situation (the sum of the forces should point in the same direction as the system object's acceleration).
- Include labeled axes on the diagram.

Table 4.1. Examples of cognitive tools—multiple representations.

Name	Representation
Motion diagram	
Force diagram (free body diagram)	
Graph	
Work-energy bar charts	
Impulse-momentum bar charts	
Circuit diagram	

(*Continued*)

Table 4.1. (*Continued*)

Name	Representation
Ray diagram	
Field lines	

Such diagrams if drawn correctly can be used to help write Newton's second law in component form—to represent the situation mathematically. Based on these considerations, we constructed a rubric to help students self-assess themselves while drawing force diagrams.

We also made a list of several types of multiple representation activities (a task may consist of some combination of these activities). Some examples are given below.

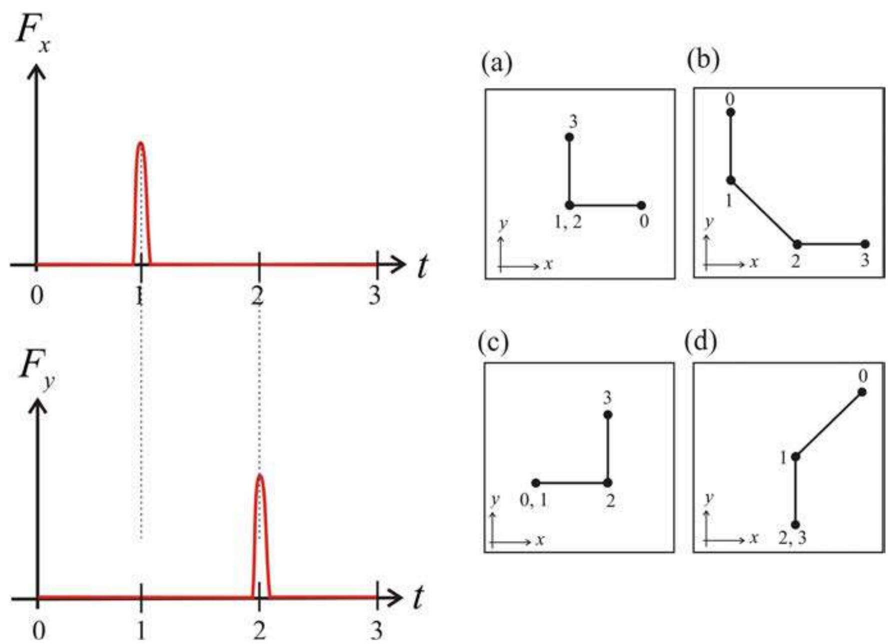
Provide students with one representation and have them create another.

Example: Draw motion and force diagrams for the process described with the following equations:

$$x : a_x = [0 + (-(100\text{ kg}) \times (10\text{ N kg}^{-1}) \times \ \cos 20°)]/(100\text{ kg})$$
$$y : 0 = [N + (-(100\text{ kg}) \times (10\text{ N kg}^{-1}) \times \ \sin 20°)]/(100\text{ kg})$$
$$0 - (16\text{ m s}^{-1}) = a_x t.$$

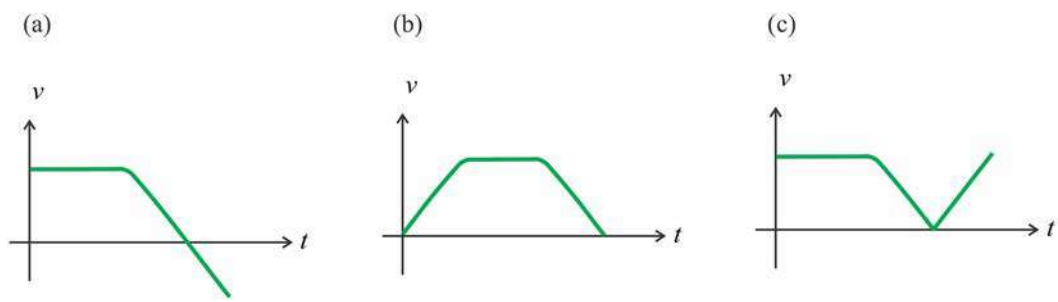
Provide students with two or more representations and have them check for consistency between them.

Example: Two forces exert impulses on a hockey puck, which can move with no friction on an icy surface. The graphs on the left in figure below show the time dependence of the x- and y-components of the sum of the forces exerted on the puck. Which of the trajectories (a)–(d) of the puck's motion in the x-y-plane shown on the right cannot be the result of these forces? The numbers correspond to successive clock readings that are marked on the force graphs.



Provide students with one representation and have them choose from a multiple-choice list a consistent different type of representation (for example, provide a word description of a process and have students select from a list a consistent graphical description of the process).

Example: In the figure below, choose the correct approximate velocity-versus-time graph for the following hypothetical motion: a car moves at constant velocity, and then slows to a stop and without a pause moves in the opposite direction with the same acceleration.



Have students use a representation while solving a problem.

Example: In a popular new hockey game, the players use small launchers with springs to move the 0.0030 kg puck. Each spring has a 120 N m^{-1} spring constant and can be compressed up to 0.020 m. Determine the maximum speed of the puck.

First, represent the process with a work-energy bar chart and then solve the problem.

Below, we show the rubrics for self-assessment of the ability to represent information in multiple ways (table 4.2).

2. The ability to use scientific equipment to conduct experimental investigations and to gather pertinent data to investigate phenomena, to test hypotheses, or to solve practical problems

As we discussed above, in ISLE, experiments play three distinctly different epistemological goals: experiments that help students devise models/explanations/relations, experiments that help them test those and experiments in which students combine accepted models to solve a practical problem (Etkina *et al* 2002). In short, an experiment can have one of the three roles: observational, testing or application experiment.

As mentioned above, when conducting an observational experiment, a student focuses on investigating a physical phenomenon without having expectations of its outcomes. When conducting a testing experiment, a student has an expectation of its outcome based on the idea under test. In an application experiment, a student uses established concepts or relationships to address practical problems. However, in the process of scientific research, the same experiment can fall into more than one of these categories. For example, an experiment that was initially planned as testing experiment can show some surprising results and thus becomes an observational experiment that eventually (after several new testing experiments) leads to discovery of a new idea.

What abilities do students need when designing experimental investigations? We have identified the following steps that students should take to design, execute and make sense out of a particular experimental investigation. We assigned a sub-ability for each step and wrote corresponding descriptors in the rubrics. The results of these discussions are presented in table 4.3.

For each of the identified sub-abilities, we devised a rubric item that describes different levels of proficiency. The rubrics for the three types of experiments are presented in tables 4.4, 4.5, and 4.6.

Students use these rubrics when they solve problems or conduct experiments. Ideally, we want them to continuously refer to the rubrics while solving a problem or designing and performing the experiment. In a lab environment, rubrics guide the students as to what experimental aspects they should specifically pay attention to. After they perform the experiment, the students write a lab report (in the lab). During the process of writing, they use the descriptors in the rubrics to improve their report. For example, in one case, students wrote that they used a thermometer to measure the temperature of a hot rock. They recorded the rock's temperature in their report. However, what students actually measured was the temperature of the water in which the rock was submerged. Using the rubrics, they self-assessed their writing and revised their description of how they used available equipment to measure the required physical quantity. In the revised report, students wrote that to determine

Table 4.2. Ability to represent information in multiple ways.

RUBRIC A: Ability to represent information in multiple ways					
Scientific ability		Missing	Inadequate	Needs improvement	Adequate
A1	**Is able to extract the information from representation correctly**	No visible attempt is made to extract information from the problem text.	Information that is extracted contains errors such as labeling quantities incorrectly, mixing up initial and final states, choosing a wrong system, etc. Physical quantities have no subscripts (when those are needed).	Some of the information is extracted correctly, but not all of the information. For example, physical quantities are represented with numbers but there are no units. Or directions are missing. Subscripts for physical quantities are either missing or inconsistent.	All necessary information has been extracted correctly, and written in a comprehensible way. Objects, systems, physical quantities, initial and final states, etc, are identified correctly and units are correct. Physical quantities have consistent subscripts.
A2	**Is able to construct new representations from previous representations**	No attempt is made to construct a different representation.	Representations are attempted, but use incorrect information or the representation does not agree with the information used.	Representations are created without mistakes, but there is information missing, i.e. labels, variables.	Representations are constructed with all given (or understood) information and contain no major flaws.

(*Continued*)

Table 4.2. (*Continued*)

	RUBRIC A: Ability to represent information in multiple ways				
Scientific ability		Missing	Inadequate	Needs improvement	Adequate
A3	**Is able to evaluate the consistency of different representations and modify them when necessary**	No representation is made to evaluate the consistency.	At least one representation is made but there are major discrepancies between the constructed representation and the given one. There is no attempt to explain consistency.	Representations created agreement with each other but may have slight discrepancies with the given representation. Or there is no explanation of the consistency.	All representations, both created and given, are in agreement with each other and the explanations of the consistency are provided.
A4	**Is able to use representations to solve problems**	No attempt is made to solve the problem.	The problem is solved correctly but no representations other than math were used.	The problem is solved correctly but there are only two representations: math and words explaining the solution.	The problem is solved correctly with at least three different representations (sketch, physics representation and math or sketch, words and math, or some other combination).
A5	**Force diagram (FD)**	No representation is constructed.	FD is constructed but contains major errors, such as incorrect mislabeled or not labeled force vectors, length of vectors, wrong direction, extra incorrect vectors are added, or vectors are missing.	FD contains no errors in vectors but lacks a key feature such as labels of forces with two subscripts or vectors are not drawn from single point, or axes are missing.	The diagram contains no errors and each force is labeled so that it is clearly understood what each force represents.

A6	**Motion diagram**	No representation is constructed.	Diagram does not show proper motion: either lengths of arrows (both velocity and velocity change) are incorrect or missing and or spacing of dots are incorrect.	Diagram has correct spacing of the dots but us missing velocity arrows or velocity change arrows.	The diagram contains no errors and it clearly describes the motion of the object. Dots, velocity arrows and velocity change arrows are correct.
A7	**Sketch**	No representation is constructed.	Sketch is drawn but it is incomplete with no physical quantities labeled, or important information is missing, or it contains wrong information, or coordinate axes are missing.	Sketch has no incorrect information but has either no or very few labels of given quantities. Subscripts are missing or inconsistent. The majority of key items are drawn.	Sketch contains all key items with correct labeling of all physical quantities, which have consistent subscripts; axes are drawn and labeled correctly.
A8	**Energy bar chart**	No representation is constructed.	Bar chart is either missing energy values, the bars drawn do not show the conservation of energy or are drawn in the wrong places. Bars could also be labeled incorrectly. The system and/or initial and final states are not identified.	Bar chart has the energy bars drawn correctly (energy is conserved), but some labels are missing or the system/ initial and final states are not identified. The bar chart matches the process described with some other representation.	Bar chart is properly labeled and has energy bars of appropriate magnitudes. The system and initial and final states are clearly identified.

(*Continued*)

Table 4.2. (*Continued*)

RUBRIC A: Ability to represent information in multiple ways					
Scientific ability		Missing	Inadequate	Needs improvement	Adequate
A9	**Mathematical**	No representation is constructed.	Mathematical representation lacks the algebraic part (the student plugged the numbers right away), has the wrong concepts being applied, signs are incorrect, or progression is unclear. The first part should be applied when it is appropriate.	No error is found in the reasoning, however they may not have fully completed steps to solve the problem or one needs effort to comprehend the progression. No evaluation of the math in the problem is present.	Mathematical representation contains no errors and it is easy to see progression of the first step to the last step in solving the equation. The solver evaluated the mathematical representation.
A10	**Ray diagram**	No representation is constructed.	The rays that are drawn in the representation do not follow the correct paths. Object or image may be located at wrong position.	Diagram is missing key features but contains no errors. One example could be the object is drawn with the correct lens/mirror but rays are not drawn to show image. Or the rays are too far from the main axis to have a small-angle approximation. Or the diagram is drawn without a ruler.	Diagram has object and image located in the correct spot with the proper labels. Rays are correctly drawn with arrows and contain at least two rays. A ruler was used to draw the images.

A11	**Graph**	No graph is present.	A graph is present but the axes are not labeled. There is no scale on the axes. The data points are connected.	The graph is present and axes are labeled but the axes do not correspond to the independent and dependent variable or the scale is not accurate. The data points are not connected but there is no trendline.	The graph has correctly labeled axes, independent variable is along the horizontal axis and the scale is accurate. The trendline is correct.

Table 4.3. Sub-abilities involved in successfully carrying out three types of experiments.

Sub-abilities involved in the ability to design and conduct an observational experiment	Sub-abilities involved in the ability to design and conduct a testing experiment	Sub-abilities involved in the ability to design and conduct an application experiment
Identifying the phenomenon to be investigated.	Identifying the model/explanation/relation to be tested.	Identifying the problem to be solved.
Designing a reliable experiment that investigates the phenomenon.	Designing a reliable experiment that allows one to compare the outcome to the prediction based on the model/explanation/relation under test using the available equipment.	Designing an experiment that solves the problem.
Deciding what is to be measured, and identifying independent and dependent variables.	Deciding what is to be measured, and identifying independent and dependent variables.	Deciding what is to be measured.
Using available equipment to make measurements.	Using available equipment to make measurements.	Using available equipment to make measurements.
Describing what is observed, both in words and by means of a picture of the experimental set-up.	Deciding whether the outcome of the experiment matches the prediction.	Making a judgment about the results of the experiment.
Describing a pattern or devising an explanation.	Making a reasonable judgment about the model/explanation/relation under test.	Evaluating the results by means of an independent method.
Identifying shortcomings in an experimental design and suggest specific improvements.	Identifying shortcomings in an experimental design and suggest specific improvements.	Identifying shortcomings in an experimental design and suggest specific improvements.

Table 4.4. Observational experiment rubric.

RUBRIC B: Ability to design and conduct an observational experiment					
	Scientific ability	Missing	Inadequate	Needs improvement	Adequate
B1	**Is able to identify the phenomenon to be investigated**	No phenomenon is mentioned.	The description of the phenomenon to be investigated is confusing, or it is not the phenomena of interest.	The description of the phenomenon is vague or incomplete.	The phenomenon to be investigated is clearly stated.
B2	**Is able to design 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 might yield interesting patterns relevant to the investigation of the phenomenon.
B3	**Is able to decide what physical quantities are to be measured and identify independent and dependent variables**	The physical quantities are irrelevant.	Only some of physical quantities are relevant.	The physical quantities are relevant. However, independent and dependent variables are not identified.	The physical quantities are relevant and independent and dependent variables are identified.
B4	**Is able to describe how to use available equipment to make measurements**	At least one of the chosen measurements cannot be made with the available equipment.	All chosen measurements can be made, but no details are given about how it is done.	All chosen measurements can be made, but the details of how it is done are vague or incomplete.	All chosen measurements can be made and all details of how it is done are clearly provided.

(*Continued*)

Table 4.4. (*Continued*)

	RUBRIC B: Ability to design and conduct an observational experiment				
	Scientific ability	Missing	Inadequate	Needs improvement	Adequate
B5	**Is able to describe what is observed without trying to explain, both in words and by means of a picture of the experimental setup**	No description is mentioned.	A description is incomplete. No labeled sketch is present, or observations are adjusted to fit expectations.	A description is complete, but mixed up with explanations or pattern. The sketch is present but is difficult to understand.	Clearly describes what happens in the experiments both verbally and with a sketch. Provides other representations when necessary (tables and graphs).
B6	**Is able to identify the shortcomings in an experimental and suggest improvements**	No attempt is made to identify any shortcomings of the experimental.	The shortcomings are described vaguely and no suggestions for improvements are made.	Not all aspects of the design are considered in terms of shortcomings or improvements.	All major shortcomings of the experiment are identified and reasonable suggestions for improvement are made.
B7	**Is able to identify 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. Terms proportional are used without clarity, e.g. is the proportionality linear, quadratic, etc.	The pattern represents the relevant trend in the data. When possible, the trend is described in words.
B8	**Is able to represent a pattern mathematically (if applicable)**	No attempt is made to represent a pattern mathematically.	The mathematical expression does not represent the trend.	No analysis of how well the expression agrees with the data is included, or some features of the pattern are missing.	The expression represents the trend completely and an analysis of how well it agrees with the data is included.
B9	**Is able to devise an explanation for an observed pattern**	No attempt is made to explain the observed pattern.	The explanation is vague, not testable, or contradicts the pattern.	The explanation contradicts previous knowledge or the reasoning is flawed.	A reasonable explanation is made. It is testable and it explains the observed pattern.

Table 4.5. Testing experiment rubric. Here, the term hypothesis stands for model/explanation/relation.

RUBRIC C: Ability to design and conduct an experiment to *test* an idea/hypothesis/explanation or mathematical relation					
Scientific ability		Missing	Inadequate	Needs improvement	Adequate
C1	**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.
C2	**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.
C4	**Is able to make a reasonable prediction based on a hypothesis**	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 based on a source unrelated to hypothesis being tested, or is completely inconsistent with hypothesis being tested, or the prediction is unrelated to the context of the designed experiment.	Prediction follows from hypothesis but is flawed because * relevant experimental assumptions are not considered and/or * prediction is incomplete or somewhat inconsistent with hypothesis and/or * prediction is somewhat inconsistent with the experiment.	A prediction is made that * follows from hypothesis, * is distinct from the hypothesis, * accurately describes the expected outcome of the designed experiment, * incorporates relevant assumptions if needed.

(*Continued*)

Table 4.5. (*Continued*)

RUBRIC C: Ability to design and conduct an experiment to *test* an idea/hypothesis/explanation or mathematical relation					
Scientific ability		Missing	Inadequate	Needs improvement	Adequate
C5	**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.	Sufficient assumptions are correctly identified, and are significant for the prediction that is made.
C6	**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.
C7	**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.
C8	**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, is consistent with the outcome of the experiment, but assumptions are not taken into account.	A judgment is made, consistent with the experimental outcome, and assumptions are taken into account.

Table 4.6. Application experiment rubric.

RUBRIC D: Ability to design and conduct an application experiment					
Scientific ability		Missing	Inadequate	Needs improvement	Adequate
D1	**Is able to identify the problem to be solved**	No mention is made of the problem to be solved.	An attempt is made to identify the problem to be solved, but it is described in a confusing manner.	The problem to be solved is described, but there are minor omissions or vague details.	The problem to be solved is clearly stated.
D2	**Is able to design a reliable experiment that solves the problem**	The experiment does not solve the problem.	The experiment attempts to solve the problem but due to the nature of the design the data will not lead to a reliable solution.	The experiment attempts to solve the problem, but due to the nature of the design, there is a moderate chance the data will not lead to a reliable solution.	The experiment solves the problem and has a high likelihood of producing data that will lead to a reliable solution.
D3	**Is able to use available equipment to make measurements**	At least one of the chosen measurements cannot be made with the available equipment.	All of the chosen measurements can be made, but no details are given about how it is done.	All of the chosen measurements can be made, but the details about how they are done are vague or incomplete.	All of the chosen measurements can be made and all details about how they are done are provided and clear.
D4	**Is able to make a judgment about the results of the experiment**	No discussion is presented about the results of the experiment.	A judgment is made about the results, but it is not reasonable or coherent.	An acceptable judgment is made about the result, but the reasoning is flawed or incomplete, uncertainties are not taken into account, or assumptions are not discussed. The result is written as a single number.	An acceptable judgment is made about the result, with clear reasoning. The effects of assumptions and experimental uncertainties are considered. The result is written as an interval.

(*Continued*)

Table 4.6. (*Continued*)

RUBRIC D: Ability to design and conduct an application experiment					
	Scientific ability	Missing	Inadequate	Needs improvement	Adequate
D5	**Is able to evaluate the results by means of an independent method**	No attempt is made to evaluate the consistency of the result using an independent method.	A second independent method is used to evaluate the results. However, there is little or no discussion about the differences in the results due to the two methods.	A second independent method is used to evaluate the results. The results of the two methods are compared correctly using experimental uncertainties. But there is little or no discussion of the possible reasons for the differences when the results are different.	A second independent method is used to evaluate the results and the evaluation is correctly done with the experimental uncertainties. The discrepancy between the results of the two methods, and possible reasons are discussed.
D7	**Is able to choose a productive mathematical procedure for solving the experimental problem**	Mathematical procedure is either missing, or the equations written down are irrelevant to the design.	A mathematical procedure is described, but is incorrect or incomplete, due to which the final answer cannot be calculated. Or units are inconsistent.	Correct and complete mathematical procedure is described but an error is made in the calculations. All units are consistent.	Mathematical procedure is fully consistent with the design. All quantities are calculated correctly with proper units. Final answer is meaningful.
D8	**Is able to identify the assumptions made in using the mathematical procedure**	No attempt is made to identify any assumptions.	An attempt is made to identify assumptions, but the assumptions are irrelevant or incorrect for the situation.	Relevant assumptions are identified, but are not significant for solving the problem.	All relevant assumptions are correctly identified.
D9	**Is able to determine specifically the way in which assumptions might affect the results**	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.

the temperature of the rock they measured the temperature of water in which the rock was submerged and waited for a certain time before recording the temperature so that the thermometer, rock and the water were in equilibrium.

3. Ability to record, represent and analyze data

Data collection and analysis are important in the practice of experimental science. These abilities are independent of the type of experiment that is being performed, and hence have been placed in a different category. We identified sub-abilities that students need for successful data collection and analysis and devised rubrics for each sub-ability. (The simplified list below is appropriate for students. Scientists do this at much more sophisticated level.):

- Ability to identify sources of experimental uncertainty.
- Ability to evaluate of how experimental uncertainties might affect data.
- Ability to minimize experimental uncertainty.
- Ability to record and represent data in a meaningful way.
- Ability to analyze data appropriately.

The rubric for each sub-ability (table 4.7) has descriptors indicating what are typical mistakes/difficulties that students have and what needs to be done for satisfactory achievement.

Over the years, we have found that a traditional approach to uncertainties prevents students from understanding the purpose of estimating the uncertainty, which also agrees with research findings (Volkwyn *et al* 2008). Therefore, we use the 'weakest link rule' where the uncertainty in the final result is determined only by the largest percent uncertainty (Good 1976). It can be the random uncertainty or the uncertainty due to the instrument with the highest percent. A handout for the students to learn about this approach can be found at https://drive.google.com/file/d/0By53x8SYAF1lLWhORU5OTnlHbHc/view.

4. Ability to evaluate

We define evaluation as making judgments about information based on specific standards and criteria (Anderson and Krathwohl 2001). More specifically, a given statement is judged by determining whether it satisfies a criterion well enough to pass a certain standard. Scientists constantly use evaluation to assess their own work and the work of others when conducting their own research, serving as referees for peer-reviewed journals, or serving on grant-review committees.

The ability to evaluate is crucial also for our students. During a physics course, students are expected to identify, correct, and learn from their mistakes with the help of an instructor. This aid may come in many forms, such as when an instructor provides problem solutions to a class, or tutoring to an individual student. However, in each case, the student relies upon an instructor (or sometimes a textbook) in order to determine whether, and how, their work is incomplete. Since the students are not given any other means with which to evaluate their work, the students come to see evaluation by external authorities as the only way for them to identify and learn from their mistakes. This dependence on external evaluation has several negative effects on students, inhibiting their learning and desire to learn (Warren 2006).

Table 4.7. Rubric for data collection and analysis.

RUBRIC G: Ability to collect and analyze experimental data					
	Scientific ability	Missing	Inadequate	Needs improvement	Adequate
G1	**Is able to identify sources of experimental uncertainty**	No attempt is made to identify experimental uncertainties.	An attempt is made to identify experimental uncertainties, but most are missing, described vaguely, or incorrect.	Most experimental uncertainties are correctly identified. But there is no distinction between random and experimental uncertainty.	All experimental uncertainties are correctly identified. There is a distinction between experimental uncertainty and random uncertainty.
G2	**Is able to evaluate specifically how identified experimental uncertainties may affect the data**	No attempt is made to evaluate experimental uncertainties.	An attempt is made to evaluate experimental uncertainties, but most are missing, described vaguely, or incorrect, only absolute uncertainties are mentioned, or the final result does not take the uncertainty into the account.	The final result does take the identified uncertainties into account, but is not correctly evaluated. The weakest link rule is not used or is used incorrectly.	The experimental uncertainty of the final result is correctly evaluated. The weakest link rule is used appropriately and the choice of the biggest source of uncertainty is justified.
G3	**Is able to describe how to minimize experimental uncertainty and actually do it**	No attempt is made to describe how to minimize experimental uncertainty and no attempt to minimize is present.	A description of how to minimize experimental uncertainty is present, but there is no attempt to actually minimize it.	An attempt is made to minimize the uncertainty in the final result is made, but the method is not the most effective.	The uncertainty is minimized in an effective way.

G4	**Is able to record and represent data in a meaningful way**	Data are either absent or incomprehensible.	Some important data are absent or incomprehensible. They are not organized in tables or the tables are not labeled properly.	All important data are present, but recorded in a way that requires some effort to comprehend. The tables are labeled but labels are confusing.	All important data are present, organized, and recorded clearly. The tables are labeled and placed in a logical order.
G5	**Is able to analyze data appropriately**	No attempt is made to analyze the data.	An attempt is made to analyze the data, but it is either seriously flawed or inappropriate.	The analysis is appropriate but it contains minor errors or omissions.	The analysis is appropriate, complete, and correct.

There are several sets of criteria and strategies that are commonly used by practicing physicists, and if we want physics students to engage in evaluation they too must value and use these strategies. Each of these strategies relies upon hypothetico-deductive reasoning (Lawson 2003), whereby the information is used to create a hypothesis, which is then tested. The logical sequence for this testing can be characterized as: if (hypothesis) and (auxiliary assumptions) then (expected result) and/but (compare actual result to expected result), therefore (conclusion) (Warren 2010). For example, when a student derives an equation and needs to evaluate it with dimensional analysis, the logical sequence is:

IF the equation is physically self-consistent,
AND I correctly remember the units for each quantity in the equation,
THEN I expect the units for each term in the equation to be identical,
AND/BUT the units for each term are/are not identical,
THEREFORE, the equation is/is not physically self-consistent.

The types of sub-abilities that students need to develop to be successful in evaluation are numerous. Some of them are:

- ability to conduct a unit analysis to test the self-consistency of an equation;
- ability to analyze a relevant limiting/special case for a given model, equation, claim;
- ability to identify the assumptions a model, equation, or claim relies upon;
- ability to make a judgment about the validity of assumptions;
- ability to use a unit analysis to correct an equation which is not self-consistent;
- ability to use a special-case analysis to correct a model, equation, or claim;
- ability to judge whether an experimental result fails to match a prediction;
- ability to evaluate the results of an experiment by means of an independent method.

Evaluation sub-abilities are integral components of multiple representation abilities, design abilities and are represented in evaluation rubrics. Not only do we want students to learn each of the evaluation strategies, we also want students to value them and incorporate evaluation into their personal learning behavior. We have developed two categories of tasks to help achieve this (see examples at https://drive.google.com/file/d/0By53x8SYAF1leWNzOWtGdjBDZW8/view). One category consists of supervisory evaluation tasks, wherein students act like a supervisor by evaluating (and, if necessary, correcting) someone else's work (usually the work of an imaginary friend). The other category consists of integrated evaluation tasks, which ask the students to evaluate, and, if necessary, to correct, their own work. For both categories of task, the evaluated work may be a problem solution, experiment design, experiment report, conceptual claim, or a proposed model. Supervisory evaluation tasks are meant to help the students learn the goals, criteria, and method of use for each evaluation strategy, while integrated evaluation tasks encourage

Table 4.8. Evaluation rubric.

	RUBRIC I: Ability to evaluate models, equations, solutions, and claims				
	Scientific ability	Missing	Inadequate	Needs some improvement	Adequate
I1	**Is able to conduct a unit analysis to test the self-consistency of an equation**	No meaningful attempt is made to identify the units of each quantity in an equation.	An attempt is made to identify the units of each quantity, but the student does not compare the units of each term to test for self-consistency of the equation.	An attempt is made to check the units of each term in the equation, but the student either misremembered a quantity's unit, and/or made an algebraic error in the analysis.	The student correctly conducts a unit analysis to test the self-consistency of the equation.
I2	**Is able to analyze a relevant special case for a given model, equation, or claim.**	No meaningful attempt is made to analyze a relevant special case.	An attempt is made to analyze a special case, but the identified special case is not relevant, or major steps are missing from the analysis (e.g. no conclusion is made).	An attempt is made to analyze a relevant special case, but the student's analysis is flawed, or the student's judgment is inconsistent with their analysis.	A relevant special case is correctly analyzed and a proper judgment is made.
I3	**Is able to identify the assumptions a model, equation, or claim relies upon. = C8**	No assumptions are correctly identified.	Some assumptions are correctly identified by student, but some of the identified assumptions are incorrect.	All of the student's identified assumptions are correct, but some important assumptions are not identified by student.	All significant assumptions are correctly identified, and no identified assumptions are incorrect.
I4	**Is able to evaluate another person's**		The student states his/her own problem solution/	The student states their own solution/claim	Student clearly states their own solution/

(*Continued*)

Table 4.8. (*Continued*)

RUBRIC I: Ability to evaluate models, equations, solutions, and claims

Scientific ability	Missing	Inadequate	Needs some improvement	Adequate
problem solution or conceptual claim by direct comparison with their own solution or conceptual understanding	No meaningful attempt is made to evaluate by direct comparison.	conceptual claim, but does not methodically compare it with the other person's solution/claim, and so does not state a judgment about the validity of the other person's solution/claim. Or a judgment is made regarding the other person's solution/claim, but no justification is given.	and compares it with the other person's solution/claim, but does not make any concluding judgment based on this comparison. Or the student does everything correctly, but their presentation is incomplete (i.e. skipping logical steps).	conceptual understanding, and methodically compares it with the other person's work. Based on this comparison, the student makes a sound judgment about the validity of the other person's work.
I5 Is able to use a unit analysis to correct an equation which is not self-consistent	No meaningful attempt is made to correct the equation, even though it failed a unit analysis.	Student proposes a corrected equation, but their proposal still does not pass a unit analysis.	Student proposes a corrected equation which passes unit analysis, but their proposal is incorrect (i.e. the student failed to remember the proper equation, and therefore proposed an equation which is not physical).	Student proposes a corrected equation which is correct, at least up to unit-less constants.

I6	**Is able to use a special-case analysis to correct a model, equation, or claim**	No meaningful attempt is made to correct the model, equation, or claim even though it failed a special-case analysis.	An attempt is made to modify the model, equation, or claim, but the modifications have nothing to do with the special-case that was analyzed.	An attempt is made to modify the model, equation, or claim based on the special-case analysis, but some mistakes are made in the modification.	The model, equation, or claim is correctly modified in accordance with the special-case that was analyzed.

Table 4.9. Communication rubric.

RUBRIC F: Ability to communicate scientific ideas					
Scientific ability		Missing	Inadequate	Needs improvement	Adequate
F1	**Is able to communicate the details of an experimental procedure clearly and completely**	Diagrams are missing and/or experimental procedure is missing or extremely vague.	Diagrams are present but unclear and/or experimental procedure is present but important details are missing. It takes a lot of effort to comprehend.	Diagrams and/or experimental procedure are present and clearly labeled but with minor omissions or vague details. The procedure takes some effort to comprehend.	Diagrams and/or experimental procedure are clear and complete. It takes no effort to comprehend.
F2	**Is able to communicate the point of the experiment clearly and completely**	No discussion of the point of the experiment is present.	The experiment and findings are discussed but vaguely. There is no reflection on the quality and importance of the findings.	The experiment and findings are communicated but the reflection on their importance and quality is not present.	The experiment and findings are discussed clearly. There is deep reflection on the quality and importance of the findings.

students to incorporate evaluation into their learning behavior. During a semester, we tend to use mostly supervisory tasks for the first few weeks so that the students can get acquainted with each strategy, and then transition to integrated tasks so that they gain experience at using the strategies to evaluate and correct their own work. Evaluation rubric is shown in table 4.8.

7. Ability to communicate

An important ability in the work of scientists is their oral and written communication, an ability that can be fostered in a physics course. For example, the quality of a lab report can be judged for its completeness and clarity. A communication ability rubric can help students know what is expected in communications in the scientific world. The communication rubric is shown in table 4.9.

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Chapter 5

Assessment

In this section, we will discuss assessment in ISLE. Since the focus of ISLE is on *doing* physics, assessment in ISLE needs to be able to (a) assess the process of doing physics, and (b) provide students with opportunities for improvement. Point (a) is self-evident if we accept the idea that learning goals and assessment should be aligned with each other (Wiggins and McTighe 2005). Point (b) is aligned with the concept of formative assessment. Formative assessment happens when the instructor uses assessment during the learning process to provide students with feedback and a pathway to improvement, while simultaneously using students' successes or failures to adjust instruction (Black *et al* 2003). Black and Wiliam (1998a) showed that the learning gains from systematic attention to formative assessment, particularly self-assessment, are larger than gains found for most other educational interventions. It is also important to understand that a scientific community relies almost completely on formative assessment and formative self-assessment to function successfully and thus the concept is a natural fit with ISLE. To make assessment more process-oriented and more formative, we have made the following changes to how we assess students in ISLE:

1. **We changed types of questions and problems** we ask and the way we ask them. Our logic is simple: if we want students to develop and improve certain scientific abilities, we need to ask questions that directly engage those scientific abilities, thereby aligning goals with assessment. Consider the following examples (they are based on the content discussed in chapter 2).

***Example* 1:** In a scenario of a book resting on top of a level table, Saalih claims that the force exerted by Earth on the book and the force exerted by the table on the book are the forces representing Newton's third law pair. Look, he says, these forces are the same in magnitude and opposite in direction, just like Newton's third law says! Explain (in terms of physics you understand) why Saalih is not correct. Draw appropriate force diagrams to support your argument. Explain which Newton's law

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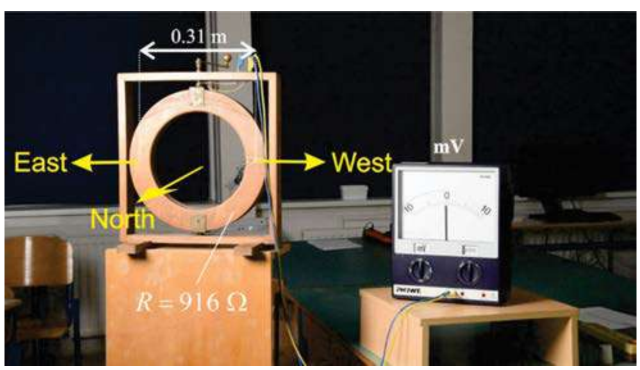
accounts for the above forces being the same in magnitude and opposite in direction in this case.

Rubric item	Criteria for adequate performance
I4 Is able to evaluate another person's problem solution or conceptual claim by direct comparison with their own solution or conceptual understanding	Student clearly states their own conceptual understanding, and methodically compares it with the other person's claim. Based on this comparison, the student makes a sound judgment about the validity of the other person's claim.
A3 Is able to evaluate the consistency of different representations and modify them when necessary	Two or more representations are constructed according to accepted standards learned in class, and the representations are consistent with each other.

***Example* 2:** You have a large coil with 1500 turns of copper wire and a voltmeter that can measure potential difference between −10 mV and 10 mV. The average diameter of the coil is 0.31 m and the resistance of the coil is 916 Ω. The coil is mounted in the wooden frame so that it can rotate around the axis that coincides with the coil diameter. The video https://mediaplayer.pearsoncmg.com/assets/_frames.true/sci-phys-egv2e-alg-21-5-14 shows two experiments. In both experiments, the voltmeter is connected to the coil ends. The experiments were performed on the Northern hemisphere. The photo below shows the initial orientation of the coil (the normal to the plane of the coil points towards the geographical North).



a. Watch the video and, collaborating with your group-mates, propose a qualitative explanation for the outcome of both experiments. Make sure your group's explanation accounts for all changes in the magnitude and in the sign of the voltmeter reading.

You can treat the voltmeter as a device that measures potential difference across its own internal resistor, which has a very large resistance (several megaohms). If you connect such a voltmeter across the coil as shown above and an induced emf appears in the coil, then the voltage measured by the voltmeter is equal to the induced emf in the coil.

b. Make a list of physical quantities that you can estimate based on data given above and analyzing the video. The video was recorded at 30 frames per second. (*Note*: for a vector quantity, you can estimate its magnitude, direction or both.) Estimate two of them.

Below, we show student work for example 1 and in figure 5.1 you can see some of the feedback from the instructor:

2. **We have created assessment tools that focus on the evaluation of 'scientific abilities.'** While these rubrics were originally developed for students to use in labs to guide and assess their experimental investigations, we have re-purposed the same rubrics for homework and exam questions as we showed in the example above. Another example is shown below (figure 5.2). Notice that this instructor uses the rubric to give the scores P (pass) and F (fail). The students need to receive all Ps on the exam to pass. They have multiple opportunities to achieve this goal.

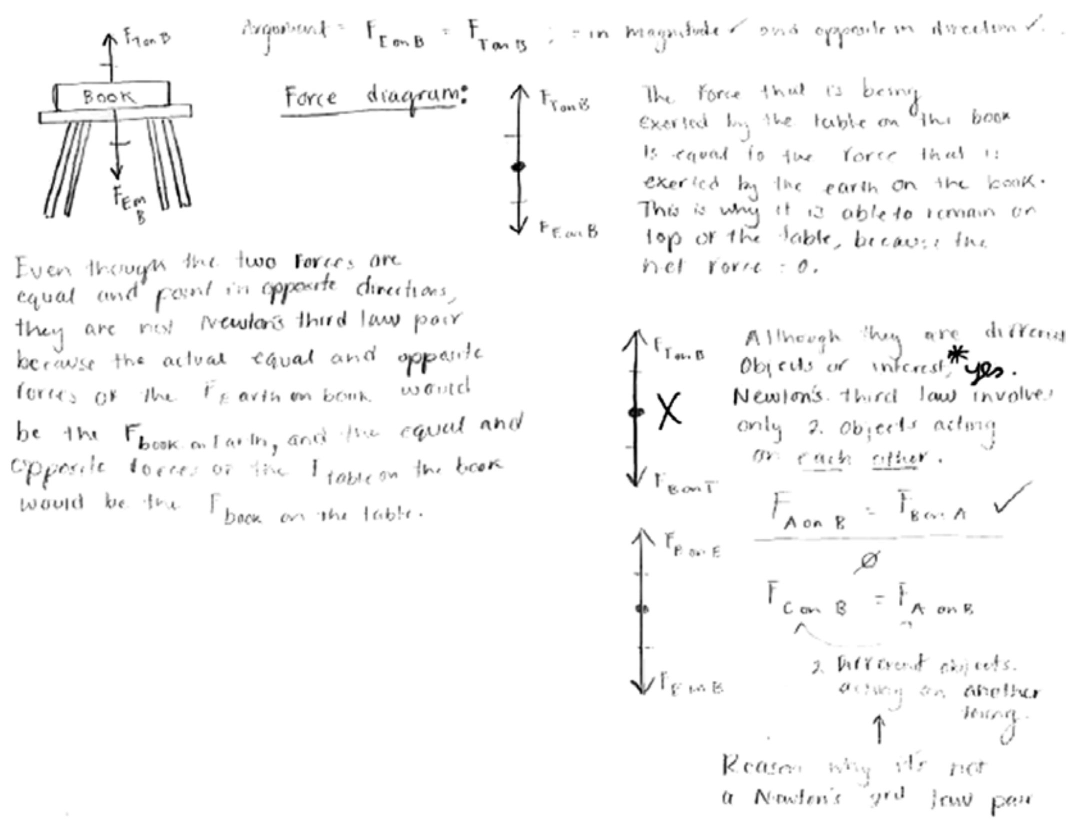
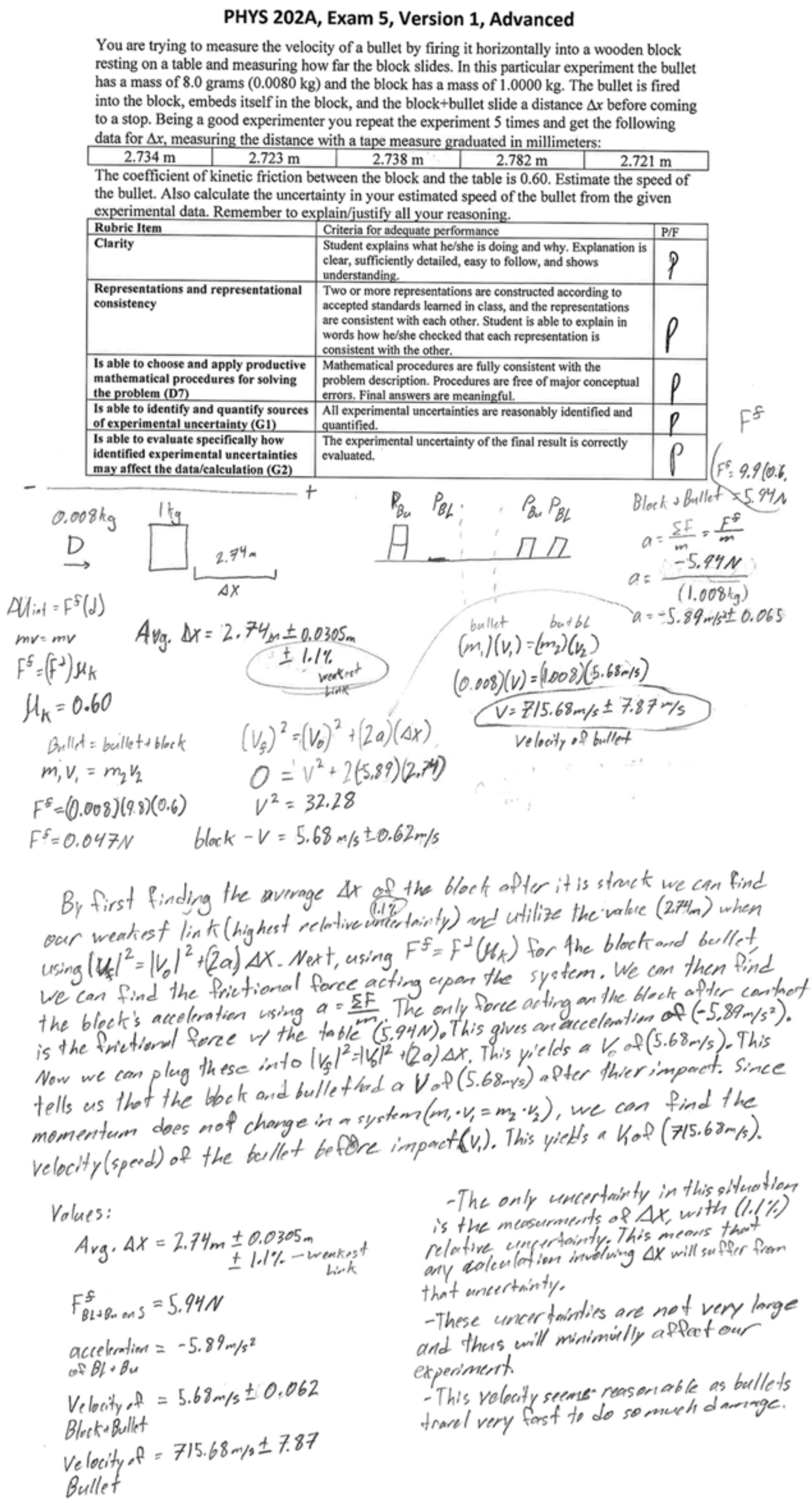


Figure 5.1. Example of student work on Newton's third law.



PHYS 202A, Exam 5, Version 1, Advanced

You are trying to measure the velocity of a bullet by firing it horizontally into a wooden block resting on a table and measuring how far the block slides. In this particular experiment the bullet has a mass of 8.0 grams (0.0080 kg) and the block has a mass of 1.0000 kg. The bullet is fired into the block, embeds itself in the block, and the block+bullet slide a distance Δx before coming to a stop. Being a good experimenter you repeat the experiment 5 times and get the following data for Δx, measuring the distance with a tape measure graduated in millimeters:

2.734 m	2.723 m	2.738 m	2.782 m	2.721 m

The coefficient of kinetic friction between the block and the table is 0.60. Estimate the speed of the bullet. Also calculate the uncertainty in your estimated speed of the bullet from the given experimental data. Remember to explain/justify all your reasoning.

Rubric Item	Criteria for adequate performance	P/F
Clarity	Student explains what he/she is doing and why. Explanation is clear, sufficiently detailed, easy to follow, and shows understanding.	P
Representations and representational consistency	Two or more representations are constructed according to accepted standards learned in class, and the representations are consistent with each other. Student is able to explain in words how he/she checked that each representation is consistent with the other.	P
Is able to choose and apply productive mathematical procedures for solving the problem (D7)	Mathematical procedures are fully consistent with the problem description. Procedures are free of major conceptual errors. Final answers are meaningful.	P
Is able to identify and quantify sources of experimental uncertainty (G1)	All experimental uncertainties are reasonably identified and quantified.	P
Is able to evaluate specifically how identified experimental uncertainties may affect the data/calculation (G2)	The experimental uncertainty of the final result is correctly evaluated.	P

Figure 5.2. Student work and criteria for performance.

3. **We allow multiple improvements.** We use the scientific abilities rubrics and the feedback that they provide to allow multiple attempts or opportunities for improvement in contexts such as lab, homework and exams. In figure 5.3, we show an example of the work of a student who attempted an exam question based on a particularly challenging cluster of scientific abilities centered

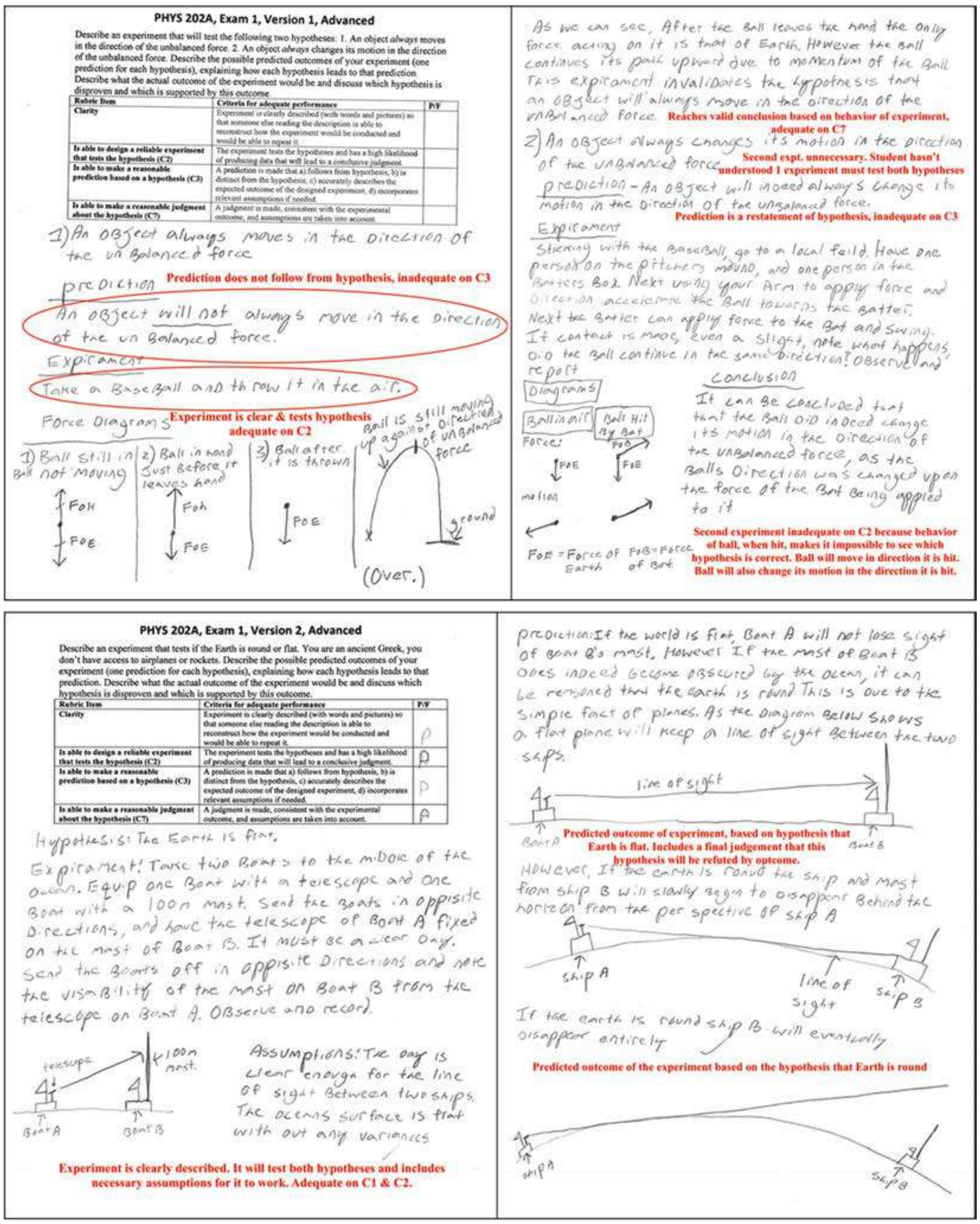


Figure 5.3. Revisions and improvement. The first panel is the first attempt, and the second panel is the second attempt. The question is different but the scientific abilities assessed are the same.

around design of a testing experiment and hypothetico-deductive reasoning. In this example, you can see in the first attempt the student had a clear difficulty on rubric item C3: 'Is able to make a reasonable prediction based on a hypothesis.' In the right column, you can see the same student making a second attempt at the same cluster of scientific abilities. This time the context is new (design an experiment to test whether Earth is round or flat), but the structure of the question is the same, namely design an experiment that will test two competing hypotheses, and requires that the student engage the same scientific abilities. In this case, the student clearly has learned from their failure the first time around and is able to make two predicted outcomes for the one experiment, one prediction for each hypothesis being tested.

4. **Evaluating student performance can be achieved in different ways**. You could score each scientific ability above on a 0, 1, 2, 3 scale where 0 = 'missing,' 1 = 'inadequate,' 2 = 'needs improvement,' and 3 = 'adequate.' A simpler 0, 1 scale could be implemented with 0 = 'inadequate' and 1 = 'adequate.' Students' grades in ISLE courses should be based on a point accumulating system. Results of the exams are not curved. Students' success should depend only on their personal effort and not on the success or failure of other students (Brahmia and Etkina 2001).

5.1 Interlude: experiments with assessment

In this interlude, I will focus on my transformation in relationship to giving grades and assessing students. Why do we give students homework and exams and then assign grades that determine whether they pass or fail the course? To pass judgment? To rank them? To filter out the weak and unworthy? To maintain standards? To reward and punish? To motivate students to work harder? What if we didn't give students grades at all? Would they even bother to show up for class? Ask a teacher if they would be willing to give up assigning grades on their students' work and you will very likely hear something along the lines of, 'I'd love to, but I can't because…' Ask the same teacher how they feel about grading and you will get variations of the same answer: it is boring, a chore, drudgery, and a pain. This is not to say that there doesn't exist a teacher who loves grading, I just have not met this singularly strange person yet. Now ask the teacher under interrogative circumstances why they dislike grading so much and here is where the agreement ends. But we will return to this later. Suffice to say that most teachers see grades and grading as an indispensable part of the teaching activity, and yet it is almost universally disliked.

What is grading like in physics? First of all, let me explain how easy it is to grade a physics student's work. (Chemistry and mathematics teachers may share a similar experience.) Let's say I give students a problem; for example, find the acceleration of some object rolling down a ramp. Then they come up with a number. This number is either correct or incorrect. I think give students full points or zero accordingly, end of story. Many physics teachers (myself included) feel slightly disturbed by this simplistic approach. In short, we feel sorry for our students. For example, did Joanna get the answer wrong because she didn't hit the right buttons on her calculator? Or did she get it wrong because of a fundamental gap in her understanding of the physics? We'd like to reward understanding, and not punish poor calculator operational skills. Years ago, when I was grading a student like Joanna's paper and found a wrong answer, I would then go back through her calculations searching for any signs or evidence that she understood what she was doing. Being an empathetic sort of person, I persisted with this style of grading for many years. I persisted in spite of some evidence that there was no substantially measurable difference in students' grades between just grading the answer and taking extra time to look through students' work to give them partial credit for understanding (Scott *et al* 2006). To me, it seemed immoral or unethical to not even try.

Looking back on this now, it is hard to describe the quixotic futility of searching for understanding by looking through Joanna's hastily scribbled calculations. To an English teacher, the hopelessness of this approach is probably obvious. But most physics instructors persist with this approach even to the present day. Needless to say, grading this way can be a real chore. Any physics teacher will attest that most students leave a trail of barely intelligible calculations on their page *if you are lucky.* In most cases, it is impossible to discern a logical chain of mathematical reasoning that could be considered (reasonably or not) to serve as a proxy for physical understanding. As I said, I persisted with this approach for a long time; far longer than I should have considering all the other conceptual transformations that had already occurred with regards to my approach to teaching and learning.

For me, implementing assessment in ISLE has been the most difficult challenge of all. The scientific abilities rubrics described in chapter 4 were originally developed for helping students self-assess themselves and improve 'on the fly' and the instructors to provide feedback and grades in the labs. They satisfy the cornerstones of formative assessment that are integral to the ISLE process: they lay out clear criteria for adequate performance on various scientific reasoning abilities. Thus, they can give students guidance on where they are going and whether they have achieved their goal yet. The rubrics directly assess the reasoning *process* rather than the end result, and they can be used to give students multiple opportunities for improvement. The problem for me was: how do I align the more restrictive exam environment, with the ISLE philosophy? In other words, how can I examine students' ability to think and reason like physicists in the context of what Bransford and Schwartz (1999) aptly named 'sequestered problem solving?' How can I give students multiple opportunities to improve without becoming swamped by the grading load?

I avoided these questions for several years until 2009, when one of my students said to me something like, 'so this weekend, I am going to take an exam for my Aikido blue belt. There's a pretty good chance that I won't get it, that I will mess up some of the more difficult sequences that I have to perform. But that's okay. I can try again in three months. Why can't assessment in our physics class be like that?' There were two key features to what he was talking about. (a) He would get a second chance, something that Professor Etkina had been inculcating into me from the very beginning, but importantly, (b) he was talking about performance assessment. This notion has been discussed in various venues. (Remember Yung Tae Kim's TED talk that I mentioned in the Interlude in chapter 3.) I'd like to say I suddenly changed everything I was doing, but I didn't. Rethinking how we assess students is hard. However, his words did plant a seed that slowly grew over the next 6–8 years.

The challenge in explaining this change is that it is not just a change in my view of assessment; it happened in conjunction with a change in my view of what learning is and the two cannot be separated. I described this dichotomy between school learning and real-life learning in detail in the chapter 3 Interlude. In school learning, you get one try (on an exam) and whether you pass or fail, the class moves on to the next topic. Many instructors recognize how disastrous this is. I see a lot of teachers try to counter-act this problem by allowing their students second tries, but students can only get partial credit. This entirely defeats the purpose of the second try because the students are *still* being punished for not getting it right the first time. This is antithetical to real-life learning.

My overarching question became: if the learning process in my physics classroom environment looks more like learning to skateboard, how can I make my assessment more aligned with how one might assess the skateboarder's ability to perform a trick? In order to make physics more like skateboarding, assessment needs to be (a) formative (Black and Wiliam 1998a) and (b) performance-based. Feedback needs to be built into the assessment process and students need multiple opportunities to improve and learn from their mistakes. We need to assess performance as a *whole* and know what are the key components of performance in a given situation.

If that is a lot to take in, I agree. I am going to share with you a work-in-progress that I am still in the process of modifying. This represents the refinement of multiple years reading theoretical models of assessment and trying to implement them practically through a process of trial and error. And it is still highly flawed—I will discuss the flaws and possible ways forward to improvement at the end.

Let me show you a small piece of what I've been doing and thinking about. Over a few years, we have developed and refined a 'problem-solving' rubric. I want to acknowledge the intellectual contribution of Yuhfen Lin to this rubric. Analogous to the way the scientific abilities rubrics identify the key sub-abilities that go into (for example) designing and executing a testing experiment, we identified four key elements that are common to solving any problem in physics, be it a closed-ended back-of-chapter problem or an open-ended real-life estimation problem with multiple possible answers. The elements are:

1. Students need to use multiple representational tools (a diagram with a coordinate system, a force diagram, a velocity versus time graph, etc) and translate consistently between those different representations. To solve a problem, students have to start by decoding a problem statement (a verbal representation) and turn it into a picture. They might then translate that into an intermediate representation like a force diagram or an energy bar chart. Then they translate that into some sort of equation (a mathematical representation) in order to solve the problem. Major failures can occur if they don't translate consistently between representations. For example, if they define their coordinate system in a particular way, they need to translate to mathematics in a way that is consistent with their chosen coordinate

system. This is in effect a combination of items from scientific abilities rubric A in chapter 4.

2. Students need to decide on an appropriate physical model with appropriate simplifications and assumptions. For example, if they analyze an inelastic collision with an energy approach, ignoring the mechanical energy that turns into internal energy during the collision, they have made an inappropriate simplification that will lead to an inaccurate answer. This is equivalent to rubric item D7 from the application experiment rubric in chapter 4.
3. Students need to evaluate whether a result is reasonable or not. In a real problem-solving process, students may have one or more false starts, so evaluation needs to happen multiple times. This is a combination of items from rubric I in chapter 4.
4. Students need to be able to verbally explain their reasoning, justifying *why* their approach is reasonable, *how* they've translated consistently between representations, *why* they chose a particular model, *what* are the key assumptions that are being made, etc.

This last point is probably the most difficult for both students and teachers to understand, but it is the most important aspect of problem-solving performance. From a performance perspective, I am constantly thinking: 'what *evidence* could a student provide to me that would convince me they actually understand what they are doing rather than blindly grabbing equations from their equation sheet?' Here is how I think about performance assessment in the context of solving a physics problem: students need to provide me with evidence that they are competent: (1) are they competent implementing various representational techniques of physics? (2) Do they competently understand the applicability and limitations of various physical models that they are using? (3) Do they recognize that physics is about describing the real-world and so can recognize when a result is not physically reasonable and re-evaluate their approach and/or assumptions? (4) Students need to be able to verbally communicate points 1–3 in a way that demonstrates understanding.

For example, I'd like students to be able to articulate that, 'I know I can use the kinematics equation $x(t) = x_0 + v_0t + \frac{1}{2}at^2$ because I'm assuming the acceleration of the car is constant over the interval I'm analyzing.'

Or imagine the following scenario: two students solve a ballistic pendulum problem using an energy approach and skipping over using a momentum approach to analyze the collision. One of the students does not explain their reasoning, but the second student writes something like

> 'I assumed that the mechanical energy of the system remained the same throughout the process. I know that some mechanical energy turns into internal energy during the collision, so the pendulum should not go as high as I calculated, but I don't know how else to analyze the problem.'

The second student has, to my mind, demonstrated that they are thinking like a physicist and are using the habits of mind I want them to develop in my physics class. The first has not. The first student may have thought this too, but there is no verbal evidence on the paper. I do not know whether they thought deeply about the problem or simply grabbed an equation from their equation sheet, hoping for the best. Because this verbal explanation of reasoning is so important, we place it as the first item on the problem-solving rubric shown below:

Rubric item	Criteria for adequate performance
Clarity	Student explains what they are doing and why. Explanation is clear, sufficiently detailed, easy to follow, and shows understanding.
Representations and representational consistency	Two or more representations are constructed according to accepted standards learned in class, and the representations are consistent with each other. Student is able to explain in words how they checked that each representation is consistent with the other.
Is able to choose and apply productive mathematical procedures for solving the problem.	Mathematical procedures are fully consistent with the problem description. Procedures are free of major conceptual errors. Final answers are meaningful.
Is able to evaluate the reasonableness of a result.	Evaluates reasonableness of a solution by correctly applying the steps of any accepted evaluation method (listed in the evaluation document).

How do we grade using this rubric? As you can see, I left the last column blank. That is because there are various ways that I have tried to grade student's work using this rubric. There was a time when I graded each rubric item on a 0–2 scale with 0 meaning 'missing or inadequate,' 1 = 'needs improvement,' and 2 = 'adequate.' I was comfortable with that, although now, with hindsight, it was *still* a tortuous process to grade. At some point, I changed to a 0 or 1 scoring system to make things easier and spend less time struggling to make sense of students' work. Then a colleague introduced me to a book entitled 'Specifications Grading' by Linda Nilson (Nilson 2015). Her idea of 'no more partial credit' and specifying criteria for adequate performance aligned perfectly with my growing ideas about performance assessment. In her book, she advocates for grading using a pass/fail system where the criteria for a passing performance are made clear to students by means of a rubric. Applied to the rubric above, students have to pass all four rubric items to pass the question. This last approach changed everything for me because I didn't need to search for understanding anymore. Either you convince me you know what you're doing, or you don't. I was finally free of agonizing over partial credit and simultaneously able to judge students' performance in a holistic way.

The first time I tried this approach it was a disaster. Using this approach on exams, I gave students opportunities to try another (similar) problem during another exam period if they failed a problem the first time. However, students were failing everything over and over again and soon the class was in open rebellion. What I came to realize is that I needed to do more than offer students multiple opportunities to demonstrate competent performance; I needed a separate bar for students who I felt had demonstrated a *sufficient* level of competence even if I didn't feel comfortable passing them. The example of the two students solving a ballistic pendulum problem using an energy approach illustrates this distinction very well. If you recall, the second student was able to explain their reasoning, but didn't use momentum to analyze the collision in a ballistic pendulum problem. What I do now for student 2 is that I do not pass them, but I write 'see me' on that student's paper. That student can come to me in office hours and fix the problem with a written explanation that shows they understood what they missed, how they fixed their answer, and why their answer is now correct. In contrast, the first student who used energy and didn't explain their reasoning has failed *both* the 'clarity' item *and* the 'productive mathematical procedures' item and would be required to redo a similar problem from scratch in another exam period.

How do I make sure I fulfill my institution's requirements that I assign students letter grades? Again, I have tried different methods. At first, I set different bars for A, B, and C by requiring that students pass a certain number of exam and homework questions to get an A, B, C, and so on. This became incredibly hard to keep track of in a large class of 120 students, so I have now settled on a simpler approach: for exams, I define two question levels: 'core' and 'advanced.' If a student passes a core question, they get four points and if they pass an advanced question, they get nine points. Letter grades are defined by how many points students accumulate during the semester. For example, this past semester, if a student passed every single aspect of the class, he/she could get 183 points. I defined an A as 164 points or higher. What this *does* mean is that students can stop coming to class, handing in homework or taking exams when they achieve the letter grade that they want. Last semester a C was 116 points, and students could stop once they achieved that, if they wanted to.

Below, I summarize three aspects of my new approach to exam writing.

1. *Designing exam questions:* Every time I write an exam question, I ask myself: 'what cluster of scientific abilities do my students need to coordinate to provide competent performance?' This allows me to ask questions in ways I'd never have asked them before. For example, I can create questions that assess scientific habits of mind students have been developing in their lab meetings. I can adapt rubric items from the scientific abilities rubrics as needed (Etkina *et al* 2006)! For example:

   After you take a flight from San Francisco to Boston you decide to estimate how fast the airplane flew. You Google the straight-line distance between San Francisco and Boston and see it is 2696 miles. Because you weren't paying careful attention at the time you flew, you estimate the flight took somewhere between 5 and 6 h. Make *reasonable* estimates of the uncertainties in the distance and time quantities. What was the average speed of the airplane? Determine the absolute uncertainty in the speed that you calculated.

Rubric item	Criteria for adequate performance
Clarity	Student explains what he/she is doing and why. Explanation is clear, sufficiently detailed, easy to follow, and shows understanding.
Is able to choose and apply productive mathematical procedures for solving the problem	Mathematical procedure is fully consistent with the problem description. Procedure is free of major conceptual errors. Final answer is meaningful.
Is able to identify and quantify sources of experimental uncertainty	All experimental uncertainties are reasonably identified and quantified.
Is able to evaluate specifically how identified experimental uncertainties may affect the data/calculation	The experimental uncertainty of the final result is correctly evaluated using the weakest link rule.

2. *Creating questions for different levels of mastery:* In the old way of doing things, I would often approach exam question writing by creating an exam question that 'an A student would be able to solve' and give partial credit to students who were unable to completely solve the problem. By creating a pass/fail system (with rubrics for every question) and defining different levels of question (core and advanced), it forced me to ask myself, 'what is my bottom line? What question(s) can I ask that allow students to display a basic level of competence in doing physics, without which, I don't feel comfortable letting them pass my class?' Versus, 'what kind of question would allow students to display a level of competence that I would feel honored to award them an A?' Thus, the example above would be an example of a core level question in which students are asked to do an almost trivial calculation, but *also* demonstrate that they can estimate and propagate uncertainties through a simple calculation. On the other hand, an advanced level question can involve more complexity and depth and open-endedness. Adequate performance on the following question means 'I'm really impressed with what you've been able to learn—I want to give you an A.' The grade boundaries are set in such a way that a student can get a C by *only* passing core questions.

   (Advanced question) Describe the steps you would take to measure the mass of a smartie (a very small, light candy) using only a meter stick, whiteboard marker as pivot, play-dough to secure the marker and a 10 g reference object. Clearly describe the steps of your experiment (a diagram could help), what you would measure and how you'd use those measurements to estimate the mass of the smartie (provide a sample calculation). Think carefully about and describe how you'd design your experiment to minimize experimental uncertainties. Also, discuss important assumptions you might need to make and/or how you'd minimize unnecessary assumptions. Remember (for example) that you meter stick may not be perfectly uniform.

Rubric item	Criteria for adequate performance
Is able to communicate the details of an experimental procedure clearly and completely	Diagrams and/or experimental procedure are clear and complete. It takes no effort to comprehend.
Is able to design a reliable experiment that solves the problem	The experiment solves the problem and has a high likelihood of producing data that will lead to a reliable solution.
Is able to choose and apply productive mathematical procedures for solving the problem	Mathematical procedure is fully consistent with the problem description. Procedure is free of major conceptual errors and will lead to a meaningful final answer.
Is able to identify the assumptions made in using the mathematical procedure	Sufficient *relevant* assumptions are *correctly* identified.

3. *Assigning grades:* I feel so much more comfortable with the way I'm grading. By asking students to provide evidence of a competent performance, I'm no longer desperately searching students' work, looking for ways to give partial credit, trying to make inferences about their reasoning process. It was such an intellectually draining approach to grading and I am happy to be free of it. Grading is still a chore, but it is a chore I no longer dread. I feel more comfortable with what I am asking of my students. Not every student in my class needs, wants, or has time to get an A. At the same time, every student can get an A if they want. Students don't have to maintain an average and their grade is not being judged relative to others' grades. I am able to set high expectations that are achievable. By achieving a certain number of points, they 'level up' like a computer game.

   In conclusion, is it working? I would say partly yes, partly not. Here is the biggest problem I'm still struggling to figure out: some students are good learners. I can see that because they take their failed exam, come to office hours, figure out what they did wrong and why and when they make a second attempt, they generally pass the second time because they've gone through this reflective process. There are, however, a large number of students that I am guessing don't fully understand how to learn from failure. At least, not in the school context. Presumably most of their life in most of their academic classes they have simply set aside an exam and seldom looked at it again. I observe that when they make their second attempt, they often make the *exact same* mistakes or display the same misunderstandings as the first time around. Or they seem to have memorized the solution to the first version and reproduce the same solution on the second attempt. This doesn't work because although the second attempt involves the same rubric items and the same competencies, I generally try to change the circumstances of the question enough so that the same ideas need to be adapted to the new context.

In future semesters, I am planning to make the scaffolding for students more explicit: I plan to require students who failed a question 'apply' to take their second attempt by (a) creating a perfect solution to the first attempt, and (b) creating a written explanation of what they didn't understand and what they learned from reflecting on their failed attempt and re-working it. I might even incentivize it by offering one point for the re-work of the first attempt and an additional three points for passing the second attempt. Other ISLE implementers are already using some variant of this idea with excellent results. Anyway, those are my thoughts at the moment as I continue this multi-year experiment with assessment. This is a journey that is not yet over.

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Chapter 6

How ISLE affects teachers and researchers

Over the years, we have used the ISLE approach in multiple courses. We have accumulated a vast amount of data to support the hypothesis that ISLE students not only learn normative physics concepts but also learn to think like scientists. They demonstrate high learning gains on standardized physics conceptual tests, on traditional problems (see Etkina and Van Heuvelen 2007, Etkina 2015) and, in addition, they show that they spontaneously use multiple representations when solving problems (Rosengrant *et al* 2009) and designing their own experiments (Etkina *et al* 2010). They also learn to design experiments and analyze data (Etkina *et al* 2008, Etkina *et al* 2010) and spontaneously engage in sense-making while doing this (Etkina *et al* 2010). Even high school students learn to identify and validate their assumptions (Bugge and Etkina 2016). We have also implemented the ISLE approach in courses and programs for future physics teachers; the reader can learn about those in Etkina (2010) and Etkina (2015b). In this chapter, we present reflections of different educators who learned about ISLE and apply this knowledge in different contexts.

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From my experience, the educational approach embedded in ISLE has been influential on teachers in disciplines outside of physics. I have been working to integrate many of ISLE's techniques into my own teaching and into my own research work. In my recent book on disability, I have argued that ISLE provides an example of an inclusive learning approach for students with disabilities (Maybee 2019). Unlike a non-constructivist approach to teaching, or what D Kim Reid and Jan W Valle have called '"transmission-infused" instruction' (Reid and Valle 2005, p 156)—which, Reid and Valle suggest, constructs students as less capable learners —ISLE's emphasis on 'active engagement, group work, authentic problem solving,

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and reconciling students' original ideas with conventional ideas' (Etkina 2015, p 673) constructs all students as valuable contributors to a vibrant classroom community and as capable learners, and so fosters inclusion.

But I also think that ISLE's approach has additional components that make it even more inclusive. ISLE's emphasis on creating a 'mistake rich' environment (Etkina 2015, p 674) in which students are encouraged 'to think like physicists' (Etkina 2015, p 670) and come up with their own theories and experiments before reading the textbook means that it provides precisely the kind of contextualized, cooperative, and student-initiated instruction that, according to Reid and Valle, is more effective for and elicits an enhanced response from disabled students (Reid and Valle 2005, p 159). Since ISLE requires students to use a variety of tools to analyze the patterns and data they develop—tables, graphs, and different sorts of charts and diagrams, in addition to mathematics—and to become aware of *how* they came to know the things they know, or *why* they know what they know (Etkina 2015, p 674), it also satisfies two of the core principles—'[e]quitable use' and '[f]lexibility of use'—of universal design for learning (UDL), which is a set of guidelines intended to help create learning environments that are accessible to all students. Valle and David J Connor explain the principle of 'equitable use' as the principle that instruction must be 'designed to be useful and accessible to people with diverse abilities' (Valle and Connor 2011, p 77); 'flexible use' is the principle that instruction must be designed in a way that 'accommodates a broad array of individual abilities and preferences' (Valle and Connor 2011, p 78). Because ISLE requires students to use a variety of tools to build and analyze information and to read the textbook only after developing ideas in class, it provides opportunities for students with different strengths, abilities and preferences to actively participate in developing knowledge.

I argue that one of the '*habits of mind and practice*' that Etkina and her colleagues have encouraged ISLE practitioners to develop also creates an inclusive learning environment (Maybee 2019). Etkina and her colleagues encourage ISLE instructors to develop the habit of '[t]reating all students as capable of learning physics and contributing to the generation of physics knowledge (as opposed to treating learning physics as a weed-out competition)' (Etkina *et al* 2017). I hope that this habit will help teachers avoid the kind of 'deficit thinking' that, according to Valle and Connor, constructs 'disabled' students as less capable learners (Valle and Connor 2011, p 69). Moreover, I think that treating all students as capable of learning physics and of contributing to the advancement of knowledge in the classroom will reduce the possibility that some students will develop what scholars call a 'fixed' mindset,' or the belief that they do not have the capacity to learn something—a belief that can undercut their motivation to learn that topic (Ormrod *et al* 2017, pp 386–7)—and so will further help ISLE-based teachers reach a wider variety of students. I used ISLE's emphasis on creating an inclusive learning environment for all students to bring many of its strategies and habits of mind to courses in my own disciplines.

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Pre-service physics teachers at Uppsala University who take their physics teaching coursework with me at the Department of Physics and Astronomy first encounter ISLE by engaging in the 'light-cone' activity (Etkina *et al* 2013). First, they experience the whole cycle in the classroom, and as a follow up activity, read about the framework in Eugenia's 2014 Millikan lecture paper (Etkina 2015). They then read the first three chapters of James E Zull's book *The Art of Changing the Brain* (Zull 2002) and produce an essay that relates ISLE to pedagogical theory (Kolb's learning cycle) and neurophysiological aspects of learning. ISLE allows us to bring together perspectives of general pedagogy, neuroscience, and physics learning in a unique and compelling way, tying together topics that pre-service teachers have only encountered separately during the course of their university education. Judging by their feedback, establishing these links typically results in great appreciation of ISLE as an instructional framework.

From a physics teacher's point of view, one of the most tangible and practical contributions of ISLE that I see is a nuanced perspective on the different roles of experiments (observational, testing and application experiments). In my experience, giving pre-service teachers the tools and language to think and talk about the possible roles of experiments invigorates their appreciation of science as a process, allows them to better interpret historical events in science, and paves the ground for their productive and meaningful use of experiments in their own classrooms.

Furthermore, doing ISLE in courses for pre-service physics teachers sets the stage for the discussion of the relationship between affect and learning. One theme that I typically encounter in pre-service teachers' reflective essays is an appreciation of calling hypotheses 'crazy ideas', thereby reducing the burden on the student to have 'correct' ideas straight-away. Starting a lesson by giving students an opportunity to observe and describe physical phenomena, and formulate testable explanations is much more emancipatory and encouraging for students than starting the lesson with an activity that elicits 'wrong' predictions and forces students into 'cognitive conflict'.

Finally, when asked to do so, pre-service physics teachers can come up with truly inspiring and creative ideas for new ISLE-style learning sequences—an indication that they can and willingly get behind the philosophy and see its practical significance for teaching.

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In my journey as a physics professor and as past Associate Director of Science Education at an Ivy League university, I aim to empower diverse demographics to wield science with compassion. My colleagues and I in the Applied Improvisation Network (AIN) and Cultivating Ensembles in STEM Education and Research (CESTEMER) have found theater improvisation (improv) to be a useful tool in science education and communication, as improv offers a laboratory for human compassion and science is done by humans. We find that ISLE is inherently valuable to applied improvisation and vice versa. The ISLE cycle provides a framework for an iterative process to design learning experiences (workshops or classes) in science, applied improv, or professional development. In all these areas, we aim to perceive reality better and to develop better and better models of reality. The fruits of this feedback cycle are the benefits of the scientific method. As we uncover our assumptions and biases, creatively brainstorm new models, test them out and evaluate our results, we achieve better results. There is no single or fixed source of authority, no perfect model, no definitive right answer. The process is inherently collaborative, allowing better models to emerge in ways that no individual may have anticipated. Read more at http://newsletter.oapt.ca/files/Improv-PHYS-ation.html#unique-entry-id-314.

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I started my career as an experimental particle physicist rather than a physics education researcher, so I was not exposed to the ISLE framework in a professional sense until quite recently when I happened to see Eugenia's Millikan Medal lecture at the 2014 AAPT meeting in Minneapolis (Etkina 2015). Her presentation hit me like a ton of bricks and almost immediately the solution to a difficult problem I had been wrestling with became crystal clear.

At the time, we were struggling with ways of improving the lab component of our introductory physics sequences, taken by over 3500 students per semester. We have developed an educational technology called IOLab[1] that can put a wireless measurement system with over a dozen sensors in the hands of every student for use both outside and inside the classroom, but we didn't have a coherent pedagogical framework that would let us exploit this technology to elevate the student experience beyond traditional 'concept verification' labs.

Hearing Eugenia explain the origin, philosophy, and research behind the ISLE framework on that fateful summer day changed everything. Her simple yet indisputable assertion that 'learning within a discipline should resemble the practice of that discipline' made it quite clear that our traditional labs were using the wrong approach in presenting students with step by step 'recipe' style activities to reinforce the concepts they learned in lecture. Indeed—the central focus of labs should not be physics concepts at all, but rather the acquisition of broad scientific skills that will enable our students to become critical thinkers and problem solvers in whatever discipline they pursue after graduation. We don't need more people that can draw free body diagrams—we need more people that can come up with ideas to explain things they don't understand; that can design an experiment to test a hypothesis; that can interpret data to arrive at a result; that can estimate the uncertainty on a result and think of ways to make this smaller; that can question assumptions; and that can clearly communicate their ideas and designs and results and conclusions with others. In other words, I realized that we needed to let the design of our lab reform be guided by the ISLE framework.

[1] See www.iolab.science for details.

With Eugenia's advice and the hard work of an amazing graduate student, we piloted our ISLE + IOLab based approach to introductory labs with one lab section in the fall of 2015. After several semesters of research and development, we recently rolled out the new approach for all students in our algebra-based sequence (about 650 students per semester), and in a few months we will start using the same labs in the calculus based sequence as well.

This large lab reform effort, which will impact about 2500 University of Illinois students per semester by the fall of 2020, was inspired and guided by the ISLE framework developed by Eugenia and her co-workers.

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I first started designing educational physics games during the summer after my second year of teaching. The goal was to create a digital environment in which students could explore physical scenarios and gain intuition about physical laws, while immersed in accomplishing goals and receiving feedback in a game-like setting. It was in pursuing this goal that I found ISLE to be an ideal framework for promoting student exploration and investigation. It has been eight years since that summer, and I have since released five full-fledged educational games that help students explore concepts of kinematics, waves, electrostatics and circuits. To date, these games have been played by over 6 million people worldwide, and have been incorporated into physics and physical science curricula in all 50 US states and over 20 countries around the world.

The reason that ISLE is so effective as a framework for educational games is that it is inherently iterative. Students are asked to invent and explore ideas based on observational evidence, design testing experiments to investigate deeper into their ideas, and refine their models of physical laws by examining the results of these experiments. This takes the natural process of deductive reasoning that many students will employ on their own from childhood, and provides a well-defined structure to make it fully scalable to any field of scientific research. In a gaming environment, this amounts to students taking time to familiarize themselves with the general behavior of the digital setting, and slowly being asked to meet goals of increasing difficulty as their ideas become more fully fleshed out by mounting evidence.

One of the best examples in which I have implemented ISLE in a gaming environment is in the game Crack the Circuit. In the game, students are asked to investigate the behavior of a 'mystery circuit' by plugging and unplugging light bulbs and flipping switches, in order to determine the underlying connections between circuit elements that result in this behavior. It starts with a simple circuit in which a single bulb is lit by a battery and wires, and slowly increases in difficulty to series and parallel circuits, and eventually combination circuits and short circuits. By providing an open-ended setting in which students can build their own circuit and compare it to the mystery circuit, they are able to iteratively build upon their ideas, all while receiving feedback to help scaffold their conceptual model of electricity.

Another example is in Wavemaker, a game-simulation hybrid in which students investigate wave superposition within a medium. The game is a fully open-ended environment in which students can send wave pulses of varying shape and amplitude through both ends of a medium, and explore the resulting superposition of the pulses in slow motion. The game comes with an accompanying lesson framework for teachers to implement in a classroom setting or assign as homework, which applies the ISLE methodology to guide students through constructing a model for the principle of superposition. By providing time for students to explore in a freeform setting, as well as structured scaffolding to test their ideas, Wavemaker can be an instrumental tool in building a rigorous model for wave superposition.

I strongly believe that the success of my educational games over the past eight years has been a result of the ISLE philosophy. By giving students time to process observational evidence, respect to come up with their own ideas, and rigor with which to test and refine these ideas, ISLE is unmatched in its ability to solidify and enhance the natural scientifically minded tendencies of physics students. I plan to continue using ISLE as an inspiration in both my teaching as well as design of educational games for years to come.

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Chapter 7

Summary and tips for those who wish to implement ISLE

7.1 ISLE from the instructor and student perspective

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' 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 should *students do* to 'come up with...' (i.e. the physical quantity of acceleration, a relationship between force and charge separation)?
2. Recognizing that the *process* of constructing new ideas is as important as the application of those ideas.
3. Creating opportunities for the students to devise multiple explanations for the same phenomenon and then systematically test them experimentally.
4. Emphasizing the value of collaboration and group work.
5. Giving students an opportunity to design their own experiments and use them in three distinct roles: to help students generate models/explanations/hypotheses, to help students test them and to help students apply them.
6. Recognizing that predictions are not personal stakes, or guesses based on intuition.
7. Encouraging students to think about 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.

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10. Designing assessments that assess more than pure content knowledge and giving students an opportunity to improve their work without punishment.

Learning physics through ISLE by a student 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 accustomed to using multiple representations other than words and mathematics to solve problems and analyze data.
8. Getting used to working with others: listening to their ideas and communicating my own.
9. Persevere in learning.

Figure 7.1 summarizes these points and shows the connections among them.

7.2 Organizing ISLE-based courses

Learning of every concept starts in class. Students work in groups on all activities using whiteboards and share their findings with the rest of the class through white board presentations. All students contribute to the descriptions of the observational experiments and possible explanations. The different points of view are necessary for the success of the whole process. They also help students see that everyone is able to

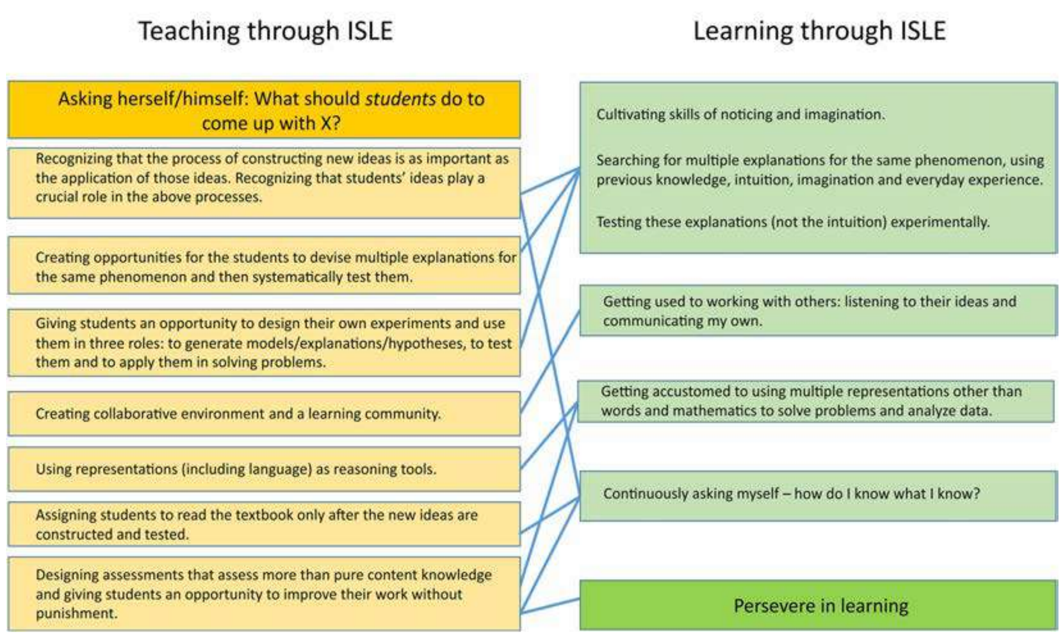

Figure 7.1. Teaching and learning through ISLE through the eyes of instructors and students.

devise new physics ideas avoiding detrimental to physics 'brilliance trap' (Cimpian and Leslie 2017). Multiple representations allow an intermediate step between phenomena and mathematics helping those who struggle with math.

The heart of the activities are experiments—observational, testing or application and their discussions (when real experiments cannot be done, they are substituted with recorded data, video, photos, simulations, etc). The instructor summarizes the findings of different groups and provides an overview, if necessary, after the students share their ideas ('time for telling'). The role of experiments means that the labs are integrated into the course and in a way 'drive it'. The role of the instructor is to help the students make sense of their experimental findings and introduce them to productive representations. After the development and testing of ideas comes the application part, where students use multiple representations to solve paper-and-pencil and experimental problems.

At home, students read the textbook and work on homework problems. For algebra-based courses, the suggested resources are the book 'College Physics: Explore and Apply' by Etkina, Planinsic, and Van Heuvelen (we also use this book in physics teacher preparation courses) and the Active Learning Guide. Both resources use experiments or examples, most of which are non-traditional in structure and relate to everyday phenomena. In addition, you can use numerous ISLE based activities that we tested and described in peer-reviewed journals (see the complete list at the end of this chapter).

Assessment focuses as much on the development of scientific reasoning and science processes as on the traditional conceptual understanding and quantitative reasoning (Etkina *et al* 2006). There are two crucial parts to the assessment: the students are familiar with the criteria (introduced through scientific abilities rubrics), and the students have multiple opportunities to improve their work without being punished for resubmissions. The grades are never curved, student receive their grade based on point-accumulation system improvement.

7.3 ISLE itself is not a guarantee for motivation

Originally, we thought that the nature of ISLE itself was motivating for students. They are excited to come up with multiple explanations and an opportunity to test their own ideas (they usually clap when the outcome of the testing experiment matches their prediction and are visibly satisfied when the outcome rejects one of the explanations as this step shows the real power of their own reasoning). However, for some students, the excitement inherent in the ISLE process is not enough. That is why a necessary element of the ISLE courses is the moment of 'need to know' before each big unit or even a small concept. The 'need to know' question is posed at the beginning of the exploration and is not answered until the end.

In addition, the cognitively demanding nature of the ISLE process causes student frustration at times. Some of them crave teacher authority and feel uncomfortable not knowing for a while what the 'correct' answer is. Encountering this frustration over the years we designed an 'expertise activity' (Brookes and Lin 2012), which engages the students in thinking what processes they go through when they develop expertise in something that they enjoy doing on their own (computer games, music, sports, gardening, cooking, etc). First, we ask them to name the areas where they feel that they are experts. We put those on the board grouping by themes —all sports together, all music instruments together, gardening and cooking together and so forth. These bigger groups are the groups that we ask the students to join and collectively come up with a learning process that they use to learn and improve in the area of their expertise. After a discussion, the groups need to put their ideas on whiteboards. Over the years, we found that the students come up with repeating steps: motivation to learn, trying on their own, reflecting on mistakes, receiving feedback from experts, and trying again. These are the steps very similar to the ISLE learning process. Pointing this out and creating the feeling that they are all experts in something and know how to learn improves motivation and encourages the students to persevere.

Using everyday apparatus and continuously relating what they are learning to their everyday experiences, using interesting problems and interesting experiments shows the students that the fundamental basic ideas can be learned with elementary (cheap) stuff. They learn to pull physics out of things that don't feel like physics. We hear the following comment 'I see physics everywhere' very often. As one of the students said: 'I was running after the bus in the morning and I felt my chemical energy being converted into kinetic and thermal, I was just thinking while running—here it goes…'

The opportunity to improve their work is also promotes student growth mindset. The fact that the course structure encourages students to improve and resubmit their work without punishment sends a very strong message: everyone can learn physics and taking more time to do it is not a fault of the learner.

Finally, different instructors have different interests and strengths. Some are interested in using phone apps, some are good video recorders, some have content interests—biology, astrophysics, history, etc. These interests make them choose different 'needs to know' and different applications. ISLE is a flexible environment that focuses on building on the strengths not only students but instructors too.

The most conducive set-ups for ISLE classes are studio format or a small classes, where the instructor can use time flexibly moving between experiments, group discussions, and whole class discussions.

However, the flexible nature of the ISLE framework allows it to be implemented in larger enrollment courses where labs are coordinated with lectures (Etkina and Van Heuvelen 2007) and problems solving recitations or just in labs only (Demaree and Lin 2006). In the case of a large enrollment course where students attend lectures (we call them 'large room meetings') together and problem-solving sessions and labs in smaller groups we suggest the following breakdown for each unit. Figure 7.2 below shows how one can implement the ISLE approach in different course formats moving from traditional teaching of disconnected lectures and labs to the logical connection where the experiments that students do in the labs are discussed and used as a basis for learning in lectures to the studio format—where there are seamless transitions from experimental work to theoretical discussions and back to

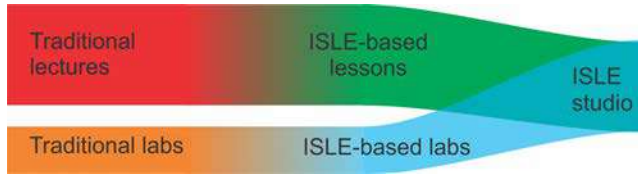

Figure 7.2. ISLE studio format is the best for implementing ISLE but a traditional structure will work too.

experimental work, students work in groups and the instructor serves as a facilitator of learning.

7.4 Unit breakdown in a large enrollment course

Let's assume that there is a 3 h lab, 80 min problem solving session and two 55 min large room meetings per week. A unit starts with a lab. The students conduct qualitative observational experiments, devise explanations and test them. Then they work on quantitative observational experiments and devise mathematical models. When they come to a large room meeting, the instructor discusses with them what they found in the lab and asks to propose experiments to test the quantitative models. After students proposed the experiments and the instructor carries them out with the students making predictions based on their models, some of the models are rejected and some are not. The instructor introduces new useful representations and the students go to a problem-solving session where they practice these representations while solving problems. The second large room meeting can be dedicated to solving more complex problems and discussion practical applications of the new idea. The details of such process are described in detail for the unit of circular motion in Etkina and Van Heuvelen (2007). In the next week's lab, the students conduct more application experiments and start observational experiments for a new unit.

Alternatively, for a shorter topic, such as Newton's third law, the students can perform observational and testing experiments (quantitative) in the lab and then have a discussion of their findings in a large room meeting. There they solve simple problems combining 2nd and 3rd laws. They practice applying the law in a problem-solving session and then in the second large room meeting they can start a new unit —friction. They conduct the observational experiments and construct models there and then, next week in the lab, apply them to solve complex experimental problems. You can find labs that fit both breakdowns at https://sites.google.com/site/scientific-abilities/ISLE-labs and the breakdown of material in a large enrollment (200 students) ISLE-based course at Rutgers University at https://sites.google.com/site/ruphysics193/ and https://sites.google.com/site/ruphysics194/.

In table 7.1, we list frequently asked questions and answers related to ISLE implementation.

7.5 Frequently asked questions

Table 7.1. Helpful tips for those who wish to ISLE-ize their courses.

FAQ	Answers
How can I apply ISLE ideas in courses other than introductory physics?	If you are not teaching introductory physics for which ISLE-based materials are created, but wish to apply ISLE philosophy to your course, a great start is the history of the subject matter. Once you know how the founding scientists came up with the ideas that your students need to learn, you will be able to design your own observational experiments for the students to come up with the explanations. Once you try them in class, you will learn what explanations students devise and what testing experiments they propose. The first time you might not have the equipment to test everything but the second time you will be ready.
What should I do when the observational experiment allows only for one explanation?	Do not worry if an observational experiment does not allow for multiple explanations, some do not and it is ok. However, even if there is only one explanation it is still very important to test this explanation. The process of designing the testing experiments and being able to make predictions for their outcomes based on the explanation under test is very important for the development of student ownership of the newly constructed ideas.
My students are not used to/don't feel comfortable to propose different explanations. What can I do?	Focus students' attention on the reasoning process, not the correct answer. Any answer that they come up with can be tested experimentally. They need to feel free to propose their explanations without the fear of being wrong.
Will my workload be unmanageable if I allow my students multiple resubmission of their work?	Resubmission of student work for extra grading might seem daunting but, in our experience, it is doable. There are several approaches to resubmissions. If you are using grading rubrics then you do not need to write any feedback, just the rubric score. In the resubmitted work, the student needs to explain what he/she did wrong, how to do it

	right and how she/he learned how to do it right. Alternatively, you can give the student a different but similar problem and let her/him solve it in front of you during designated hours. We usually make these hours not very convenient for the students so that they need to make an effort to come. This reduces the risk that they will not give full attention to the first attempt. However, in our experience this is not an issue.
Will I cover all the topics I need/am required to cover in my physics course?	This is both a simple and a difficult question to answer. The simple answer is: if you want students to engage in doing physics, you will 'cover' fewer topics than you did when you were lecturing to them. The longer answer is: please ask yourself where this pressure to 'cover *n* topics' is coming from. Covering more topics does not lead to students being able to reason with that knowledge. Covering more topics leads to shallow and fragmented understanding. It is often our experience that physics professors tend to exaggerate how many topics they cover. While we do not want you to place your job at risk by refusing to cover all the topics listed in the course catalogue, it is time for change: try to make the case for a process-focused approach to learning physics to your department chair. See if you can get people on board with the idea of fewer topics and more depth.
I see the need for change and I want to switch to ISLE, but ISLE is overwhelming. I can't hold it all together in my head.	What we have presented in this book didn't all happen overnight. It has been a 20–30 year journey of experimentation with many mis-steps on the way for us. Like your students learning physics, you need to re-construct ISLE for yourself in a way that works for you and makes sense to you. Probably the easiest entry point is to have students engage in design labs that ask students to 'design an experiment to achieve goal X' (to explore a phenomenon, to test and idea, to solve a practical problem) instead of giving students step-by-step 'cookbook' instructions. Maybe start with only reforming the labs and build

(*Continued*)

Table 7.1. (*Continued*)

FAQ	Answers
	up from there. (We have a lot of examples of these and you can adapt them to your circumstances.) Always keep the underlying principle in your mind: we want to engage students in inquiry learning by having them engage in authentic scientific practices.

7.6 Summary

In this book, we described an approach to teaching physics that allows all learners to experience physics as a process not a static set of rules. We provided evidence why such approach is important in the 21st century and discussed in detail how to implement it. We encourage our readers to try it. If you decided to try and have questions, please do not hesitate to e-mail us. We will be happy to answer all your questions.

Here are our e-mails:

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7.7 List of additional resources for ISLE-based activities

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