Investigative Science Learning Environment – A Science Process Approach to Learning Physics

E. Etkina[1*] and A Van Heuvelen[2]

[1] Graduate School of Education, Rutgers University,
New Brunswick, NJ, 08901

[2] Department of Physics and Astronomy, Rutgers University,
Piscataway, NJ, 08854

Abstract:

In this chapter we describe an interactive method of teaching, Investigative Science Learning Environment (*ISLE*), that helps students learn physics by engaging in processes that mirror the activities of physicists when they construct and apply knowledge. These processes involve observing, finding patterns, building and testing explanations of the patterns, and using multiple representations to reason about physical phenomena. *ISLE* is a comprehensive learning system that provides a general philosophy and specific activities that can be used in "lectures" (interactive meetings where students construct and test ideas), recitations (where students learn to represent them in multiple ways while solving problems) and labs (where students learn to design their own experiments to test hypotheses and solve practical problems). In *ISLE,* students are assessed for conceptual understanding, for problem-solving ability, and, most importantly, for their use of various scientific abilities. We have developed activities that help students acquire some of the abilities used by scientists in their work: experiment design, model building, use of multiple-representations, evaluation, etc. To determine the degree to which the students have acquired these abilities and to simultaneously provide feedback to the students, we have developed a set of rubrics that can be used by instructors for grading and by the students for self assessment. In this chapter we also provide a theoretical basis for the *ISLE* structure (using brain and cognitive research), explain how this learning system addresses the needs of the 21st century science education and workplace, and how it is different from other reformed curricula.

* To whom correspondence should be addressed. E-mail: etkina@rci.rutgers.edu

Table of Contents

1. Introduction

1.1. The ISLE – helping students learn to do science

As instructors, how do we create an environment in which students can discover and learn physics for themselves - to own it, so to speak? In this chapter we describe an interactive method of teaching—Investigative Science Learning Environment (*ISLE*), a Science Process Approach that addresses this question[1]. There are two key features of this approach. One feature involves students' development of their own ideas by

(a) observing phenomena and looking for patterns,

(b) developing explanations for these patterns,

(c) using these explanations to make predictions about the outcomes of testing experiments,

(d) deciding if the outcomes of the testing experiments are consistent with the predictions, and

(e) revising the explanations if necessary.

Another key feature is encouraging students to represent physical processes in multiple ways, thus helping them develop productive representations for qualitative reasoning and for problem solving. The combination of these features is applied to every conceptual unit in the *ISLE* learning system.

1.2. In what courses can it be used?

ISLE as a method of instruction can be used in any science or physics course, from elementary school to graduate school. It is being used, has been used, and can be used with a variety of physics populations, including:

- Large-enrollment calculus-based introductory physics courses for honors or at-risk students in large universities (about 250 students);
- Regular calculus-based introductory physics courses in small universities (about 60 students)
- Large enrollment algebra-based introductory physics course for science majors (500-600 students);
- High school college preparation, honors physics classes and AP B courses;
- Physics methods courses for pre-service high school physics teachers;
- Science methods courses for pre-service elementary teachers;

- Professional development programs for in-service elementary, middle school and high school teachers;
- Summer programs for gifted students.

A list of publications about ISLE courses and conference talks is posted at http://paer.rutgers.edu/scientificabilities. The *ISLE* method can be potentially adapted to other levels.

In this chapter we:

- Describe *ISLE* briefly to provide an outline of the most important elements and how they work together;
- Supply a detailed description of how the *ISLE* curriculum is implemented for a unit on circular motion in an algebra-based physics course;
- Provide reasons for different elements of *ISLE* based on cognitive studies, studies of workplace expectations and sociology;
- Provide a list of available resources; and
- Describe learning outcomes in *ISLE* courses.

2. A brief description of ISLE: How does it work in a classroom?

2.1. The ISLE sequence used in concept construction consistently mirrors scientific practice

ISLE students start each conceptual unit by observing carefully selected physical phenomena[2]. Students do not make predictions about the outcomes of these experiments; instead they collect data and look for patterns in the data. Then students construct ideas/rules to explain their experimental observations. We try to choose experiments which are easy to explain or for which the data patterns are clear. However, when appropriate, students are encouraged to suggest multiple explanations for the same experiment. The fact that all explanations have equal weights before they are tested allows students to freely express their ideas, often based on everyday experience, without waiting for authority for validation. Students can use their contextual and epistemological resources to help in constructing explanations[3]. Students then have to come up with experiments that will test each of the proposed explanations/rules by predicting the outcomes of new experiments using hypothetico-deductive reasoning (if-then)[4]. They learn that explanations cannot be proved, only rejected. Consequently, the best testing experiment is one whose outcomes can be predicted differently based upon different competing models and some of the models produce predictions that do not match the outcome of the testing experiment. After performing the testing experiments, students revise and/or discard their explanations when necessary. Sometimes testing experiments reveal new features of the phenomenon that students try to explain, and the cycle starts again. They then use tested explanations/rules to explain everyday experiences and to solve problems.

Often we offer students alternative ideas to test at this stage of the cycle. These ideas are based on “student misconceptions” documented by physics education research (PER). Some students might have the same ideas even after the cycle is completed. Thus “testing” them provides an opportunity for the students to examine why a particular idea leads to unsuccessful predictions. However, students do not have a personal stake in these predictions, as they are testing “somebody else’s” ideas.

Students follow similar cycles for each conceptual unit and continuously reflect on “how they know what they know.” (An example of *ISLE* cycle is provided later). At each stage students work collaboratively (in groups), sharing ideas and trying to convince each other. This approach resembles the processes that the scientific community uses to acquire knowledge.

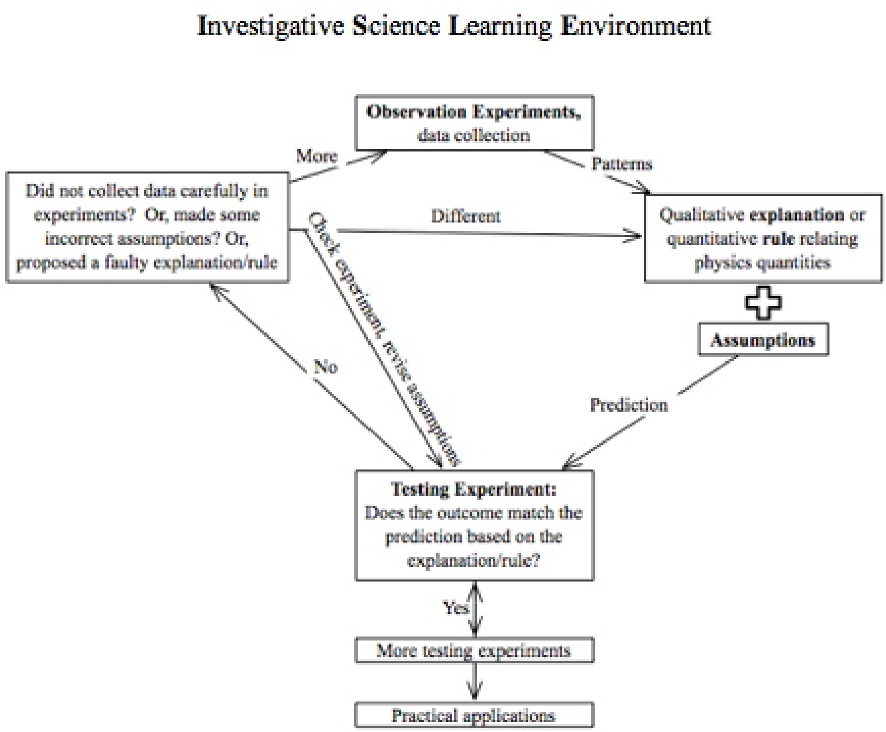


Fig. 1: ISLE cycle: the main elements and their logical connections.

The sequences of observational experiments, finding patterns, explaining patterns, testing and applying them repeats twice for each conceptual unit; first at a qualitative level and then at a quantitative. It is represented diagrammatically in Figure 1.

2.2. ISLE is different from many reformed curricula – students' original ideas are not elicited at the beginning of instruction in a unit

This aspect of *ISLE* instruction differs from traditional and from some reformed approaches to physics instruction in several ways. The instructor does not provide students with ready-made physics concepts to discuss nor show experiments to illustrate concepts/rules that were presented earlier. *ISLE* students do not read the textbook before coming to class. Most importantly, the instructor *does not elicit predictions* before the observational experiments. Students' alternative ideas are addressed naturally at the concept construction or concept testing stages of the cycle. The reason for this departure from the "traditional" constructivist approach to curriculum development is explained later, in the section entitled "Cognition: how do people change conceptions?"

2.3. ISLE emphasizes multiple representations at all stages of concept construction

Another feature of *ISLE* is that students master the concepts that they devise by using various thinking and learning strategies and by being active participants in all parts of their learning. They learn to represent physical phenomena in multiple ways.[5,6] 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, for example, constructing free-body diagrams to help students see a pattern in the data. Among non-traditional physics representations, the system uses energy bar charts[7] for situations involving work and energy and graphical representations of flux and emf to analyze electromagnetic induction processes. 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. They use the mathematical descriptions to make predictions about the outcomes of testing experiments. After concepts have been constructed and tested, students use the different representations to reason qualitatively and quantitatively about physical processes – a strategy commonly used by scientists. Students learn to take a more complex situation apart, solve the parts, and reassemble the parts to answer a bigger question.

2.4. ISLE treats language carefully

We pay special attention to language as one of the representations that students use.[8] We provide the names for the new concepts only after students have constructed and tested them and have a relatively strong understanding. We also avoid using conventional terms that have been found to cause difficulties in student learning. For example, we do not use the word “heat” in order to avoid the confusion between the concept of internal energy and the process of its transfer. We call the process “heating”. Other modifications involve the naming of forces – for example, alternative labels for what are traditionally called weight and tension forces. When talking about all forces, we use the linguistic construct emphasizing that forces involve an interaction between two objects (for example, the force that the Earth exerts on an object $\vec{F}_{\text{E on O}}$) as opposed to a label that treats force as an entity that is part of an object (for example, the weight $\vec{w}$ of an object).

2.5. New approach to assessment: focus on scientific abilities in addition to content

In *ISLE,* students are assessed for conceptual understanding, for problem-solving ability, and, most importantly, for their use of various scientific abilities. We have developed activities that help students acquire some of the abilities used by scientists in their work: experiment design, model building, use of multiple-representations, evaluation, etc.[9] Similar tasks are used for formative assessment activities.[10] To determine the degree to which the students have acquired these abilities and to simultaneously provide feedback to the students, we have developed a set of rubrics that can be used by instructors for grading—but most importantly by the students for self assessment.[9]

2.6. ISLE in your class: planning of one cycle

The *ISLE* system has been used in large classes (over 500 students) and in smaller classes. The format for the instruction depends on the number of lecture, recitation, and lab classes each week. Materials that are used in the course are now packaged in *The Physics Active Learning Guide,*[11] which provides cues on where to use particular activities and hints for instructors (in the instructor version).

For example, in one large class, a two-week unit starts with students observing phenomena in the first lecture (we will call lectures “large-room meetings”, as the students participate actively during these periods). These phenomena are lecture demonstrations selected according to the criterion of simplicity – the pattern that we want the students to see should be clear. The students work in groups of two/three to record their observations, look for patterns in these observations, and analyze the experiments in various ways to help produce qualitative explanations that account for their observations. Here the instructor helps them by suggesting what representation to use for their analysis. Students then use the different explanations to make predictions about a testing experiment proposed by the professor or they suggest their own testing experiments. This is done through interactions with representatives of the groups, voting, or an electronic response system. The testing experiments are used to discriminate among the different explanations.

The main difference between the observational experiments at the beginning and the testing experiments that come later is that students do not make predictions about the outcomes of the observational experiments but they do make predictions for testing experiments based on the explanations that they are testing. In this first large-room meeting or in a second one, students identify relevant physical quantities. Students look for patterns in experimental data that relate these quantities—to devise a relationship between them – called a “rule”. These “rules” are then subjected to experimental testing again. Sometimes students analyze data that is collected by them during a demonstration or often they observe the experiment from which the data can be collected but use the table of prepared data for their analysis. Then, students use the qualitative explanations and the quantitative rules to reason about new processes, to represent them in multiple ways, and to solve problems of easy to moderate difficulty. All this happens in an interactive format using a peer instruction approach[12].

During one or more recitations in this first week of the development for a particular unit or early in the second week, students work in groups on problems—qualitative problems, multiple representation activities, and often on more complex multi-part problems. They also evaluate solutions to the problems devised by other students. The lab related to this conceptual area occurs during the second week and involves more complex quantitative testing experiments and experiment problems. Students design their own experiments[13] to test a concept or to solve a problem. They practice hypothetico-deductive reasoning (if, then, but, therefore[4]) to make predictions and to assess the results of the experiment. In lectures during this second week, a new cycle starts. As stated earlier, different formats are used depending on the size of the class and the class time available for each part of the course—lecture, recitation, and laboratory.

Students go through the same cycle for many concepts. The most difficult part of the cycle is to provide challenging questions that are based on real life examples so that the students can see that the explanation that they invented “works” or “makes sense” for the real world and addresses the ideas that they had before. This sequence allows the students to answer the question “how do I know this?” at every step of the cycle.

The rationale for different elements of *Investigative Science Learning Environment* and the practical implementation comes from several different areas: workplace studies, studies of the nature of science and scientific reasoning, brain studies, studies of students’ learning of science, and studies of cognitive apprenticeship that will be discussed later in sections 4 and 5.

2.7. Assessment of student learning

Assessment approaches that we use in the course send messages to the students about what they should focus on, and provide feedback whether their efforts were successful. By changing assessment tasks we can shift the attention of our students to what we consider important. Traditionally there are two types of assessment used in physics courses – formative and summative.

Formative assessment happens when the instructor assesses a small chunk of knowledge, provides feedback to the students during their learning to improve it, and modifies her/his subsequent instruction based on student responses. (These are questions in large room meetings, recitation questions, tutorial questions, quizzes, etc.) Black and Wiliam[10] showed that the learning gains from systematic attention to formative assessment, including feedback for the students, are larger than gains found for most other educational interventions. Examples of summative assessment are final exams – students are assessed on big units and with little feedback other than a numerical grade.

There are five major changes that *ISLE* system brings to the assessment practices:

- **New focus in assessment:** Assessment focuses not only on the evaluation of knowledge but on the evaluation of "scientific abilities". These abilities include an ability to represent information in multiple ways, an ability to design experiments to test ideas, an ability to describe data collection and analysis, an ability to evaluate somebody else's reasoning, etc.[14,15] Specially designed video problems assess students' ability to collect data to solve experimental problems that require the integration of knowledge from multiple areas.[16] Newly developed "surprising data tasks" assess students' ability to revise their ideas when they encounter anomalous data.[9,17] These new assessment tasks are available at http://paer.rutgers.edu/scientificabilities.
- **Emphasis on feedback:** A large emphasis in formative assessment is placed on feedback. For each scientific ability, we use a specially designed and validated rubric.[9] Students use the rubrics for self assessment and the instructors use them to provide feedback for the students. The rubrics are available at http://paer.rutgers.edu/scientificabilities.
- **Non-traditional exam problems**: Exams used for summative assessment consist not only of traditional one step and multi-step physics problems but also of problems that involve multiple representations, evaluation, and design. We developed special *ISLE* exam questions that have been used in all *ISLE* courses.[18]

- **Lab design exams:** In some *ISLE* courses students have exams in the laboratory – laboratory practicals.[19] During these exams students need to design and conduct original experiments to test ideas invented in class, to test alternative theories, and to solve experimental problems.
- **No curve:** Students' grades in *ISLE* courses are based on a point accumulating system. Results of the exams are not curved. Students' success depends only on their personal effort and not on the success or failure of other students.[20]

3. An example of how ISLE works in one unit: circular motion

<u>Sample activities for large-room meetings, recitation, and laboratory for one unit:</u> We will outline the routine for a unit on circular motion for a large enrollment algebra-based college physics course (the mathematical level can be decreased for a high school course or increased for a calculus-based class). We assume that there are two large-room meetings during the week, followed by one recitation and one laboratory the following week. This unit comes after students learned linear kinematics and dynamics. All of the activities used in the description below can be found in *The Physics Active Learning Guide*[11].

Large Room Meeting 1

Observation Experiments: The first large-room meeting starts with several demonstration experiments or videotaped experiments of objects moving in a circle at constant speed [the videos are available at[21]]: a person hits a rolling bowling ball with a mallet so that the ball moves in a circle, a rollerblader initially skating straight holds a rope whose other end is held by another person. The rollerblader then moves in a circle around this other person. Students are asked to identify objects interacting with the object of interest and then to make front view free-body diagrams (as seen in the plane of the circle as the object approaches). They then look for patterns in the motion and in the diagrams that can be the basis for a provisional rule for a circular motion at constant speed. After drawing the diagrams they find that the net force exerted on the moving object is always horizontal and points to the center of the circle.

The above observational experiments are examples of experiments from which students can clearly see a pattern. This does not mean that they let go of their original ideas. In the case of circular motion there are two alternative ideas that students have: there must be a force in the direction of motion, and there is a force outward. Both of these ideas are based on everyday experience.

Provisional rule(s): Students devise a provisional rule: it appears that when an object moves at constant speed in a circle, a net force is horizontal and points toward the center of the circle (rule 1). At this point some of them still think that when an object moves in a circle there is an outward pushing force (rule 2) or a force in the direction of motion (rule 3). Thus if some of the students suggest that such forces should be present, the instructor accepts these rules as provisional rules.

Testing Experiment (s): Now students need to use the invented rule or rules to predict what will happen if a person rolls a small ball inside a ring. Students draw free-body diagrams and see that there is a net force exerted on the ball - the normal force of the ring on the ball which points toward the center. Thus, according to rule 1, the ball, if it is already in motion, should move in a circle inside the ring. According to rule 3 (force in the direction of motion) the ball should not move in a circle, as there is no force exerted on it along the circle. Students test their prediction by observing the experiment. As they observe the ball rolling inside the ring, the second prediction is not supported, and rule 3 is rejected. The next prediction is about what happens if part of the ring is removed. When students use rule 1, they say that if the ring is removed, there will be no net force exerted on the ball, thus it should move in a straight line according to Newton's first law. If they use rule 2, then the ball should fly outward. Then they perform the experiment or watch it. The ball moves in a straight line, and rule 2 is rejected. After this experiment the instructor might ask them why do we feel that we are thrown outward when in a car that is making a turn if there is no outward force exerted on us? This exercise allows students to connect new knowledge to the ideas they had before without decreasing their confidence.

The third testing experiment involves a prediction about the tension force exerted by a string on a ball swinging like a pendulum bob. Is this force smaller, the same or more than when the ball hangs at rest? (A spring scale supports the top end of the string). This is a more complicated situation than students encountered before – the speed of the motion changes. But if you focus students' attention only on the lowest point of the swing, they can make the prediction using a free-body diagram. There are two objects that exert forces on the bob – the Earth and the string. Students predict that if the net force points towards the center of the circle, the point of the pendulum's support, then the force of the string should be greater than the downward force of the Earth on the ball – greater than the tension when the ball was at rest. This is a counterintuitive prediction that is based on the rule that students invented; thus they are really excited to see the outcome of a testing experiment that can be easily performed in a lecture or a lab setting.

Qualitative kinematics of circular motion: Fred Reif and Joan Heller developed a concrete diagrammatic method for helping students gain a qualitative understanding of acceleration during two-dimensional motion. It helps students develop a "feel for" centripetal acceleration instead of seeing it as just v^2/r. We first introduce this method (Figure 2), and then students apply it to the motion of an object moving in a circle at constant speed and discover that at different points the acceleration points toward the center of the circle.

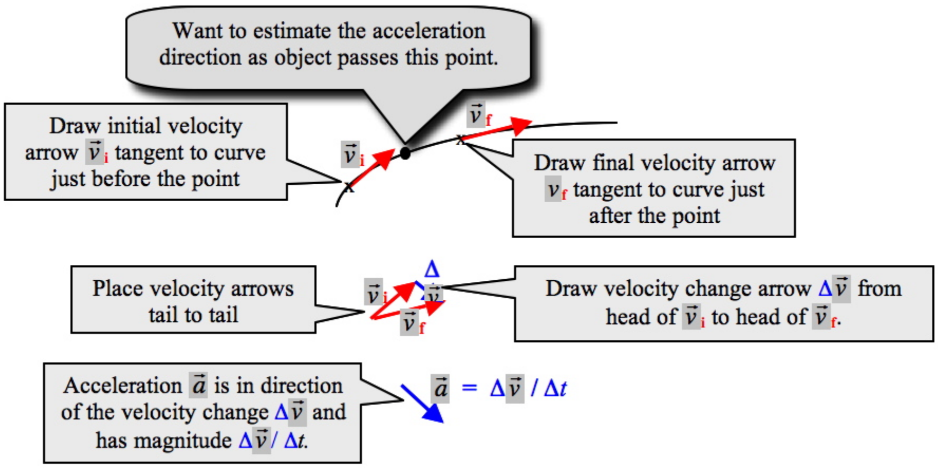


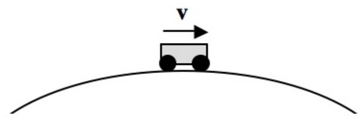
Figure 2: Building a reasoning skill: Using a velocity subtraction technique to find the acceleration of an object.

Large-Room Meeting 2

Newton's second law qualitative concept building and representing: In the first circular dynamics large-room meeting, students learned that: (a) the net force that other objects exert on an object moving at constant speed in a circle points toward the center of the circle; and (b) the direction of the acceleration of this circling object also points toward the center of the circle (based on the use of the graphical velocity subtraction technique). Based on these observations, students realize that the familiar Newton's second law also applies to two-dimensional circular motion.

Qualitative circular motion reasoning with Newton's second law: A very important aspect of *ISLE* is reasoning with multiple representations. An example of such a multiple representation reasoning activity is given in Figure 3. When performing these activities, students do not look for a numerical answer. They work in groups of two during class and then the instructor discusses possible correct and incorrect answers. A follow up activity can be a multiple-choice question which students answer via a personal response system.

Representing and reasoning: A battery powered toy car moves at constant speed across the top of an almost frictionless circular hump, as shown at the right.



(a) Use the graphical velocity subtraction technique to decide if the car is accelerating when passing across the top of the hump and, if it is accelerating, to estimate the direction of the acceleration.
(b) Construct a free-body diagram for the car when passing across the top of the hump. Make the force arrows the correct relative lengths.
(c) Use Newton's second law to qualitatively compare the results of parts (a) and (b) to be sure they are consistent. If not, revise your work on one part or the other.

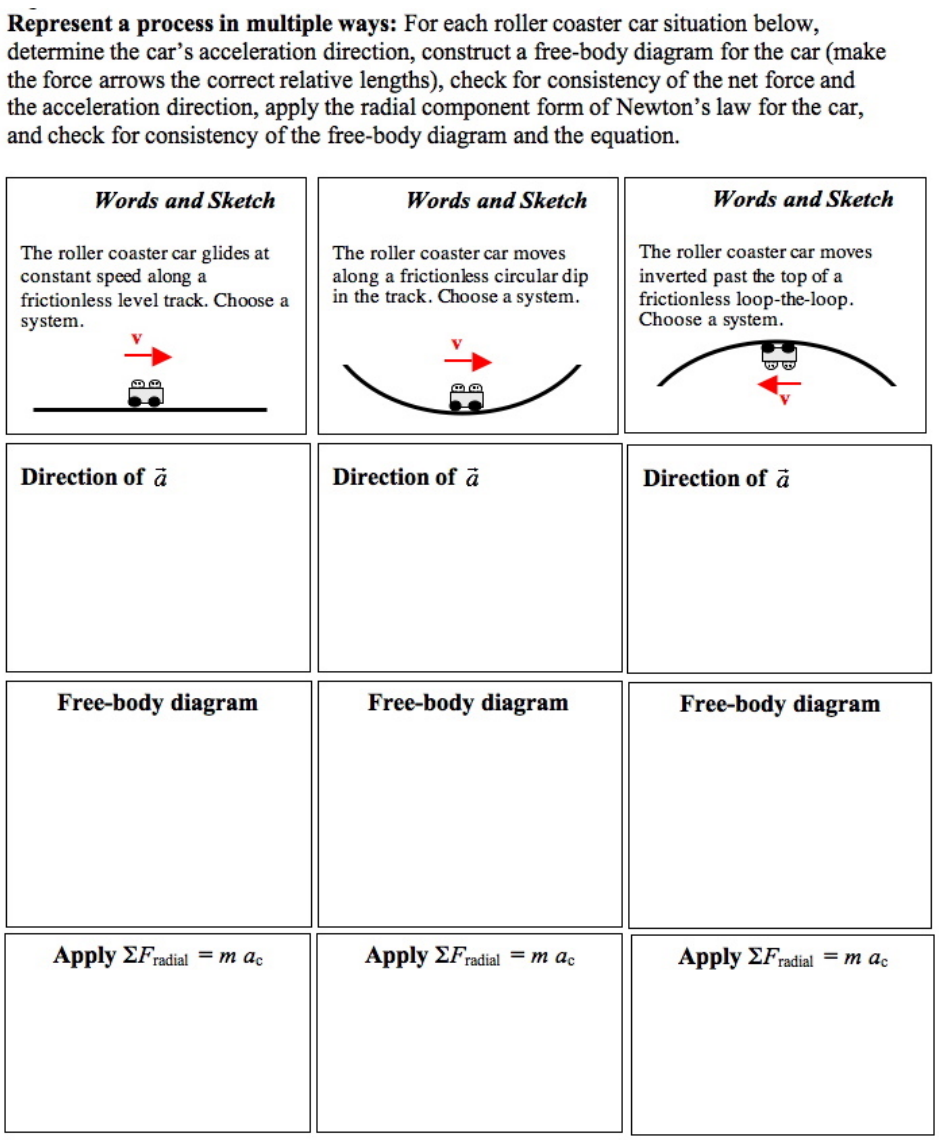
Fig. 3: Represent and reason: Analyzing the car's motion using different representations and looking for consistency among them.

Quantitative centripetal acceleration: We use the graphical velocity subtraction method to help students determine how the magnitude of the centripetal acceleration depends on the speed of an object moving in a circle and on the radius of the circle. Students, guided by the instructor, perform two activities that lead them to the understanding of how the acceleration is related to the speed of the object and the radius of the circle.

Quantitative testing experiment for Newton's second law as applied to circular motion: Students now have Newton's second law in component form (from their study of translational dynamics) and a quantitative expression for centripetal acceleration. They can now use these concepts to make predictions about the outcomes of several testing experiments. One of them involves objects of different mass and the same surface placed on a rotating platform at the same distance from the center. Students need to use Newton's second law and their knowledge of circular motion to predict which object will fly away first. It is very important here that students actually draw free body diagrams and reason quantitatively before they make the prediction. As before, the prediction is counterintuitive – all objects should fly off at the same time, and students often do not think that the experiment will work. However, the success of the experiment makes them feel confident about their ideas.

Recitation

Now, the emphasis is on problem solving—applying the concepts and strategies that were learned earlier. Below we provide examples of several non-traditional activities. In recitations students work in groups on a set of problems from the *The Physics Active Learning Guide* (***ALG***).



Represent a process in multiple ways: For each roller coaster car situation below, determine the car's acceleration direction, construct a free-body diagram for the car (make the force arrows the correct relative lengths), check for consistency of the net force and the acceleration direction, apply the radial component form of Newton's law for the car, and check for consistency of the free-body diagram and the equation.

Words and Sketch The roller coaster car glides at constant speed along a frictionless level track. Choose a system. v	***Words and Sketch*** The roller coaster car moves along a frictionless circular dip in the track. Choose a system. v	***Words and Sketch*** The roller coaster car moves inverted past the top of a frictionless loop-the-loop. Choose a system. v
Direction of $\vec{a}$	**Direction of** $\vec{a}$	**Direction of** $\vec{a}$
Free-body diagram	**Free-body diagram**	**Free-body diagram**
Apply $\Sigma F_{\text{radial}} = m\, a_c$	**Apply** $\Sigma F_{\text{radial}} = m\, a_c$	**Apply** $\Sigma F_{\text{radial}} = m\, a_c$

Fig. 4: Represent a process in multiple ways: Moving from concrete to abstract representations to analyze motion and interactions.

Representing processes in multiple ways: These activities ask students to represent a situation in different ways, including free-body diagrams, mathematics, etc. They do not solve problems to find a numerical answer. (Figure 4). The students are relating the abstract mathematical representation to more concrete sketches and diagrams.

Equation Jeopardy Problems: Students are given a mathematical description of a circular motion process and need to construct a description in words and in a sketch that is consistent with the word description (Figure 5). They are learning to read the mathematical language of physics with understanding.[22]

Evaluation Problems: Students are given the solution to a problem. The solution has mistakes, which they need to identify and correct (Figure 6). This helps develop the very important science process ability of evaluation.

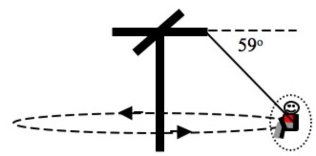
Equation Jeopardy: Write in words a problem and construct a sketch for a situation involving circular motion that is described mathematically below (there is more than one possibility). Provide all the details for this situation.

$$200\text{ N} + (50\text{ kg})(9.8\text{ m/s}^2) = (50\text{ kg})\, v^2/(12\text{ m})$$

Fig. 5: Equation jeopardy: Moving from abstract to concrete representations to analyze motion and interactions.

Evaluation problem—amusement park ride: (a) Identify any errors in the solution to the following problem. (b) Provide a corrected solution if there are errors.

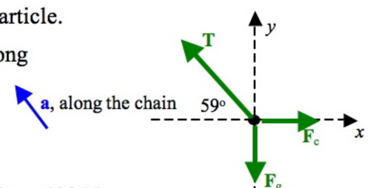
The problem: 80-kg Samuel rides at a constant 6.0-m/s speed in a horizontal 6.0-m radius circle in a seat at the end of a cable that makes a 59^0 angle with the horizontal. Determine the tension in the cable. Assume that $g = 10$ N/kg



Side view

Proposed solution: The situation is pictured above. We simplify by assuming that Samuel, the system, is a particle.

A free-body diagram for Samuel is shown at the right along with the acceleration direction.



Represent mathematically and solve:

$$F_c = m(v^2/r)$$
$$= (80\text{ kg})(6.0\text{ m/s})^2/(6.0\text{ m}) = \underline{480\text{ N}}.$$

Fig. 6: Evaluation problem: Finding mistakes and omissions in the proposed solution.

Posing problems: Students are provided with a picture of a situation and need to devise a problem based on the situation (Figure 7).

Problem posing—hammer throw:
An Olympic throw for a 7-kg hammer (the ball connected to the wire) is a little less than 90 m. Invent two problems for this situation and use the principles of physics to solve these problems about the hammer throwing situation depicted at the right.

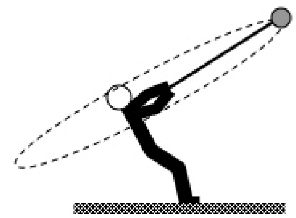


Fig. 7: Pose a problem: Using a picture of a situation to propose a reasonable problem.

Laboratory

In the laboratory students work on the following experiment; Design two independent methods to determine the net force exerted on the bob of a conical pendulum by other objects as the bob moves at a constant speed in a circle of a chosen radius.

Equipment: A conical pendulum with a long string, a ring stand, a watch with a second hand and a large piece of paper.

For each method include: a) a complete description with a labeled diagram; b) a free-body diagram if needed; c) the quantities that you will measure and the quantities that you will calculate; d) the mathematical procedure that you will use to determine the net force; e) additional assumptions that you make, and f) sources of experimental uncertainty and ways to minimize them. Then perform the experiment, record data in an appropriate way and find the value of the net force. Decide if the results of the two methods agree with each other.

4. Our motivation and theoretical base: Why does ISLE emphasize scientific abilities, multiple representations, and specific pedagogical strategies?

While designing a curriculum, one considers three important elements: the goals for the course, ways to achieve the goals, and ways to assess if the goals are achieved. The goals of the curriculum are student learning outcomes. The ways to achieve them are the sequence and content of the activities in which students engage and the organizational structure of the activities. Assessment is the instruments that we use to determine if the students have achieved the desired learning outcomes (see the discussion above). In this section we describe how we chose the goals for ISLE and the ways to achieve them. The choice of goals and ways to achieve them came from four large theoretical fields:

- The needs of the 21st century workplace;

- Scientific epistemology;
- Brain research;
- Cognitive studies;

Table 1 summarizes how different elements of ISLE relate to the recommendations of these four fields.

4.1. The needs of the 21st century workplace: what do students need for success in their future lives and for success in the science workplace?

An important purpose of education is to prepare new generations for productive lives in society. In the 20th century 80 percent of the workforce was in unskilled jobs where they needed to follow clear directions. In the 21st century, 85 percent of new jobs involve skilled workers who need to make creative decisions based on data.[23] What knowledge and what abilities are needed to succeed in this 21st century workplace? This question has been addressed by individual research studies examining the need for various process abilities and for declarative knowledge of people in the workplace.[24,25,26,27] Duggan and Gott[28] studied the science used by employees in five science-based industries: a chemical plant specializing in cosmetics and pharmaceuticals, a biotechnology firm specializing in medical diagnostic kits, an environmental analysis lab, and engineering company manufacturing pumps for the petrochemical industry, and an arable farm. They found that most of the scientific conceptual understanding used by employees was learned on the job, and not in high school or university courses. They concluded that "A secure knowledge of procedural understanding appeared to be critical." Aikenhead[29] observed the practice of six acute care nurses to see what knowledge and abilities they used in their work. He summarized his own and other studies as follows:

> In science-rich workplaces, procedural knowledge had a greater credence than declarative knowledge (Chin et al)[24], and employees consistently used concepts of evidence in their work to such an extent that Duggan and Gott[18] concluded: procedural knowledge generally, and concepts of evidence specifically, lie at the heart of … science-based occupations. (P. 271)

Even for consumers of mass media and for thoughtful decision makers, people not in the science workplace, these reports concluded that procedural knowledge and concepts of evidence where more important than so-called declarative knowledge. Therefore all of our students would benefit by placing more emphasis on developing the abilities used in the practice of science.

Table 1. The ISLE model of learning combines suggestions of four areas

	Workplace studies	**Scientific epistemology**	**Brain research**	**Research on learning**
Observation of selected phenomena and description of observations	Ability to collect data	New data are either unexpected or anomalous	Activation of sensory cortex through concrete experiences	Successful construction of knowledge in a non-threatening atmosphere
Finding a pattern	Ability to analyze data	Making decisions on what data to keep and what are outliers	Categorization of knowledge is the essence of all cognitive functions	Decision making, having control over knowledge construction
Devising explanations and rules using different types of reasoning—inductive, analogical, hypothetico-deductive	Ability to interpret data	Ideas have to account for existing data	Activation of existing networks and association with existing knowledge using frontal integrative cortex	Multiple explanations allow the use of prior knowledge in a non-threatening manner
Representing phenomena and explanations in multiple ways	Ability to represent data	One of the approaches used in science to solve problems	Cognitive networks are formed by inputs arriving simultaneously	Helping learners focus on the construction and use of knowledge and not on the right answer
Making predictions and designing testing experiments	Ability to design experiments	Hypothetico-deductive reasoning	Activation of additional connection in the brain	Active construction of knowledge, making connections with existing knowledge
Conducting testing experiments and revising rules and explanations	Ability to conduct experiments	Based on results of testing experiments, scientists might reject the new idea	Active testing of ideas involving motor brain	Experiencing cognitive conflict when the prediction does not match the outcome of a testing experiment, revising the explanation
Applying new rules and explanations to the every-day life phenomena		Application is another way of testing new ideas, also establishing the coherence of knowledge	The change or adjustment of *weights* (transmitting capability) in the connections or synapses between nodes	Connecting new knowledge to the existing one, seeing old knowledge not as wrong and needed to forget, but as useful
Applying new rules/ explanations to solve practical problems, build devices.	An ability to design a system, component, or process to meet desired needs			Seeing knowledge as useful increases motivation.

There have been a plethora of national studies and reports concerning desired outcomes of science education that support the same conclusions. We summarize briefly six of these reports:

- Shaping the Future: Perspectives on Undergraduate Education in Science, Mathematics, Engineering, and Technology, National Science Foundation report on education[30];
- Survey of former physics majors in the workplace by an American Institute of Physics[31],
- What Work Requires of Schools: A SCANS Report for America 2000, the US Department of Labor study that discusses what is expected of college graduates entering the 21st century workplace[32];
- Criteria for Accrediting Applied Science Programs by the new Accreditation Board for Engineering and Technology (ABET 2000)[33] that indicates the abilities that engineering colleges must show their students have developed during their undergraduate study;
- "How people learn" published by the National Research Council[34] that reviews cognitive studies and makes suggestions for learning systems based on these studies; and
- The National Science Education Standards that serve as a guide for public school education in this century[35].

These research studies and national reports provide a clear message. The words *inquiry* and *investigation* are ubiquitous. The AIP survey of former physics majors working in industry found that they spend much more time designing products and designing, performing and analyzing scientific investigations than they do using pure physics knowledge learned in universities. The engineering ABET accreditation Criterion 2 requests, among other things, engineering graduates who have:

- an ability to design a system, component, or process to meet desired needs,
- an ability to design and conduct experiments, as well as to collect, analyze and interpret data.

"How people learn"[34] suggests that our courses should help students develop the intellectual tools and learning strategies needed to acquire knowledge. The National Science Education Standards[35] indicate that inquiry is crucial and includes the abilities to:

- identify questions and concepts that guide scientific investigation;

- design and conduct scientific investigations;
- use technology and mathematics to improve investigations and communications;
- formulate and revise scientific explanations and models using logic and evidence;
- recognize and analyze alternative explanations and models; and last, but not least,
- communicate and defend a scientific argument.

Bruce Alberts, President of the National Academy of Sciences, says: "This ability to inquire is what we want for all students by the time they reach 12th grade. Today, even at the end of college we are far from this goal."[30] As we see, these studies indicate that there is a national need for graduates who have learned the practice of science rather than for students who have learned scientific facts and laws—so-called declarative knowledge.

These studies also emphasize the importance of problem-solving abilities. However, the need is to analyze complex, poorly-defined problems that are common in the practice of everyday science rather than solving the well-defined end-of-chapter problems found in textbooks. Other frequently mentioned abilities needed for the future include the ability to work effectively on teams and the ability to communicate clearly.

In summary, 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.
- At all stages of learning students work in groups and communicate their ideas with each other.
- Students collect, analyze and interpret data and later in each unit design their own experiments to test ideas and to solve problems.
- Students solve traditional back-of-the-chapter problems but also complex problems.

If we agree that the methods through which scientists acquire knowledge should be central to the learning of science (in our case, physics), we need to agree on what methods physicists actually use to acquire knowledge.

4.2. Scientific epistemology: how do scientists acquire knowledge?

The studies discussed in the previous section indicate a need for students to acquire the process abilities that scientists use in their work. Thus, it is important to understand the nature of these abilities—how do scientists construct and apply knowledge? Analysis of the history of physics,[36] philosophy of science,[37] and work of educators studying the nature of science[38] shows that there is no consensus on many of these issues. Some argue that the scientific process starts with a puzzling observation that makes a scientist wonder what is going on[4]. Others think that in many cases a great deal of data have to be collected before scientists can even ask the why question.[39] Some philosophers of science argue that the original data themselves are not as pure as one might think but are instead viewed and interpreted based on the theories or paradigms that they subscribe to at that time.[37,40;41] Harre considers that data are the "most dubious of the elements" of a scientific investigation (p. 11): can scientists even notice a phenomenon if we do not have some kind of idea of why it is happening? However, others disagree—they think that having an unexpected observation might lead to new thinking. Scientists can have unexpected new data in areas where there is an existing paradigm or in the areas where there is no existing paradigm. The former becomes "anomalous data" that scientists explain by revising existing explanations. The latter becomes "puzzling data" that scientists explain by creating new theories.

How do scientists arrive at their explanations? Some feel strongly that scientists generate explanations (hypotheses) mostly by using analogies, relating new phenomena to something that they already understand.[8] Often a new representation of knowledge helps invigorate a field of study—for example, the introduction of Feynman diagrams into quantum electrodynamics. Others focus on the collaborative and discursive nature of science,[42] and yet others emphasize thought experiments, creativity, imagination, and pure luck.[36] A. Lawson[43] argues that scientists often use hypothetico-deductive reasoning to test new theories—a method to make a judgment about an explanation based on the match between a prediction and the outcome of a testing experiment. Some historians of science argue that many fundamental testing experiments in the history of science did not clearly support or disprove a hypothesis but were still considered supportive experiments because of the political climate at that time.[44] It is also debatable how many testing experiments are needed for a hypothesis to be accepted.[45] Some philosophers of science disagree with this whole process. They feel that having obtained the original data, scientists do not construct their explanations using hypothetico-deductive reasoning but instead continue the trial and error process to find reliable patterns.[39]

As we see, it is difficult to find a sequence of steps that can be called a "scientific method" that is used by all scientists to acquire knowledge. However, one can discern elements on which most of the scientists agree. These are: empirical evidence, inductive and hypothetico-deductive reasoning, coherence of ideas, the testability of ideas, and collegiality.

Unfortunately, as many science education researchers point[46,47,48], the practice of formal schooling in science differs significantly from the practice of science by scientists. However, there are various teaching strategies that help students think like scientists[49,50,51]. Different studies indicate that students with appropriate instruction are capable of developing explanations for observed phenomena and of testing their explanations by predicting the results of new experiments.[52,53,54] Lawson and colleagues found that students who can devise multiple explanations are better in the acquisition of new concepts.[55] Specific strategies that help students build explanations include scaffolding[56] and social interaction.[57]

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

- Students conduct observations and collect data. The choice of these first observational experiments by the instructor (scaffolding) is extremely important – they need to be simple enough for the students to see a pattern that is not obscured by effects secondary to the phenomenon under study. The instructor helps students focus their attention on the relevant features of the observed phenomena (scaffolding). Students interact with each other to agree on the important features of the observed phenomena (social interaction).

- Students analyze the observations by representing data in multiple ways, finding patterns, and explaining them using inductive, analogical and hypothetico-deductive reasoning and different representations. The main criterion of the quality of an explanation suggested by the student is its potential testability – one can make a prediction about an outcome of a particular experiment based on the explanation. Here the help from the instructor comes in the form of productive representations that she/he suggests for the students (scaffolding). Sometimes it is a graph, sometimes it is a free body diagram, and sometimes it is a picture of field lines.

- Students make predictions based on their explanations, handle anomalous data, and revise their explanations based on new evidence. Students can do this if they have an opportunity to communicate with each other, argue about possible outcomes of testing experiments, and discuss reasons for the mismatch (social interaction). The scaffolding role of the instructor is to envision what equipment might be needed for testing experiments, what experiments can be used to test students alternative explanations, and to describe experiments that physicists performed but that cannot be conducted in the classroom (historical data).

4.3. Brain research: how does a human brain create, store and access knowledge?

It took thousands of years for scientists to construct ideas that our students are asked to learn in two semesters. To have any chance of success, we need to structure students' learning experiences in a way that is matched to the characteristics of their minds—to make an impedance match between the learning system and the student mind.[58] Thus our next theoretical prospective comes from brain studies. There is no consensus in this field either. However, some major ideas can connect brain studies to the design of a physics learning system

Early theories indicated that all of an organism's experience is stored in network-like systems (*maps)* that consist of connections between the neurons in the cerebral cortex.[59] The network-like systems classify new incoming experiences by associating them with existing systems of connections. For Hayek there was no basic core of elementary sensation. Instead, this association of the new with the old connection system was the essence of sensation, perception, and memory. Though he suggested this theory a long time ago, the corresponding brain structures were discovered later.

J. Fuster[60] introduced a new word, "cognit", a generic term for any item of knowledge representation in the cerebral cortex. It consists of component network nodes--elementary representations of perception that have been associated with one another by learning or past experience.

A cognit is made of these nodes (assemblies of neurons) and relations between them. Learning takes place by a "change or adjustment of *weights* (transmitting capability) in the connections or synapses between nodes."(p.57) The individuality of human knowledge derives from "the practically unlimited possible combinations of neurons or subsets of them in a reservoir of 10 billion cortical neurons." (p. 14). Cognitive networks are largely self-organized by *auto-association*. They are formed by inputs arriving simultaneously, in temporal correlation, to cell groups or existing networks of association in the cortex, where those inputs establish new associations. Thus, the new associations are simply expansions of preexisting nets. Inputs that meet at the same time to facilitate a set of synapses and thus to build a network need not be of external origin (sensory). They may originate internally by activation of previously formed networks.

The essence of all cognitive functions is categorization of knowledge. "Reasoning and intelligence are closely dependent on the proper categorization of phenomena, external and internal" (p.58). Thus, for example, an incoming sensory input activates an old network of associative memory by virtue of the fact that some of that input is a component of that network, or is one of its originally associated constituents, or is closely related to one. The new input then becomes associated with the old reactivated network, expanding and updating the latter. Of course, the old memory may be a very different ranking in the cortex than the new information, and consequently the new memory will be hierarchical. The retrieval of memory—recall, recognition, remember—is essentially, as we shall see below, an associative process.

An important part of the cortex, the *amygdala*, is the evaluator of the affective and motivational values of stimuli, and probably plays a role in learning, though the possible mechanisms underlying this role are still obscure. 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.

J. Zull[61] in his book relating the results of brain studies with student learning suggests that when meeting a new situation, our brain progresses through a cycle of concrete experience, reflective observation, abstract hypothesis, and active testing. Concrete experience comes from the sensory cortex; reflective observation involves the integrative cortex in the back; creating new abstract concepts occurs in the frontal integrative cortex; and active testing involves the motor brain. This cycle shows how different parts of the brain work together to make sense of new information.

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 and thus are essentially changes in weights in existing cognits.
- When students devise explanations they use their own language, 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 “delete” or “erase” old ideas. Instead, they examine their applicability through testing experiments.
- The *ISLE* system specifically focuses on the steps where students can be successful: describing their observations, suggesting possible explanations, and describing the results of testing experiments.

4.4. Cognition - how do people learn and change conceptions?

Cognitive sciences use the studies of brain functions to address the question: what is learning and how can we help our students learn more effectively? The term *learning* within cognitive science is synonymous with understanding. Current views of learning include the idea that individuals construct knowledge.[62] Numerous studies involving a variety of disciplines and age groups[63,64] demonstrate that for many students a constructivist approach (when students create their own understanding of concepts rather than absorb explanations given by their teacher) works better than a traditional one. The knowledge that a learner already possesses, affects his or her ability to learn new knowledge. If the new knowledge conflicts with previously constructed knowledge, the new knowledge will not make sense to her and may be constructed in a way that is not useful for flexible application.[65,66,67,68,69,70] People tend to recast new data into their preexisting view/models of the world rather than revising their explanations/views of the world.[47] These ideas are consistent with the research on brain function and development discussed earlier—the human brain constructs new knowledge by expanding on existing knowledge. In summary, prior knowledge is a basis for the construction of new knowledge and is simultaneously an impediment to it.

In the early 1980s Strike and Posner[71] suggested a new *conceptual change* science-learning model that took into account the benefits and difficulties of prior knowledge for learning. They argued that if a learner is confronted with an experience that contradicts her/his prior ideas, and thus is dissatisfied with them, then she/he will be able to adopt new ideas, if these new ideas are intelligible, plausible, and potentially productive. The authors suggested that this change will occur if the students are asked to use their knowledge to predict what will happen in a particular experiment. If they view the experiment and find a mismatch between the prediction and its outcome, it produces a cognitive conflict between their prior ideas and the experience. The teacher can then propose a new concept if it addresses the criteria of intelligibility, plausibility and productivity. The conceptual change theory was modeled after how scientists change their theories based on their falsification.[72] It also turned students into active participants in the learning process, thus addressing recommendations of cognitive science. The influence of conceptual change theory can be seen in many successful physics curricula such as *Physics by Inquiry*[73] and *Interactive Lecture Demonstrations*[74]. L. McDermott[75] suggested a formula for learning (elicit-confront-resolve) that is based on conceptual change theory.

However, as time went by, the field of science education began to feel uneasy about conceptual change theory, and even its own creators started to revise it based on the data on student learning. Researchers found that cognitive conflict and deep engagement were often insufficient to induce change.[76,77] Learners' characteristics such as motivation,[78] affective resistance,[79] and beliefs about learning,[80] became more important in understanding how people learn. A revision of conceptual change theory brought ideas of "intentional conceptual change," a process when learners consciously focus on the construction of knowledge. Unlike unintentional constructions of knowledge, intentional level processing is *goal-directed and under the learner's control*. Rather than learning from simple exposure, students' goals guide the learning process.[81] Intentional level processing is not only initiated by the learner, but is also under the learner's conscious control. For the learner who is *not* engaged in intentional, goal-directed processing of information, processing resources are controlled by other factors (such as background knowledge, task difficulty, topic familiarity, and so forth). Dole and Sinatra argue that what is lacking in the science education model for conceptual change is a description of the role of the student's intentions in bringing about change. Some researchers argue that it is doubtful that students approach learning with goals of making sense of the material and coordinating it with their prior knowledge. Social goals may become more important and short-circuit instructional intentions.[82]

Another important consideration is that the authoritative climate in classrooms allows very little student control over learning activities and consequently decreases the probability of a mastery orientation.[83,84] Some researchers argue that grade-based competition also affects whether students focus on mastering the material or alternatively on performing better than their peers.[83,85,86]

We want to bring another consideration into the discussion of conceptual change theory of learning. As we discussed above, creating a cognitive conflict between students' prior ideas and their immediate experiences does not necessarily enhance learning. We speculate that a repetitive cognitive conflict might even hinder it. Some studies 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.[48] We do not have information about studies that investigated student attitudes or self-efficacy beliefs if they are subjected to the conflict resolution situations on a regular basis. Indirect evidence that this method might have a negative effect comes from the use of the MPEX[87] in reformed courses (all of which use the cognitive conflict approach and in all of them students showed a drop in attitudes—in the MPEX score). An exception is the work of Elby[88] and subsequently Redish and colleagues[89] who started using students resources instead of confronting "misconceptions".

We have anecdotal evidence that consistently encouraging students to make predictions before they observe new phenomena lowers their appreciation of a physics course. In 2002 one of the authors (AVH) taught two lecture sections of the introductory physics course for engineering students at Ohio State University. The students had the same recitation and the same labs. The course followed the ISLE approach. The only difference was that in the first lecture section (about 100 students) the professor did not elicit any predictions before showing students observational experiments, which were then used to construct explanations. In the second section (about 100 students) he asked the students to predict the outcomes of the observational experiments before they helped develop explanations. There was no difference in the performance of students on exams. However, the course evaluations of the professor were significantly different. On all counts AVH received scores about 1 point (out of 4 points) lower in the section where he elicited predictions before the observational experiments. Students' comments were also different. Students enjoyed the course in the first section and provided very positive comments. The comments in the second section showed some dissatisfaction with the course.

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. As we know from brain studies[61] negative emotions can be detrimental to learning.

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

- Students are not told about physics concepts but construct them actively.
- Observational experiments that start every conceptual cycle are chosen in a way that students are able to describe them in their own words, thus connecting them to prior knowledge.
- Students use their prior knowledge to generate explanations for observed phenomena.
- Students undergo conceptual change when they design and conduct testing experiments for their explanations and when they use new ideas to explain real-life phenomena.

5. Cognitive apprenticeship: how to structure a learning environment to help students acquire cognitive skills?

The recommendations from the above four theoretical areas explain the logic of the *ISLE* cycle, which mirrors some of the scientific processes, and addresses cognitive processes and the needs of the future workplace. However, these areas do not provide guidance for designing practical teaching strategies. One method that helps develop an approach is cognitive apprenticeship.

The central feature of the *ISLE* system is student learning of physics concepts by "replicating" the processes of science. Successful participation in this process requires various abilities: to design experiments, to collect and represent data, to devise and communicate explanations, to make predictions of the outcomes of specific experiments based on the explanations, and to evaluate reasoning and experimental design. How do *ISLE* students acquire these cognitive abilities? One of many ways to acquire a cognitive skill is through cognitive apprenticeship.[90,91,92] Barab & Hay[46] synthesized the literature related to apprenticeship learning and provided a useful distinction between formal schooling and participatory science learning based on cognitive apprenticeship. Their paper can be used as a "guide for educators in both the design and evaluation of participatory science learning experiences" (p.71). According to Barab & Hay,[46] the notion of cognitive apprenticeship includes:

1) The development of learning contexts that model proficiency,
2) Providing coaching and scaffolding as students become immersed in authentic activities,
3) Slowly removing scaffolding as students develop competence, and
4) Providing opportunities for independent practice so that students gain an appreciation of the use of domain-related principles across multiple contexts.

There are two different instructional models based on the cognitive apprenticeship.[93] In a *simulation* model, educators create an environment that supports students in doing science as part of their classroom activities. In a *participation* model, students do science "at the elbows" of scientists. *ISLE* is an example of a simulation model of cognitive apprenticeship. Initial observations of phenomena are usually done under the guidance of the instructor or with the help of carefully designed curriculum materials which students use while performing the observational experiments. The instructor and/or materials guide students through data collection and representation, encouraging them to devise explanations and helping them to design testing experiments. If this part of the cycle is done in large-room meetings (as discussed in the example above), then the professor demonstrates the experiments and the students record their observations. If the observations are done in labs, then the instructor discusses students' findings and helps them identify the patterns. These represent steps 1 and 2 of the cognitive apprenticeship method.

After students devise and test a qualitative explanation for some conceptual area, they work in groups in recitations representing their ideas and the phenomenon in multiple ways, evaluating others' reasoning, and solving problems. The role of the instructor here is to monitor the group work but not provide extensive guidance for the students. This part of the cycle corresponds to step 3 of the cognitive apprenticeship method. Finally, students work in labs designing their own testing experiments or solving experiment problems. Laboratory write-ups do not provide guidance for the students on what experiment to design or how to conduct it but they still scaffold their experiences asking questions relevant to the generic aspects of scientific investigations (to draw a picture of the apparatus, to think of data representations, to evaluate assumptions, to minimize experimental uncertainties, etc.). To solve the problems, students often need to bring together several ideas and make estimations. This part corresponds to step 4 of the cognitive apprenticeship method. The relationship between the steps of the cognitive apprenticeship and the structure of *ISLE* course is summarized in Table 2.

Table 2. ISLE and cognitive apprenticeship.

Cognitive apprenticeship	*ISLE* structure
The development of learning contexts that model proficiency	Students observe carefully chosen experiments in large room meetings or labs – this is a context that we choose for them to develop confidence as when they describe what they observe, they are usually successful
Provide coaching and scaffolding as students become immersed in authentic activities	Students identify patterns in observations and start thinking about explanations (authentic science activity); they devise explanations with the help of the professor in large-room meetings or in labs.
Slowly removing scaffolding as students develop competence	Students work in groups in recitations; the instructor does not scaffold their discussions.
Provide opportunities for independent practice so that students gain an appreciation of the use of domain-related principles across	Students design experiments in labs to test ideas and solve real-life practical problems; the labs are open-ended and allow multiple designs. Students need to integrate several concepts to solve experimental problems.

6. ISLE implementation: available materials, support, and pitfalls

6.1. What materials are available for those who want to implement *ISLE*?

A variety of materials are now available (Fall 2006).

1) The Physics Active Learning Guide (Student Edition)
2) The Physics Active Learning Guide (Teacher Edition)
3) A complete ISLE Laboratory Program (for algebra- and calculus-based physics)
4) A set of ISLE Video Experiments
5) A set of Higher-Level Thinking Formative Assessment activities

These are described briefly below. Eventually, a ***complete set*** of curriculum materials will be published by Addison Wesley, including a textbook, the *ALG*, a bank of test questions and problems, and so forth.

1. The Physics Active Learning Guide (Student Edition[94])

This guide includes four main categories of activities.

Qualitative Concept Building and Testing Activities:

We provide a variety of experiments that could be used in a large room or in a laboratory setting. We also have a new type of experiment – videotaped experiments that have several advantages over traditional lecture demos or lab exercises (http://paer.rutgers.edu/pt3). They allow everyone to see the details and also they allow students to see a phenomenon in slow motion, frame by frame (a frame is 1/30 or 1/15 of a second). This opportunity is invaluable when watching phenomena that happen quickly – the motion of a cart down a ramp, the motion of a falling object, or the motion of a swinging bob attached to a spring scale. The experiments usually involve relatively simple apparatus. Students observe these experiments, record what they observe, and identify patterns in these observations. They then develop a qualitative explanation for the patterns that have been identified—a provisional conceptual model. They then use their own explanation to make a prediction about the outcome of a new testing experiment (also in the *ALG*). If their prediction is incorrect, they have to revise the explanation, revise how they applied their explanation, evaluate how the testing experiment was performed, or evaluate their interpretation of the experiment outcome. The *ALG* provides scaffolding for the students for all these activities.

Conceptual Reasoning Activities:

This part includes situations that the students can analyze using their qualitative explanation(s). Often this reasoning is facilitated using qualitative-concrete representations of physical phenomena (motion diagrams, free-body diagrams, qualitative work-energy bar charts, ray diagrams, and so forth). This part has "Reasoning skills" – text boxes that guide students step-by-step through the mastering of the skill of making a particular representation – such as a motion diagram or a free body diagram. The skill box is followed immediately by one or two activities that help students self-assess whether they mastered this particular skill.

Quantitative Concept Building and Testing Activities:

These sections of the *ALG* contain activities that help students develop a quantitative relationship between physical quantities. Sometimes the *ALG* provides a series of experiments in which students devise physical quantities and relationships between them. (These experiments can often be easily reproduced in a lecture or laboratory setting.) Sometimes the experiments are described and students are provided with a table of collected data that they have to analyze. In some situations, an activity is a guided derivation that helps students construct a new relationship using physical quantities and concepts developed earlier. After a relationship is developed, the *ALG* describes testing experiments for this relationship but not their outcomes. Students use the relationship that has been developed to make a prediction about the outcomes. They need to consider the assumptions that they used to make a prediction in addition to the relationship under test. Then they perform the experiment and compare the outcome to the prediction. If their prediction is incorrect, they have to revise the rule, revise how they applied their rule, evaluate how the testing experiment was performed, or evaluate their interpretation of the experiment outcome. Students have to decide if the outcome of the experiment and their prediction were within experimental uncertainties.

Quantitative Reasoning:

This section provides a problem solving strategy for a particular chapter and a variety of problem types that students can solve in lectures, recitations, or for homework. In most chapters this section has six different types of activities, which are described in Table 3.

The problem solving strategy has the same five general steps that repeat from chapter to chapter and the specific sub-steps that are relevant for a particular content area. These general steps and modifications for a particular chapter (circular motion described above) are shown in Table 4.

2. The Physics Active Learning Guide (Instructor Edition[95]).

This has the same activities as the student edition but also includes guidance for instructors about how to use the activities and reasons for using them.

3. The ISLE Laboratory Program

This is a complete laboratory program for algebra-based and calculus-based physics courses. It is available at http://paer.rutgers.edu/scientificabilities.

In *ISLE* labs students design their own experiments being guided by questions that focus on the general steps of a scientific investigation. The labs involve rela tively simple equipment and experiment design to achieve some goal and the solution of a problem that involves experimental apparatus. The students are expected to take charge of the lab activities—these are not cookbook labs.

4. A set of ISLE Video Experiments

This is a set of experiments that have been videoed, compressed, digitized and placed on a website accessible to anyone (http://paer.rutgers.edu/pt3). Each experiment is accompanied by questions that can be used with students relative to the videoed experiment. As of August 2006 there were about 200 such experiments. The website is updated regularly.

Table 3. Types of quantitative reasoning activities.

Type of activity	Short description
Contextually interesting problems	Relatively standard problems which have interesting contexts
Multiple representation problems	Students represent a word problem in different ways (such as, a sketch, graph, diagram, and equation)
Equation Jeopardy problems	Students are given an equation and are asked to construct other representations of a physical process that are consistent with the equation.
Problem-posing problems	A physical situation is described in one way and students are to invent a problem involving the situation.
Evaluation problems	Students are provided a solution for a problem and are asked to evaluate it for errors or in other ways.
Design and analyze problems	More complex problems where students need to design an experiment to achieve some goal and to development an appropriate mathematical solution to answer the question. The problems often involve concepts from different conceptual areas (for example, energy and circular motion).

Table 4. Problem solving strategy.

General steps of the problem solving strategy	Modifications of the steps for the circular motion chapter
Picture and translate	Sketch the situation described in the problem statement. Choose a system when the object is at one particular position along its circular path. Draw an axis in the radial direction toward the center of the circle.
Simplify	Decide if you can consider the system as a particle Determine if you can ignore any interactions of objects outside the system with the system object. Determine if the constant speed approach is appropriate.
Represent physically	Indicate with an arrow the direction of the acceleration when passing the previously determined position Draw a free-body diagram for the object at the instant it passes that position.
Represent mathematically	Convert the free-body diagram into the radial component form of Newton's second law. For objects moving in the horizontal plane, you may also need to apply the vertical component form of Newton's second law to solve the problem

Solve and evaluate	Solve the equations formulated in the previous two steps and evaluate the results to see if they are reasonable (the magnitude of the answer, its units, how the solution changes in limiting cases, and so forth.

5. Higher-level thinking formative assessment activities

This set of activities (available at http://paer.rutgers.edu/scientificabilities) was developed with support of the National Science Foundation. These activities can be used in large-room meetings, recitations, and laboratories to help students develop science process abilities such as: model building, testing models, using multiple representations for qualitative reasoning and problem solving, experiment design, evaluation, anomalous data activities.

6.2. ISLE users can get support in many ways

Support is available to ISLE users in several ways.

1) The Principal Investigators on the project can be contacted by email concerning specific questions: Eugenia Etkina (etkina@rci.rutgers.edu) or Alan Van Heuvelen (alanvan@physics.rutgers.edu).
2) The principal investigators lead workshops in which participants receive curriculum material and training in using the materials. These workshops include:

- 3-day NSF supported workshops for two-year college professors and high school teachers [organized by Curt Hieggleke (Joliet Community College) and Tom O'Kuma (Lee College)]—look for ads in *The Physics Teacher*; and
- Full-day workshops at the summer AAPT meetings (look in the *Announcer*).
- Eventually, Addison Wesley will support regional workshops for colleges and universities interested in the *ISLE* learning system.

3) This paper provides the most detailed description of ISLE. Shorter papers are also available.
4) Solutions for all ALG problems are now available on the Addison Wesley Website.

6.3. Frequently asked questions about implementing ISLE

1) Can students construct most of physics by themselves?
2) Will students participate?
3) How do I find appropriate testing experiments?
4) What if I have a separate lab course?

5) Is it necessary to train the TA?
6) Will students like it?
7) What do I need to leave out?

Here are the answers.

1. Can students construct most of physics by themselves? The answer is yes. It might seem impossible for the students to discover all of the concepts of physics when it took physicists thousands of years to do it. However, they are not exactly repeating the historical path of physicists because of the guidance, scaffolding, and the selection of experiments for the first observations of the phenomena. The major difficulty in implementing *ISLE* is a need for the instructor's mental shift. The instructor is no longer presenting and illustrating the concepts but is creating an environment and providing guidance to help the students "construct" the concepts themselves. Although the *ISLE* cycle mirrors processes that physics instructors use when "doing physics", it represents a change in the approach to teaching physics.

2. Will students participate? They will, if you have patience. When students work in groups devising explanations, it takes time for them to come up with testable ideas. The instructor has to be patient and should not dismiss the explanations that she/he knows to be wrong. She/he should focus the attention of students on different ways of testing suggested explanations. This poses another difficulty – the need to think of testing experiments "on the spot".

3. How do I find appropriate testing experiments? Use the literature describing historical experiments and students' ideas recorded by PER researchers[96]. In addition, the *Physics Active Learning Guide* provides many testing experiments that can be used in classes.

4. What if I have a separate lab course? It is best if there is a conceptual coordination between the lab and lecture course. Labs serve an important purpose in the *ISLE* cycle. Students either conduct observational experiments in labs and then devise explanations under the guidance of the instructor, or they conduct testing and application experiments in lab after the explanations have been developed in lectures. The former approach works in small courses and the latter in large enrollment courses. In a large course, the labs are stretched over a week and it is difficult to have students in the lecture who have all already had the same lab experience. We have not implemented *ISLE* in courses that do not have integrated labs, lab courses that are synchronized with the lecture course, or some kind of mini-labs; however there was a successful case of the implementation of *ISLE* design labs in a traditional course.[97]

5. Is it necessary to train the TAs? Yes. Training teaching assistants (TAs) is an important issue in large enrollment courses. In labs and recitations *ISLE* students work in groups, thus TAs should be trained in facilitating group work. TAs need to learn not to "explain" material to the students but to be patient, to allow students to devise "wrong" explanations, and to be prepared to design testing experiments if necessary. Our experience is that at least one one-hour weekly training session is necessary. During these sessions TAs should work in groups through all student recitation activities, design lab experiments, analyze data, etc. Another helpful strategy is to have a lab coordinator who can observe and provide feedback to the TAs during their first weeks of teaching.

6. Will students like it? Not immediately. Students' attitudes and expectation might pose an obstacle in *ISLE* implementation. Many students come into physics courses expecting to be told some information and provided with clear instructions on how to perform lab experiments. *ISLE* lab experiments are not like this. Thus, students experience a "shift". Xueli Zou documented the time frame for this shift in the *ISLE* course structured around labs[98]. During the first 3-4 weeks students are very frustrated – they do not know "what to do or how to do it". During the next three or four weeks, they "know what to do but still do not know how to do it". During the rest of the semester, students "know what and how" and started to enjoy the creative process.

In 2006, Ruibal Villasenhor and Etkina[99] conducted a qualitative study of *ISLE* students' attitudes and expectations. In-depth interviews of nine students indicated that their attitudes towards this innovative method of teaching are shaped by prior expectations, perceptions of the level of difficulty of the subject, and of their learning styles. Those who perceived the subject of physics as difficult and thought that they learn best by listening to a lecture and doing practice problems were less likely to appreciate *ISLE*. Also, those who did not understand the goals of the course and the goals of individual activities were more likely to criticize the system. We suggest that *ISLE* adopters put a special effort into explaining the reasons behind the *ISLE* philosophy and structure to the students and provide explanations for different activities. A sample motivational power point presentation is available at http://paer.rutgers.edu/scientificabilities .

7. Do I need to leave out a great deal of material? Roughly, about 10%-15%. A common concern is that the instruction suggested here takes more time and consequently some conceptual material may have to be omitted. First, there is ample evidence that moving quickly through chapter after chapter at high speed does not mean students have learned much. Second, spending more time on most important ideas helps students remember them better. You don't have to worry about omitting some

material if you use the extra time to go into greater depth about the most important ideas.

For example, we omit calculations of rotational inertia in courses for engineers. We omit special relativity in the course for biology majors (it hurts, but we do it). Every professor has special subjects that they do not want to omit. Thus, a list by us of subjects that can be omitted will turn off some professors. You will have to make your own decision about which mini-subjects to omit.

7. Evaluation of *ISLE*: Does the system work?

To evaluate *ISLE* we use a variety of traditional and non-traditional instruments.

7.1. Traditional instruments:

The Force Concept Inventory[100] was used for pre-post assessment of *ISLE* students in several courses. The gains of *ISLE* students are comparable to the gains of students in reformed courses[54]. Xueli Zou's students at California State, Chico achieved a gain of 0.60 in 2001 during her first year of teaching using *ISLE*; Alan Van Heuvelen achieved 0.64 in 2001 teaching engineering students at Ohio State University.

On the conceptual survey of Electricity and Magnetism (CSEM, [101]), *ISLE* calculus-based students consistently showed very high post-test scores. Students of four different *ISLE* instructors in calculus-based courses at Chico and Ohio State ranged from 63 to 74% (the average for calculus-based courses is 47%).

In 2004 AVH included 8 multiple-choice problems on the final exam in his *ISLE* algebra-based course that had been used previously in the same course when taught traditionally (the problems were selected by the previous instructor). The average of the ISLE students was 15 percentage points higher than the traditionally taught students (73% correct compared to 58% correct).

7.2. Non-traditional instruments

We used several non-traditional assessment measures to determine if ISLE students acquire abilities used in the practice of science and engineering. We will briefly describe the results.

In 2003/05 Rosengrant, Van Heuvelen, and Etkina[102] conducted a study of students' use of multiple representations while solving multiple-choice exam problems in mechanics and static electricity in a large enrollment (500 students) introductory course for biology and health profession majors. In particular they focused on the use of free-body diagrams. The sample for the study had 240 randomly selected students. The data were collected from the exam problem sheets where students sometimes do work to solve problems. Their grade was based on the answers circled on the scan sheet. The study found that more than 60% of the students drew free-body diagrams while solving multiple choice problems even though they knew that there will be no credit given for the work. Thus one can say that they drew diagrams to help solve the problems. This number reflects only the students whose exams sheets had the diagrams. There could have been others who drew diagrams on extra paper. The study also found that those who drew correct diagrams were much more successful in getting the right answer for the problems.

In the laboratory course accompanying the course in which the multiple representation study was conducted, Murthy and Etkina[103] studied students' abilities to design experiments to solve experimental problems, choose a correct mathematical procedure to analyze data, and to communicate details of experimental design. The course had about 500 students and the sample for the study had 50 randomly selected students. Murthy and Etkina analyzed lab reports of the students at the beginning, middle and at the end of the semester using the scientific ability rubrics developed by Rutgers PAER group as a part of the NSF funded ASA [Assessing Student Achievement] project.[104] They found that over the course of one semester students significantly improved on all three abilities. Studies that are being conducted in a smaller (170 students) course for science majors will produce data on other scientific abilities such as developing and testing explanations, data analysis and interpretation, and others.

A subsequent study by Karelina and Etkina[105] found that students' behavior in *ISLE* labs resembles that of scientists: they spend ample time discussing the experimental design, assumptions, and experimental uncertainties before they carry out the experiment; when they have a question about the validity of a certain assumption, they check it out experimentally without relying on a TA. Their behavior can be explained by the scaffolding questions in the lab write-ups, the behavior of the TAs who are trained not to answer their questions directly, and by the rubrics that they use for self assessment. The study was extended to the observations of students in traditional labs. The authors found that these students behave differently: they follow the instructions without questioning; every time they are "stuck", they call a TA who resolves their difficulty; and in general, the time that they spend making sense of the same experiment is about 1/3 of that of the *ISLE* students.

In 2002/03 X. Zou who is using *ISLE* in an electricity and magnetism semester of a calculus based course for engineers (50 students) at California State University, Chico conducted a study of students' epistemological beliefs.[106] Zou's students had to answer "convincing" questions such as "How would you convince a student in your physics class that the energy is conserved" (pre-test question) and "How would you convince a student in your physics class that electric charges (i.e., electrons) can move freely in an aluminum pie pan?" (post-test). She coded students' responses according to four epistemological dimensions: 1) *Naïve knowing*: referring explicitly to the authority (i.e., professor or textbook) or repeating formal definitions, equations, or typical explanations from the authority; 2) *Developmental knowing*: citing an example (which was considered as experimental evidence in the coding), but not illustrating it in detail; 3) *Transitional knowing*: describing one or more examples in detail but without logical interpretation of evidence; 4) *Scientific knowing*: clearly describing an experiment and exhibiting a hypothetical-deductive thinking pattern. The results of her work show that after a semester of *ISLE*, there was a significant improvement (from 7% to 70%) in students' ability to respond to convincing questions via scientific knowing. The details of her findings are given in Table 5. In the spring 2003 X. Zou and D. Van Domelen conducted a study comparing responses of *ISLE* students and traditionally taught students at California State University, Chico and Kansas State University on a post-test question using a multiple-choice format. The choices for the students followed the epistemological dimensions described above. 24% of traditionally taught students chose a response based on naïve knowing (authority) and 45% chose the response based on scientific knowing (hypothetico-deductive reasoning). In contrast, none of the *ISLE* students chose the authority response and 66% chose hypothetico-deductive reasoning.

More studies need to be done to evaluate how *ISLE* students differ from traditional students; however, even now we can say that they learn the content at the same level as students in courses taught through interactive engagement techniques and make significant progress in acquiring scientific abilities.

Table 5. Distribution of ISLE student's responses to the pre-test and post-test "convincing" questions (Zou, 2003).

	Code 1	**Code 2**	**Code 3**	**Code 4**
Pre-test	28%	15%	50%	7%
Post-test	0	0	30%	70%

8. Summary

In this chapter we described a comprehensive learning system – *Investigative Science Learning Environment* - in which student learning, carefully guided and scaffolded, mirrors processes by which physicists construct and apply knowledge. The *ISLE* system also helps students acquire tools and abilities that physicists use in their work. The goals of the learning system are consistent with the goals of science education in the United States and with the needs of the workplace. The logic of the system is consistent with scientific epistemology. The theoretical foundation is based on research concerning brain development and cognition. Practical implementation follows the recommendations of the studies of cognitive apprenticeship and formative assessment.

The system can be used in large or small enrollment courses and has been piloted in several universities with regular, honors, and low-achieving students in algebra-based and calculus-based courses. The system can be used in a standard lecture-recitation-laboratory format setting of an existent course, without any need for additional human resources or room renovations. A large set of curriculum materials is being developed and many of them are presently available for use. Preliminary content and process assessments of student learning show that the system is successful in helping students learn the traditional content of physics. In addition students acquire expert-like abilities such as the use of multiple representations during problem solving, hypothetico-deductive reasoning, and the ability to design scientific investigations.

9. Acknowledgments

The development and implementation of *ISLE* would not be possible without Xueli Zou, Suzanne Brahmia, Michael Lawrence, David Brookes, David Mills, and Pearson Addison Wesley. We are grateful for the support provided by NSF grants DUE-0088906 and DUE 0241078. We thank all people who contributed to the development of *ISLE* materials: Sahana Murthy, Michael Gentile, David Rosengrant, Marina Milner-Bolotin, Anna Karelina, Maria Ruibal Villasenhor, Aaron Warren, Richard Fiorillo, Gabe Alba., Hector Lopez, Chris D'Amato, Christine Osborne, Jim Flakker, and many others. We thank the AAPT for giving us an opportunity to lead ISLE training workshops and Thomas O'Kuma and Curtis Hieggelke for arranging workshops for two year college professors. We thank all who implement ISLE in their classrooms

References

[1] E. Etkina and A. Van Heuvelen, Investigative Science Learning Environment: Using the processes of science and cognitive strategies to learn physics, in *Proceedings of the 2001 Physics Education Research Conference*. (Rochester, NY, 17-21, 2001).

[2] Careful selection means that experiments are simple, focus on one phenomenon and the pattern is easily identified. For example one can choose to record position of a cart pulled by a spring to study how acceleration of a cart depends on the forces exerted on it by other objects and its mass. A similar experiment in which the cart is pulled by a hanging object is more complicated; the force exerted on the cart depends

on its mass. Thus when we select an observational experiment using which students will construct Newton's second law, we choose the first experiment.

[3] D. Hammer and A. Elby, Tapping epistemological resources for learning physics, *The Journal of Learning Science* **12**(1), 53 (2003).

[4] A. Lawson, The nature and development of hypothetico-predictive argumentation with implications for science teaching, *International Journal of Science Education* **25**(11), 1387 (2003).

[5] A. Van Heuvelen, Learning to think like a physicist: A review of research-based instructional strategies, *American Journal of Physics* **59,** 891 – 897 (1991).

[6] A. Van Heuvelen and X. Zou, Multiple representations of work–energy processes, *American Journal of Physics* **69**, 184. (2001).

[7] A. Van Heuvelen, *ActivPhysics on line workbook.* (Pearson Addison Wesley, San Francisco, CA, 2004.)

[8] D. T. Brookes. Unpublished doctoral dissertation, Rutgers University, 2006.

[9] E. Etkina, A. Van Heuvelen, S. White-Brahmia, D. T. Brookes, M. Gentile, S. Murthy, D. Rosengrant, and A. Warren, Scientific abilities and their assessment, *Phys. Rev. ST Phys. Educ. Re*s. **2**, 020103 (2006)

[10] P. Black and D. Wiliam, Assessment and classroom learning, *Assessment in Education* **5**(1), 7 (1998).

[11]A. Van Heuvelen and E. Etkina, *The Physics Active Learning Guide*, (Pearson Addison Wesley, San Francisco, CA, 2006.)

[12] C. Crouch et al., Peer Instruction: Engaging Student One-on-One, All at Once, this volume

[13] E. Etkina, S. Murthy, and X. Zou, Using introductory labs to engage students in experimental design, *American Journal of Physics*, **74**, 979 (2006).

[14] E**.** Etkina, Formative and summative assessment in a physics class: time to change, in *Proceedings of the 2002 Physics Education Research Conference*, (Boise, Idaho, 25–31, 2002).

[15] E. Etkina, Developing and assessing students' scientific abilities, Invited presentation at the AAPT National Meeting, Miami, Florida, January, 2004.

[16] D. Brookes, E. Etkina, M. Lawrence, and J. Timofeeva, Video Problems: A New Type of Context-Rich Problem, AAPT National Meeting, Sacramento, California, August 2004.

[17] E. Etkina, A. Warren, and M. Gentile, The role of models in physics instruction, *The Physics Teacher*, **44** (1), 34 (2005).

[18] E. Etkina. S. Brahmia. and A. Eisner, New format of exam questions, AAPT National meeting, Madison, Wisconsin, August 2003.

[19] M. Milner-Bolotin, E. Etkina, and A. Van Heuvelen, Innovative lab exams, AAPT National Meeting, Austin, TX, January 2003.

[20] S. Brahmia and E. Etkina, Implementing ISLE in a large-enrollment physics course: lessons learned, AAPT National meeting, Madison, Wisconsin, August 2003.

[21] http://paer.rutgers.edu/pt3/experimentindex.php?topicid=58cycleid=9

[22] A. Van Heuvelen and D. Maloney, Playing physics Jeopardy, *American Journal of Physics*, **67**, 252 (1999).

[23] R. Marshall and M. Tucker, *Thinking for living.* (Basic books, 1992).

[24] P.Chin, H. Munby, N. L. Hutchinson, J. Taylor, and F. Clark, in *Reconsidering science learning*, edited by E. Scanlon, P. Murphy, J. Thomas, A& E. Whitelegg (Routledge Falmer, London, 2004), pp. 118-134

[25] M. Coles, in *Proceedings of the 8th symposium of IOSTE*, edited by K. Colhoun, R. Panwar, & S. Shrum (Faculty of Education, University of Alberta, Edmonton, 1997), **1**, pp. 292-300.

[26] R. Gott, S. Duggan, and P. Johnson, What do practicing applied scientists do and what are the implications for science education?, *Research in Science & Technological Education* **17**, 97 (1999).

[27] E. Lottero-Perdue, and N. W. Brickhouse, Learning on the job: the acquisition of scientific competence, *Science Education* **86**, 756 (2002).

[28] S. Duggan, and R. Gott, What sort of science education do we really need?, *International Journal of Science Education* **24**, 661 (2002).

[29] G. S. Aikenhead, Science-based occupations and the science curriculum: concepts of evidence, *Science Education*, **89**, 242 (2005).

[30] *Shaping the Future: New Expectations for Undergraduate Education in Science, Mathematics, Engineering, and Technology*, NSF Directorate for Education and Human Resources Review of Undergraduate Education, p. 65, May 15, 1996. See recommendations at http://www.ehr.nsf.gov/ehr/due/documents/review/96139/four.htm.

[31] R. Czujko, The Physics Bachelors as a Passport to the Workplace: Recent Research Results, in *The Changing Role of Physics Departments in Modern Universities*, edited by E. F. Redish & J. S. Rigden, AIP Conf. Proc. **399** (Woodbury, NY, 1997).

[32] *What Work Requires of Schools: A SCANS Report for America 20*00, U.S. Department of Labor, Secretary's Commission on Achieving Necessary Skills, 200 Constitution Avenue, N.W., Washington, D.C., 20210 (1991). See also the US Labor Department sponsored study: A.P. Carneval, L.J. Gainer, & A.S. Meltzer, *Workplace Basics: The Essential Skills Employers Want*, (Jossey-Bass Pub., San Francisco, 1990).

[33] See the ABET home page at http://www.abet.org/forms.shtml

[34] J. D. Bransford, A. L. Brown, and R. R. Cocking, *How people learn: Brain, mind, experience, and school.* (National Academy Press, 1999).

[35] National Research Council, *National Science Education Standard.* (National Academy Press, 1996).

[36] G. Holton and S. Brush, *Physics, the Human Adventure* (Rutgers University Press, 2001).

[37] T. S. Kuhn, *The Structure of Scientific Revolutions* (University of Chicago Press, 1970).

[38] N. G. Lederman, F. Abd-El-Khalick, R. L. Bell and R. S. Schwartz, Views of nature of science questionnaire: Toward valid and meaningful assessment of learners' conceptions of nature of science, *Journal of Research in Science Teaching* **39**, 497 (2002).

[39] D. Allchin, Lawson's Shoehorn, or should the philosophy of science be rated 'X'?, *Science & Education* **12**, 315 (2003).

[40] R. Harre, *The philosophies of science* (Oxford University Press, 1972).

[41] B. Y. White and J. R. Frederiksen, Inquiry, modeling, and metacognition: Making science accessible to all students, *Cognition and Instruction* **16**(1), 3 (1998).

[42] R. Driver, P. Newton, and J. Osborne, Establishing the norms of scientific argumentation in classrooms, *Science Education* **84**, 287 (2000).

[43] A. Lawson, What does Galileo's discovery of Jupiter's moons tell us about the process of scientific discovery?, *Science & Education* **11**, 1 (2002).

[44] H. Collins and T. Pinch, *The Golem* (Cambridge University Press, 1993).

[45] D. Mayo, *Error and the Growth of Knowledge* (University of Chicago Press, 1996.)

[46] S.A. Barab and K.E. Hay, Doing science at the elbows of experts: Issues related to the science apprenticeship camp, *Journal of Research in Science Teaching* **38**, 70 (2001); J. S. Brown, A. Collins, P. Duguid, Situated cognition and the culture of learning, *Educational Researcher* **18**(1) 32 (Jan-Feb, 1989).

[47] C.A. Chinn and W. F. Brewer, The role of anomalous data in knowledge acquisition: a theoretical framework and implications for science instruction, *Review of Educational Research* **63**, 1 (1993).

[48] C. A. Chinn and B. A. Malhotra, in *Designing for science: Implications from everyday, classroom, and professional settings*, edited by K. Crowley, C. D. Schunn, & T. Okada (Erlbaum, 2001), p 351

[49] J. Hawkins and R. D. Pea, Tools for bridging the cultures of everyday and scientific thinking, *Journal of Research in Science Teaching* **24**, 291 (1987).

[50] K. S. Kitchener, Cognition, metacognition and epistemic cognition: A three-level model of cognitive processing, *Human Development* **26**, 222 (1983).

[51] F. Reif, and J. Larkin, Cognition in scientific and everyday domains: Comparison and learning implications, *Journal of Research in Science Teaching* **28**, 733 (1991).

[52] P. Zachos, L. T. Hick, W.E.J. Doane, and S. Sargent, Setting theoretical and empirical foundations for assessing scientific inquiry and discovery in educational programs, *Journal of Research in Science Teaching* **37**, 938 (2000).

[53] U. Zoller, Scaling-up of higher-order cognitive skills-oriented college chemistry teaching: An action-oriented research, *Journal of Research of Science Teaching* **36**, 583 (1999).

[54] D. Zollman, Learning cycles for a large-enrollment class, *The Physics Teacher* **28**, 20 (1990).

[55] A. E. Lawson, W. P. Baker, L. DiDonato, M. Verdi and M. Johnson, The role of hypothetico-deductive reasoning and physical analogues of molecular interactions in conceptual change, *Journal of Research in Science Teaching* **30**, 1073 (1993).

[56] L. Vygotsky, *Mind in Society: The development of higher psychological processes* (Harvard University Press, 1978).

[57] J. Lave, *Cognition in practice: Mind, mathematics and culture in everyday life* (Cambridge University Press, 1998).

[58] A. Van Heuvelen, Millikan lecture 1999: The workplace, student minds, and physics learning systems, *American Journal of Physics* **69**(11), 1139 (2001).

[59] F. A. Hayek, *The Sensory Order* (University of Chicago Press, 1944).

[60] J. M. Fuster, *Cortex and mind* (Oxford University Press, 2003).

[61] J. Zull, *The art of changing the brain* (Stylus Publishing, 2002).

[62] Center for Psychology in the Schools and Education (2003). *Learner-centered psychological principles: A framework for school reform and redesign.* http://apa.org/ed/lcpnewtext.html (accessed 05/03/2003)

[63] R. F. Gunstone and I. J. Mitchell, in *Teaching Science for understanding: A human constructivist view*, edited by J. J. Mintzes, J. H. Wandersee, & J. Novak (Academic Press, 1998), p. 133.

[64] R. R. Hake, Interactive-engagement versus traditional methods: A six-thousand-student survey of mechanics test data for introductory physics courses, *American Journal of Physics* **66**, 64 (1998).

[65] C. W. Anderson, in *Strategic teaching and learning: cognitive instruction in the content areas*, edited by B.F. Jones, A.S. Palincsar, D.S. Ogle & E.G. Carr (Association for Supervision and Curriculum Development, 1987), p. 73.

[66] L. B. Resnick, Mathematics and science learning: A new conception, *Science* **220**, 477 (1983).

[67] L. B. Resnick, *Education and learning to think* (National Academy Press, 1987).

[68] L. Schauble, Belief revision in children: The role of prior knowledge and strategies for generating evidence, *Journal of Experimental Child Psychology* **49**, 31 (1990).

[69] E. von Glasersfeld, Cognition, construction of knowledge, and teaching, Synthese 80, 121 (1989).

[70] E. von Glasersfeld, A constructivist's view of learning and teaching, in *The Proceedings of the international workshop on research in physics education: Theoretical issues and empirical studies,* edited by R. Duit, F. Goldberg & H. Niedderer (Bremen, Germany, March 5-8, 1991, Kiel, Germany: IPN, 1992).

[71] K.A. Strike and G. J. Posner, in *Cognitive structure and conceptual change,* edited by L.H.T.West & A. L. Pines (Academic Press, 1985), p. 211.

[72] K. Popper, *The logic of Scientific Discovery* (Hutchinson, 1980).

[73] L. C. McDermott and the Physics Education Group at the University of Washington *Physics by Inquiry*, (John Wiley & Sons, Inc., 1996).

[74] D. R. Sokoloff and R. K. Thornton, Using interactive lecture demonstrations to create an active learning environment, *The Physics Teacher*, **35**, 340 (1997).

[75] L. C. McDermott, Millikan Lecture 1990: What we teach and what is learned—Closing the gap, *American Journal of Physics* **59**(4), 311 (1991).

[76] J.A. Dole and G.M. Sinatra, Reconceptalizing change in the cognitive construction of knowledge, *Educational psychologist* **33**, 109 (1998).

[77] P. R.Pintrich, R. W.Marx and R. A. Boyle, Beyond cold conceptual change: The role of motivational beliefs and classroom contextual factors in the process of conceptual change, *Review of Educational Research*, **63**(2), 167 (1993).

[78] P. R. Pintrich, in *New perspectives on conceptual change Amsterdam,* edited by W.Schnotz, S. Vosniadou, M.Carretero (Pergamon, 1999), p. 33.

[79] E.A. Linnenbrink, and P.R. Pintrich, in *Reconsidering conceptual change: Issues in theory and practice*, edited by M. Limon & L. Mason (Kluwer Academic Publishers, 2002), p. 115.

[80] G.M. Sinatra, S. Southerland, F. McConaughy and J. Demastes, The role of intentions, beliefs and knowledge in learning about evolution, in, *Epistemological beliefs and learning: What do we know and how do we know it?*, Symposium presented at the American Educational research Association Annual Meeting, L.D. Bendixen, Chair (Seattle, WA, April 2001).

[81] M. G. Sinatra and P. R. Pintrich, in *Intentional Conceptual Change,* edited by M. G. Sinatra & P. R. Pintrich (Lawrence Erlbaum Associates, 2003), p. 1.

[82] H. Wentzel, Social competence at school: Relation between social responsibility and academic achievement, *Review of Educational Research*, **61**, 25 (1991).

[83] C. Ames, Classrooms: Goals, structures, and student motivation, *Journal of Educational Psychology*, **84,** 261 (1992).

[84] R. Ryan, J. Connell and E. Deci, A motivational analysis of self-determination and self-regulation in education, in *Research on motivation in education*, **2**, edited by C. Ames & R. Ames (Academic, 1985), p. 13.

[85] E. Elliott and C. Dweck, Goals: An approach to motivation and achievement, *Journal of Personality and Social Psychology*, **54**, 5 (1988).

[86] W. Grolinick and R. Ryan, Autonomy in children's learning: An experimental and individual difference investigation, *Journal of Personality and Social Psychology*, **52**, 890 (1987).

[87] E. F. Redish, R. N. Steinberg, and J. M. Saul, Student expectations in introductory physics, *American Journal of Physics*, **66**(3), 212 (1999).

[88] A. Elby, Helping physics students learn how to learn, *American Journal of Physics (Supplement)*, **69**, S54 (2001).

[89] E. F. Redish and R. F. Lippmann, Improving student expectations in a large lecture class. AAPT National Meeting, Rochester, NY, July, 2001.

[90] J.S. Brown, A. Collins, and P. Duguid, Situated cognition and the culture of learning, *Educational Researcher*, **18**, 32 (1989).

[91] A. Collins, J. S. Brown, and S. E. Newman, in *Knowing and learning: Essays in honor of Robert Glaser*, edited by L. B. Resnick (Lawrence Erlbaum Associates, 1989), p. 453.

[92] A.H. Shoenfeld, *Mathematical problem solving.* (Academic Press, 1985).

[93] S.A. Barab, K.Squire, and B. Dueber, A co-evolutionary model for supporting the emergence of authenticity, *Educational Technology Research and Development*, **48**, 37 (2000).

[94] A. Van Heuvelen and E. Etkina. *The Physics Active Learning Guide, Student Edition.* (Pearson Addison Wesley, 2006).

[95] A. Van Heuvelen and E. Etkina. *The Physics Active Learning Guide, Instructor Edition.* (Pearson Addison Wesley, 2006).

[96] For examples see A. B. Arons. *Teaching Introductory Physics.* (John Wiley & Sons, 1997); R. D. Knight. *Five Easy Lessons*. (Addison Wesley, 2004).

[97] D. Demaree and Y. Lin, Assessing ISLE labs as an enhancement to traditional large-lecture courses at the Ohio State University, in 2005 Physics Education Research Conference (Salt Lake City, UT, August 2005), edited by P. Heron. L. McCullough, and J. Marx, *AIP Conf. Proc*. **818**, 101 (2006).

[98] X. Zou, E. Etkina and A. Van Heuvelen, Laboratory investigations as a part of ISLE project, AAPT National meeting, Rochester, NY, July, 2001, (2001).

[99] M. Ruibal Villasenhor, A. Karelina, and E. Etkina, Student response to innovations in introductory physics, *AAPT Announcer*, **36** (2), 74, 2006.

[100] D. Hestenes, M. Wells and G. Swackhamer, Force Concept Inventory, *The Physics* Teacher, **30**, 159 (1992).

[101] D. Maloney, T. O'Kuma, C. Hieggelke, and A. Van Heuvelen, Surveying students' conceptual knowledge of electricity and magnetism, *Am. J. Phys. (Supplement)* **69**, S12 (2001).

[102] D. Rosengrant, A.Van Heuvelen, and E. Etkina, Free-body diagrams: Necessary or sufficient?, in 2004 Physics Education Research Conference (Sacramento, CA, August 2004), edited by J. Marx, P. Heron, & S. Franklin, *AIP Conference Proceedings*, **720**, 177 (2005).

[103] S. Murthy and E. Etkina, Development of scientific abilities in a large class, in 2004 Physics Education Research Conference (Sacramento, CA, August 2004), J. Marx, P. Heron, & S. Franklin, Eds., *AIP Conference Proceedings*, **720**, 133 (2005).

[104] The project is described at http://paer.rutgers.edu/scientificabilties

[105] A. Karelina, E. Etkia and M. Ruibal Villasenhor, Student response to innovations in introductory physics, *AAPT Announcer*, **36**(2), 134 (2006).

[106] X. Zou, How students justify their knowledge in the Investigative Science Learning Environment, in *Proceedings of the 2003 Physics Education Research Conference* (Madison, Wisconsin, 2003).