Using introductory labs to engage students in experimental design

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The Investigative Science Learning Environment (ISLE) engages students in processes mirroring the practice of science. Laboratories play a central role in this learning environment. Students in ISLE laboratories design their own experiments to investigate new phenomena, test hypotheses, and solve realistic problems. We discuss various issues associated with implementing these labs in large enrollment introductory physics courses. We present examples of experiments that students design, include a sample of student work, and discuss issues related to the choice of experiments for design and practical implementation. We also review assessment techniques and show results of students' acquisition and transfer of some laboratory-related abilities.

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I. INTRODUCTION AND MOTIVATION

According to the American Association of Physics Teachers, the important goals of introductory physics laboratories should be designing experimental investigations, evaluating experimental data, and developing the ability to work in groups.[1] Studies and reports by ABET (the engineering accreditation organization),[2] the National Science Foundation,[3] and the American Institute of Physics[4] suggest that achieving these goals can help our students in their future work. Students' engagement in activities similar to those of scientists is a top priority in all of these reports. However, student work in traditional instruction often differs from the practice of science and engineering. In particular, students in laboratories often do prescribed experiments following recipe-like instructions to verify a model. They seldom design their own experiments, formulate their own questions, or reconcile unexpected results.

There are efforts from the middle school[5] to the college level to make laboratories more "science process oriented." At the college level, examples include a prototype introductory physics laboratory for a self-paced course,[6] the Scientific Community Labs at the University of Maryland,[7] SCALE-UP,[8] and ISLE (Investigative Science Learning Environment) labs pioneered by Zou in small and medium enrollment physics courses.[9]

Central to ISLE laboratories is student design of experiments to investigate phenomena (suggested by a lab write-up), test explanations of the observed phenomena, and apply the explanations to solve realistic problems. In this paper we first describe how the ISLE labs address the above goals. We then discuss how the ISLE labs can be modified so they can be implemented in large enrollment courses, what strategies can be adopted to help instructors teach in this lab environment, whether students in ISLE labs acquire some of the laboratory-related abilities that have been identified as important goals, and how students perceive their learning.

II. ISLE AND ISLE LABORATORIES

ISLE is a system used in introductory physics courses that engages students in processes similar to the ones that scientists use to construct and apply knowledge.[10] Students start each conceptual unit by analyzing patterns in experimental data (often students collect the data but sometimes data tables are provided). They use multiple representations of the data to construct possible explanations or mathematical relationships. In the next and crucial step, students test their constructed ideas using hypothetico-deductive reasoning.[11] Students predict the outcomes of new experiments using their constructed ideas, perform the experiments, and revise their ideas if the outcomes do not match the predictions. Finally, they apply these ideas to solve problems. The experiments that students observe or perform are grouped as observational, testing, or application experiments according to their role in constructing scientific knowledge.[12]

There are no traditional lectures in ISLE. Instead, students attend large room meetings that are interactive, use elements of peer instruction, and a personal response system. Recitation activities involve group work on multiple representation problems,[13] conceptual questions, and complex problems. (Examples of activities and their sequences for large room meetings and recitations can be found in Ref. 14).

In the ISLE labs students collect data that they later analyze, or test explanations that they constructed in large room meetings, or apply concepts to solve problems. The laboratories utilize many traditional laboratory setups, but students do not receive instructions on how to perform the experiments. Instead, students have to design the experiments themselves to achieve specific goals.

III. INITIAL DEVELOPMENT OF ISLE LABORATORIES

The ISLE laboratories were developed and first used in calculus-based introductory physics courses with a class enrollment of about 50 students (divided into two lab sections) in a medium-sized state university.[10] The professor who taught the course and designed the labs was also the lab instructor. The labs were central to student learning. For each unit, students designed experiments to collect data that would help them construct a desired concept (for example, momentum conservation). They discussed their findings with the professor in the following large room meeting, developed

Table I. Portion of rubric (only one ability is shown) that provides scaffolding to students in designing and perform experiments and writing lab reports.

Scientific Ability	0: Missing	1: Inadequate	2: Needs Improvement	3: Adequate
Is able to evaluate the results by means of an independent method.	No attempt is made to evaluate the consistency of the results using an independent method.	A second independent method is used to evaluate the results. There is little or no discussion about the differences in the results due to the two methods.	A second independent method is used to evaluate the results. Some discussion about the differences in the results is present, but there is little or no discussion of the possible reasons for the differences.	A second independent method is used to evaluate the results. The discrepancy between the two methods, and possible reasons are discussed. A percentage difference is calculated in quantitative problems.

multiple representations to describe the concept, and then returned to the lab to design new experiments to test the proposed concept. For each experiment a brief outline of relevant scientific procedures was provided to students. Examples of lab experiments that were used in this course are available.[15] Studies showed that students acquired abilities to design experiments and reason hypothetical-deductively and showed conceptual gains typical for interactive engagement courses.[16]

The professor was crucial in this setting. She observed students' work and challenged their thinking through Socratic dialogues. She knew what the students did in a particular lab and based her large room meeting discussions on students' lab experiences. She helped students design experiments using her knowledge and experience of ISLE methods.

Can these laboratories be implemented in large enrollment algebra-based courses that follow the ISLE curriculum but whose labs are taught by TAs with little or no experience? Can they work in courses with multiple sections that meet on different days of the week? To address these issues we modified the initial ISLE labs and modified the content of the experiments to make them suitable for the algebra course, and changed the structure of lab guidelines. We also paid special attention to instructor training.

IV. ISLE LABORATORIES IN LARGE ENROLLMENT COURSES

We made three important modifications to support student work through the design process. First, we put the guiding questions in all lab write-ups into a consistent format. They require students to focus on the same elements of the experimental design and communication (see examples in Secs. IV A–IV C). Second, we provide students with self-assessment rubrics that assist them in their work and helped them write lab reports.[17] (A rubric is an ordered list of descriptors indicating different levels of performance.) Our rubrics contain descriptors (on a scale of 0 to 3) of writing in response to each guiding question in the lab write-up. The rubrics were developed and validated by our research group of nine members, who achieved an inter-rater reliability of at least 80%. An example of a rubric used when students design an experiment to determine an unknown quantity is shown in Table I. Usually students have four to five rubrics to help them in each lab. All rubrics that students use in labs are available.[18] Third, we added reflection questions at the end of each experiment to help students focus not only on the physics aspects of the lab, but also on the processes that they followed to achieve the results.

One of the practical constraints we faced in the large enrollment classes was that students from different sections performed labs on different days of the week, but they all met the same day for the large room meeting. Thus, we could not have students design experiments in the laboratories to construct all of the concepts in the course, as in the original ISLE labs. However, students could perform some observational experiments in the labs the week before the discussions in the large room meeting. Students were required to bring their data to the large room meeting, and the instructor started the discussion with an analysis of the lab results. Most of the lab experiments in the large enrollment courses were testing or application experiments done the week after students constructed concepts in large room meetings.

This discussion shows that the ISLE laboratories are flexible in terms of the method of implementation. Although the large room meetings and labs we describe in this paper both followed the ISLE curriculum, the labs could be implemented in parallel with any physics course. For example at The Ohio State University in 2004/05, ISLE laboratories were successfully implemented in some sections of a large traditional calculus-based introductory course where the lectures and the recitations did not follow the ISLE format.[19]

In the following we describe several examples of different types of experiments students design with the laboratory guidelines in an algebra-based introductory physics course. We also discuss issues involved in the choice of experiments of a particular type, features of the guidelines, and important points related to their implementation.

A. Observational experiments

Students perform these experiments when they investigate a new phenomenon that has not yet been discussed in the large room meetings. Although in some cases the students might have expectations of the outcomes of these experiments, we do not require them to make predictions. Students collect, analyze, and find patterns in the data. The experiments can be qualitative or quantitative and require different levels of creativity. The following examples are as they appeared in the lab write-ups for students.

Example 1, a qualitative observational experiment (performed before students learn right-hand rules). You have a cathode ray tube that has a beam of moving electrons. The beam produces a bright spot where it hits the screen. You also have a bar magnet with labeled poles. Design an experiment to determine the pattern between the orientation of the magnet and the deflection of the beam. Available equipment: bar magnet and cathode ray oscilloscope.

Write the following in your lab report:

1. Devise a procedure for your investigation and describe your design.
2. Draw a labeled diagram.
3. Record your observations. Decide how you can best represent the data. A table and/or a picture may be helpful.
4. Find a pattern from your observations between the orientation of the magnet and the deflection of the beam.
5. Reflection: give an example from everyday life where you need to find a pattern in some phenomenon or process.

After students perform this experiment in the laboratory, they use the result they found to formulate the right-hand-rule in the large room meetings.

Example 2, a quantitative observational experiment (performed before students study Ohm's law). Design an experiment to determine the relation between the current through a resistor and the voltage across the resistor. Available equipment: a voltage source (such as a variable power supply), resistors, ammeter, voltmeter, and connecting wires.

Write the following in your lab report:

1. Devise a procedure for your investigation and describe your design.
2. Draw a circuit diagram.
3. What important physical quantities change during the experiment? What are the independent and dependent variables in your experiment?
4. List sources of experimental uncertainties. Evaluate how these will affect the results.
5. Connect the circuit according to your diagram and perform the experiment.
6. Record your data in an appropriate manner.
7. Describe the pattern you found between the current and the voltage as a mathematical relation.
8. Reflection: discuss whether the pattern you found makes sense.

Notice the patterns in the guidelines for the students as they perform observational experiments. The guidelines do not tell them what to do in terms of the particular experiment, but instead guide them through the generic steps of the experimental process relevant to this type of experiment. The guidelines for Example 2 can be used for almost any observational experiment where students need to find and analyze the pattern in the data.

B. Testing experiments

Testing experiments are performed after students have some understanding of the material from large room meeting discussions. Here the goal is to design an experiment whose outcome they can predict based on the hypothesis to be tested. The hypothesis could be an explanation of a pattern in the data or a formal relation between variables. One of the important aspects of designing a testing experiment is to understand the difference between a hypothesis that is being tested and a prediction of the outcome of the experiment that one makes based on this hypothesis. Thus, the prediction can only be made after the experiment is designed. In everyday language, the words "explanation" and "prediction" are often used interchangeably; hence it is important to help students learn the difference between the two. To make a prediction students need to accept the hypothesis (explanation or relationship) that they are testing as true (at least for the time being) and then use it to make a prediction about the outcome of the experiment. They also decide what additional assumptions they need to make and how these might affect the outcome of the experiment and their judgment about the hypothesis. We emphasize that when the prediction agrees with the experimental outcome, it means only that the hypothesis cannot be rejected. On the other hand, if the prediction does not agree with the experimental outcome, either the additional assumptions need to be reconsidered, or the hypothesis needs to be revised or rejected.

How do we pick experiments to serve as testing experiments? One way is to ask students to test "hypotheses" that were found as students' alternative conceptions by physics education researchers. Some examples include objects always move in the direction of the net force exerted on them by other objects, batteries are sources of constant current, and the image formed by a plane mirror is on the surface of the mirror.

Other experiments in this category might be testing if a quantitative relationship, found to be valid in one situation, applies to a different situation, for example, whether a linear relation between current through a resistor and the voltage across it found in Example 2 is applicable to a light bulb. Students also can design experiments to discriminate between different mathematical models that describe a given physical system.

Example 3 shows the guidelines in the laboratory write-up that students receive. These guidelines are applicable to all testing experiments.

Example 3. Your friend says that as current flows through a circuit, it is used up by the elements of the circuit. Design an experiment to test your friend's idea. Available equipment: a voltage source, resistors, light bulbs of different ratings, ammeter, and a voltmeter.

Write the following in your lab report:

1. State the hypothesis you will test.
2. Devise an experiment to test the hypothesis. Write an outline of your design and procedure.
3. Draw a circuit diagram.
4. List the assumptions you are making.
5. Make a prediction of the outcome of the experiment based on the hypothesis you are testing and your assumptions.
6. List sources of experimental uncertainties.
7. Perform the experiment. Record your data in an appropriate format.
8. Did the experimental outcome support the prediction? Did you account for experimental uncertainties?
9. Based on the prediction and the outcome of the experiment, what is your judgment about the hypothesis you were testing?
10. Reflection: discuss how the hypothesis you tested was different from the prediction you made.

Experiment #1:

Heat water with the object in it. Measure the initial temperature of the object T_{io} by measuring the temperature of the hot water it is in. Mass the cold water (mass of the container and water – mass of the container), measure the initial temperature of cold water. Put the cold water in the calorimeter, then the hot object in the calorimeter and wait a little. Measure the final temperature. Solve for the specific heat

$Q_{gained\ by\ water} = Q_{lost\ by\ object}$

$m_w c_w (T_f - T_{iw}) + m_o c_o (T_f - T_{io}) = 0$

<*Student draws a picture here*>

Assumptions:

1) The system is the object and water only but not the calorimeter.
2) No heat is lost to the calorimeter by the system. If it is, T_f will be less than it would have been. So the specific heat will be less than the real value.
3) No heat is lost to the air when we transfer the hot object. If heat is lost our T_{io} is more than the real T_{io}. Specific heat will be less than the actual value.
4) The water and object have no temperature gradient. If it did our T is wrong. We should stir the water to avoid temperature gradient.

Measurement of mass. The smallest division on the scale is 0.001kg.

$m_o = 0.22kg \pm 0.001kg,\ m_w = 0.075kg \pm 0.001kg$

Uncertainty in mass is: $\frac{0.001}{0.22} \times 100 \simeq 0.45\%,\quad \frac{0.001}{0.075} \times 100 \simeq 1.3\%$

Measurement of temperature: The smallest division on the thermometer is 1°C.

$T_{iw} = 20^\circ C \pm 0.5^\circ C,\ T_{io} = 57^\circ C \pm 0.5^\circ C,\ T_f = 27^\circ C \pm 0.5^\circ C$

What we are measuring in our experiment is the difference in temperature

$T_f - T_{iw} = 27^\circ C - 20^\circ C = 7^\circ C$ and $T_{io} - T_w = 57^\circ C - 27^\circ C = 30^\circ C$.

Uncertainty in temperature is: $\frac{1^\circ}{7^\circ} \times 100 = 14.29\%,\quad \frac{1^\circ}{30^\circ} \times 100 = 3.33\%$

The weakest link is in the temperature measurement. It is 14.29%

$m_w c_w (T_f - T_{iw}) = -m_o c_o (T_f - T_{io})$

$(0.075kg)(4186J/kg/^\circ C)(27^\circ C - 20^\circ C) = -(0.22kg)(c_o)(27^\circ C - 57^\circ C)$

$c_o = 332.9\ J/kg/C$

Experiment #2:

Put the cold object (room temperature) in hot water in the calorimeter. Measure mass of hot water before. Measure the temperature of the hot water first, then temperature of object and water.

<*Student draws picture here.*>

Assumptions:

1) The system is the object and water.
2) No heat is lost to the calorimeter. If heat is lost the specific heat will be less.
3) There is no temperature gradient in the water.
4) The object is really at room temperature.

Uncertainty in mass.is the same as before.

Temperature measurement:

$T_{iw} = 71^\circ C \pm 0.5^\circ C,\ T_{io} = 24^\circ C \pm 0.5^\circ C,\ T_f = 61^\circ C \pm 0.5^\circ C$

We are measuring the difference in temperature $T_{iw} - T_f = 71^\circ C - 61^\circ C = 10^\circ C$

and $T_w - T_{io} = 71^\circ C - 27^\circ C = 24^\circ C$.

The weakest link is in the measurement of the temperature difference

$T_{iw} - T_f = 10^\circ C$. Uncertainty is $\frac{1^\circ}{10^\circ} \times 100 = 10\%$.

We should stir to get best reading. We should move quickly.

$m_w c_w (T_f - T_{iw}) = -m_o c_o (T_f - T_{io})$

$(0.075kg)(4186J/kg/C)(61^\circ - 71^\circ) = -(0.22kg)(c_o)(61^\circ - 24^\circ)$

$c_o = 385.7\ J/kg/C$

The two numbers are not the same even with uncertainty. The percentage difference between the two is $\left(\frac{385.2 - 332.9}{332.9}\right) \times 100 = 15.7\%$. Experiment #1 had a smaller result. This could be due to greater loss of heat when we transferred the object.

Shortcomings: There was splashing of water since the calorimeter was small. We should try to minimize the time it took so that objects do not cool down.

Fig. 1. A student's report for the lab in which she designed and performed the experiment described in Sec. IV C.

C. Application experiments

The goal of application experiments is to solve a realistic problem or determine an unknown quantity. Thus students design and perform these experiments after they become familiar with a particular concept, or they combine several concepts to solve the experimental problem. We encourage students to come up with multiple designs and then choose the best ones they can perform with the available equipment. Students solve these experimental problems using at least two different methods and then compare the results. Thus the understanding of the assumptions and uncertainties becomes especially important.

Example 4. Design two independent experiments to determine the specific heat of the given object. The material from which the object is made is not known. Available resources: a hot plate, Styrofoam container and cover (or a calorimeter), balance, digital thermometer, and water. Examine the equipment to find how you can use it to achieve the goal. Come up with as many designs as possible. Choose the best two designs. Indicate the criteria that you used to decide which designs were the best. For each method, write the following in your lab report:

1. Draw a labeled diagram. Describe your experimental procedure.
2. Construct the mathematical procedure you will use.
3. List all assumptions you have made in your mathematical procedure. Explain how each assumption could affect the result. How do you know if the assumptions are valid?
4. List sources of experimental uncertainty. Decide what is the largest source of uncertainty and how you can minimize it. Use the weakest link rule to estimate the uncertainty in your result.
5. Perform the experiment. Make sure you take steps to minimize experimental uncertainties. Record your measurements in an appropriate format.
6. Calculate the specific heat capacity, based on your procedure and measurements.
7. After you have done both experiments, compare the two outcomes. Discuss if they are close to each other within your experimental uncertainty. If not, can the difference be explained by the assumptions you made in your procedure?
8. List any shortcomings in the experiment designs. Describe possible improvements.
9. Reflection: Explain why you had to do two independent experiments, and why one was not enough.

Figure 1 contains a transcript of a student's lab report for Example 4.

V. IMPLEMENTATION OF ISLE LABORATORIES

A. Lab structure

We now describe the implementation of the ISLE laboratories in two algebra-based two-semester large enrollment courses for science majors at Rutgers University. We then focus on the general issues that might be considered when implementing such laboratories. Both courses covered common introductory physics topics such as mechanics, thermodynamics, fluids, electricity and magnetism, waves, light, and modern physics. In one course the laboratory accompanied a lecture-recitation course, which was taught using the ISLE approach. There were two 55 min large room meetings and one 55 min recitation per week. Students performed 10 labs in each semester. Almost all 450 students who took the laboratory course were enrolled in the lecture-recitation course. There were 10 teaching assistants (20 lab sections), many of whom were first year physics graduate students whose first language was not English. About half of the TAs were engineering graduate students. None of the TAs was involved in physics education research activities. We have implemented ISLE labs in this course from Spring 2004 until the present. In the first year we implemented ISLE labs only in the second semester (Spring 2004) of the course. During the first semester of the course (Fall 2003), students performed non-traditional experiments but these were not design experiments. (Examples of these non-traditional experiments can be found in Ref. 20.)

The other course was an integrated lecture-recitation-lab course with 200 students that also followed the ISLE curriculum. This course had two 55 min large room meetings, one 80 min recitation, and a 3 h lab per week (8 lab sections). During each semester students performed 11 labs. There were 5 lab TAs for this course. We implemented ISLE labs beginning in Spring 2004.

B. A typical lab session and grading

Each laboratory session usually contained two experiments. The first experiment had a set-up provided for the students for which they had to devise a procedure. The second experiment required a design "from scratch." To do the latter, students first discussed possible experimental setups, the mathematical procedure they would use, and the assumptions they made. Then they assembled the apparatus and collected and analyzed their data. Students wrote responses to the write-up questions during the lab period. They used the rubrics to self-assess their report and then revised the report if necessary. Although students worked in groups to design and perform the experiments, each student wrote her/his own report. To grade student reports, the TAs used the same rubrics that the students used. In order to reduce the grading load on the TAs, they concentrated on a few abilities in the rubrics for each experiment.

C. TA training

Two of the authors led hour long weekly training sessions in which the TAs designed and performed the experiments. The leader and the TAs discussed and tried several methods of achieving the goal of the experiment, discussed important theoretical assumptions and experimental uncertainties in each method, and possible student difficulties with the design or physics. They examined how to evaluate the effects of assumptions and uncertainties quantitatively. Another important aspect that was discussed in the training sessions was how to use the rubrics to provide feedback on student work. We found that the most difficult aspect for TAs as well as students was analyzing the effects of their theoretical assumptions and experimental uncertainties.

TAs responded differently to the innovations in the labs. Some TAs appreciated the new approach, found it stimulating for the minds of the students, and after teaching the reformed laboratories became interested in physics education research. Some TAs did not like the innovations. They thought that the lab write-ups did not provide enough guidance for the students.

D. Addressing common concerns

Now that two years have passed from the first implementation of the laboratories in the algebra-based course we can summarize our experience and provide some advice for those who decide to implement ISLE labs.

1. Q: Do I need to change the way I teach in lectures to use these laboratories?
   A: Although ISLE as a course structure incorporates the labs naturally, it is possible to implement ISLE labs with any course structure. For example, ISLE labs were adapted at The Ohio State University without any changes to the lectures. It would be beneficial to the students if the lab content and lecture content are coordinated. However, if they are not, the experiments should be mostly testing or application experiments.
2. Q: How can I devise new design experiments?
   A: One requirement for observational and testing experiments is that the students be familiar with the equipment; thus the equipment needs to be simple. Bowling balls, low friction carts on tracks, hot wheels tracks and carts, and lenses and mirrors are good examples. To devise an observational experiment you need to decide what pattern you want students to find and pose a question in a way that will limit the number of possible designs. The equipment that students use should allow them to see the pattern clearly. To come up with testing experiments it is helpful to study the literature about students' alternative conceptions and then use them as hypotheses to test. It is better if equipment allows students to design several different experiments. Many experiments with guidelines are available.[15]
3. Q: How do I help TAs adapt to the new lab environment?
   A: Structured TA lab training sessions are important. TAs first need to design experiments and analyze data themselves, and then learn about other possible designs that students might invent. They need to be able to recognize original designs and support students in their work. It takes time to learn to recognize student frustration and when they need some hints with a design. It is helpful for new TAs to observe an experienced TA and then to have a discussion about the strategies.

4 Q: Are there any other steps I could do to prepare beforehand?
   A: We used a small group of undergraduate students to pilot test the labs in the summer. Observing these students design and perform the experiments showed us where students may have difficulty and what experiments were not successful. Usually difficulties arose when students had to use multiple concepts to solve a problem. Unsuccessful experi-

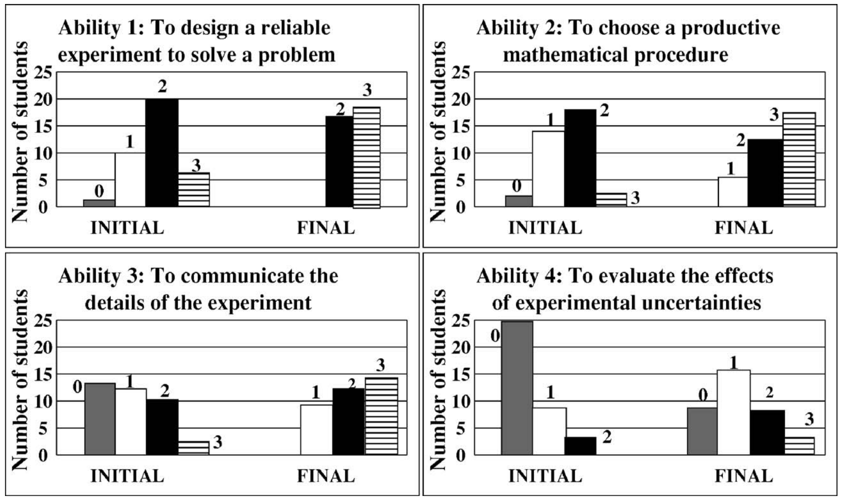

Fig. 2. Rubrics-based scores of 35 randomly selected students on experimentation-related abilities. Initial refers to week 3 and final refers to week 10 in the semester. The bar for each score represents the number of students whose reports received that score for a particular ability.

ments were those where students did not have enough data points to see a pattern, where it was only one way to design an experiment to achieve a particular goal, or where the equipment was not adequate for the task. Pilot testing does not resolve all problems and make all experiments perfect. We closely monitor what happens in the labs, survey students' opinions, and revise experiments and revise some reflection questions every year.

VI. STUDENT LEARNING

After the ISLE labs were implemented, we noticed gradual improvements in student write-ups. By the end of the first semester all students drew pictures describing their experiments and noted the details of the procedure in words. They wrote predictions for testing experiments and assumptions for application experiments (see an example of student work in Fig. 1). We attribute this improvement to the guiding questions in the lab write-ups and to the rubrics. Although the changes in the writing were clear, we wanted to use quantitative methods to assess whether students improve their experimental abilities, whether they can transfer what they learn in labs to a different context, and whether they understood and appreciated the new labs.

A. Acquisition of experimentation-related abilities

We studied changes in students' abilities to design a reliable experiment to answer a problem, to choose an appropriate mathematical procedure to analyze their data, to communicate details of the experiment, and to evaluate the effects of experimental uncertainties. The data in Fig. 2 came from the scores of lab reports based on the rubrics.[21] The histograms represent the scores that students' reports received on these tasks during the third week and the tenth week of the semester. The sample in Fig. 2 consisted of 35 randomly chosen students who were distributed among 4 lab sections in Spring 2004. This was the second semester of the 450 student course. However it was the first semester of ISLE labs for students. We found that students improved on the ability to design an experiment, to devise a mathematical procedure to solve an experimental problem, and to communicate the details of the procedure. These changes were statistically significant. The details of this analysis are given in Ref. 22.

We find the students' improvement to be quite robust. In a study with 100 students in the second year of implementation (Fall 2004 and Spring 2005) of the labs we found similar improvement in students' abilities.[23] One might ask if students who take a traditional introductory physics lab automatically acquire these abilities. Our data on students' low initial scores show that even though students had previously taken one semester of physics, they had not acquired these abilities. The changes in students' ability to evaluate experimental uncertainties were not significant. This result is consistent with previous research on the difficulty students have in understanding experimental uncertainties.[24,25]

B. Transfer of abilities

We studied whether students were able to transfer abilities such as designing experiments, testing hypotheses, representing ideas in multiple ways, and communicating that they acquired in labs. We use the term transfer when a student can apply something learned in one context to a different context or to different content.[26] This study was done in the 200 student course in Fall 2004. We asked students a final exam question similar to an experiment that they had performed in the second lab of the semester, three months before the exam. The problem was "Design an experiment to test the proposed hypothesis that an object always moves in the direction of the net force exerted on it by other objects." When students worked in groups in the lab, they had guidelines and rubrics helping them design an experiment to test this hypothesis and represent their reasoning using motion diagrams and free-body diagrams. None of this scaffolding was present in the exam. Other differences between the two situations were that students worked individually in the exam and had a different environment—exam hall instead of a lab. Thus, the content of transfer in our study can be classified as near, while the context can be classified as far.[26]

To analyze transfer we scored students' exam answers using the rubrics. Table II shows the percentage of students whose exam answers received a given score on the relevant items in the rubrics. We call this percentage the rate of trans-

Table II. Students' performance on the final exam question related to designing experiments ($N=181$). The transfer rate is the percentage of students who received the score from Table I (based on the relevant rubric) in the parentheses for the particular ability.

Students performance on final exam	Transfer rate
Drew pictures (score 3)	94%
Drew physical representations (motion diagrams, free-body diagrams) (score 3)	45%
Designed experiment to try to reject the proposed hypothesis (score 3)	58%
Prediction was based on hypothesis to be tested and effects of assumptions (score 3)	16%
Prediction was based on hypothesis to be tested but not on effects of assumptions (score 2)	64%
Considered assumptions (score 2 or 3)	47%

Table III. Students' responses on the open-ended survey question that asked them to describe three important things they learned from labs.

What students said they learned	Percent of students
Physics content (understand concepts better)	33%
To apply physics to real world	26%
To work in groups with other people	28%
Design experiment	24%
Scientific processes: prediction, assumptions, uncertainties	23%
Communicate in writing	14%
Solve problems experimentally	16%
Operate equipment, use computer probes	13%
To figure out things independently, without a teacher	10%

fer. Typically the rate of transfer is measured by the percentage of students who can solve a problem similar to a problem that they were taught to solve. Our results are encouraging because the rate of transfer for some abilities was much higher than the typical success rates of transfer, which has been found to be about 20%.[27] Also, our findings are consistent with the results previously reported for ISLE labs in medium enrollment courses.[28]

To find whether students' positive performance on the exam question was a false indicator of transfer, we compared their scores on this particular question with their scores on the entire exam. On the transfer questions students received an average score of 60% with a standard deviation of 21%. The average score on the entire exam was 69% with a standard deviation of 15.5%. Thus the exam question we analyzed was not too easy. We chose the same question for the exam as the experiment in the lab to control the fact that students already knew the physics content.

C. Students' perceptions about the goals of the laboratories

Laboratories in which students design their own experiments to investigate phenomena were also implemented by the University of Maryland PER group. Lippmann[7] studied students' perceptions of the goals of the (Scientific Community) labs and found that they did not match with the goals of the lab designers. The goals of the latter were to help students learn to design experiments and learn how to interpret data. However, only 14% and 8% (of the 125 students surveyed in Ref. 7), respectively, identified these as important goals of the labs. Nearly one-third of the respondents mentioned that building on the physics concepts learned in lectures was the purpose of the labs.

The ISLE laboratories have goals similar to those of the Scientific Community Labs, but are more structured and explicitly focus students' attention on the development of reasoning and experimentation-related abilities. To investigate whether ISLE students understand and share the goals of the labs, we administered an anonymous survey at the end of the second semester in the 200 student course. The survey had open response questions and Likert-type questions. In the former, students were asked to name the three most important things that they learned in the labs (see Table III). Our students, similar to Lippmann's, said that the labs helped them improve their understanding of physics. However, a higher percentage of ISLE students said without prompting that they learned how to design an experiment (24% vs 14% in Lippmann's study).

In the Likert-type part students had to rank the statements provided that represented the goals of the labs as "not achieved," "somewhat achieved," or "successfully achieved." A majority of students agreed that the labs either somewhat achieved or successfully achieved the goals of helping them learn to design experiments, make predictions of the outcomes of new experiments based on constructed concepts, and use the results of the theoretical assumptions and experimental uncertainties to interpret their experimental data. The details of this study can be found in Ref. 29.

VII. SUMMARY

We have described laboratories in large enrollment courses that engage students in experimental design, hypothesis testing, and other activities mirroring the practice of science. We suggested that laboratory write-ups provide guidance for the students in terms of an expert-type approach to experimental design and contain reflection questions. We introduced rubrics that guide students' work, help them focus on the most important parts of scientific investigation, self-assess their work, and help TAs to evaluate students' work. We described TA training necessary for the successful implementation of the labs and the general steps involved in the writing and implementing the labs. We found that with these elements in place, students improve on several experimentation-related abilities and on writing, and can transfer some of these abilities into a new context. They also understand the goals of the labs and agree that the labs achieve these goals.

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