Enhanced student learning in the introductory physics laboratory

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Abstract

We have taken laboratory experiments, modified them to include aspects of peer instruction and collaborative learning, and used pre- and post-tests to measure student learning gains in two of these labs. Our modification includes adding conceptual questions to the laboratory that lab groups answer online and then, as directed by the instructor, they discuss their answers with other students. By comparing student performance on pre- and post-tests in two laboratories that used this technique and two that did not (the control group), our data indicate that this modification substantially increases student learning (increases the average student learning gain from pre- to post-test by 50–100%). It seems that using labs with these modifications increases students' readiness to communicate and their ability to transfer knowledge or apply concepts to novel situations.

Introduction

There are a variety of reforms [1–3] designed for introductory physics laboratories that show promise for improving student learning. Many, however, require abandoning traditional laboratory exercises, purchasing new equipment and/or specialized training for instructors, making widespread implementation difficult. In hopes of improving student learning without requiring large scale curricular or equipment changes, we developed and then tested a technique to enhance student learning through less drastic laboratory modifications. We found that including aspects of peer instruction and collaborative grouping enhances student conceptual understanding as measured by pre- and post-testing.

Description

In investigating what students learn as a result of introductory physics labs, we have introduced two minor modifications that can be incorporated into both traditional and non-traditional labs. Our first modification is to embed questions into the laboratory and use web-based software (BeyondQuestion v.1.2) to collect student responses as they work through the laboratory instructions. The questions embedded into the lab involve a fairly minor revision of standard lab instructions. These questions are usually one of three types: *predictive* (According to your ray diagram, what type of image will you see? As the cart goes up and down the slanted air track, what will the velocity versus time graph look like?), *observational* (What happened when you tried the experiment?) or *explanatory* (Why is the image on the screen inverted? Why is the velocity graph a straight line?). We insert the questions in key places where students might be

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confused about what will happen or may have alternative concepts to explain the results. Free-response questions can be used, but we usually select multiple choice questions with ‘none of the above’ as one choice. Multiple choice questions simplify the record keeping, force students to choose one answer and be prepared to defend it, and reduce the time spent deciding on the exact wording of an answer.

Eric Mazur has demonstrated the effectiveness of periodically submitting questions to students in a classroom setting and having them discuss their answers in the pedagogy that he calls Peer Instruction [4]. This first modification, which is embedding questions into the lab instructions, is a modification of Peer Instruction that incorporates it into the laboratory setting. Each student lab group discusses each question as they reach the appropriate point in the lab and enters into their computer one answer for the group. The BeyondQuestion program allows the lab instructor to receive these answers in real time.

Our second modification involves the use that the instructor makes of this information. The instructor identifies student lab groups that submitted different answers, pairs them up, and requires that they discuss their answers with each other. After a brief time of discussion, the student lab groups return to the apparatus to continue the lab experiment. Over the course of the laboratory period, the instructor may pair groups up frequently or only occasionally. This cycle of prediction, investigation and analysis is one of the most effective ways to promote learning of concepts [5]. Interactive Lecture Demonstration adapts this sequence for the classroom and has proven to be very effective in increasing student learning of concepts [6].

Measuring student learning gains

To determine whether this method indeed enhances student learning, we enlisted the help of our colleagues as their students did experiments in optics and kinematics. All classes (multiple sections of the same calculus-based introductory physics course at Eckerd College) used the same set of laboratory instructions, and for all classes these instructions included the embedded multiple choice questions that we prepared. Some classes (group A) used our strategy. As described above, the students in these classes recorded their answers on the computer using BeyondQuestion. These answers appeared on the instructor’s computer and then, based on directions from the instructor, different groups discussed their answers with other lab groups. In the other classes (group B), the lab groups had very little interaction with each other. The students answered the same questions on paper but did not give their answers to the instructor until they turned in the lab and did not discuss their answers with other lab groups.

In both the optics and the kinematics experiments, the students had not been introduced to the material in class, so the labs were their introduction to the material covered in the lab. Furthermore, in all classes, the instructor did not give an introductory explanatory lecture, but explained that the material the students needed was included in the lab instructions themselves. The instructor’s explanations in all classes were primarily limited to answering procedural questions about the lab exercises themselves.

To measure how much students learned in the laboratory we used a multiple choice test administered to the classes both prior to and following the lab exercises. We chose to use pre-tests and post-tests so we could focus on student learning gains in the lab. This removed any bias in the data that might come from students who had previously studied this material. Furthermore, since the instructors gave little or no instruction on the laboratory concepts, any improvement in student scores from the pre-test to the same test taken after the lab was due to what students learned reading and working on the lab that afternoon and not the differences between instructors and types of instruction.

The student populations in all sections were similar in composition: a mix of primarily biology and marine science students along with a few chemistry and physics majors. The data are from sections of this course taught by four different instructors from Spring 1998 to Spring 2000. The average final grade in the courses was in the B-range. We tested student learning in a traditional optics lab as well as in a kinematics laboratory based on both *Workshop Physics* [1] and *RealTime Physics* [2].

Traditional optics lab

The optics lab we used was a standard geometric optics lab that included finding the

Table 1. Comparison of pre-test and post-test scores. Some lab groups (group A) used BeyondQuestion and collaborative grouping. Other lab groups (group B) did not. The questions on the pre-test and post-test were identical. The Gain (*g*-factor) is the average of all the individual students' fractional increase in scores from pre-test to post-test.

Laboratory	Group	Number of students	Final course GPA	Average number of correct answers Pre-test	Average number of correct answers Post-test	Gain (*g*-factor)
Optics	A	35	B	3.1	7.4	0.66 ± 0.09
(10 question pre/post-test)	B	32	B+	2.8	5.7	0.40 ± 0.08
Kinematics	A	35	B−	1.1	4.5	0.50 ± 0.17
(10 question pre/post-test)	B	27	B−	0.4	2.6	0.25 ± 0.13

focal length of curved mirrors and lenses, and image magnification. The lab was essentially 'Experiment 41: Lenses and Mirrors' in *Physics Laboratory Experiments*, a standard physics laboratory manual [7]. Thus, in this testing of our method, we took a traditional lab, embedded questions in the lab instructions, and gave the instructions to two groups: labs that used our technique (group A) and control labs (group B). For this lab, we developed a ten-question multiple choice pre- and post-test (the post-test was identical to the pre-test) to test student understanding of concepts covered in the laboratory (see Appendix A for pre/post-test).

As shown in table 1, for both classes, the pre-test average score was about 3 out of 10 questions correct. The post-test averages for the two classes were significantly different. Group B, the control group, improved to an average of 5.7 out of 10 correct. Group A, in which the lab groups were paired for discussion, improved to an average of 7.4 out of 10 correct. Perhaps a more useful measure, though, is the fractional increase in percentage correct, defined as the Gain or *g*-factor

$$\text{Gain } (g\text{-factor}) = \frac{S_\mathrm{f} - S_\mathrm{i}}{100 - S_\mathrm{i}}$$

where S_i and S_f are the pre- and post-test scores expressed as percentages. The value of the gain ranges from 1 (when a student gets all the problems right on the post-test that she or he missed on the pre-test) to 0 (student shows no improvement from pre- to post-test) or even negative values (student misses more questions on post-test than pre-test). Since the gain (*g*-factor) is the improvement in the score (final score minus initial score) divided by largest possible improvement (perfect score minus the initial, pre-test score) for each individual student, comparing the average *g*-factors between groups of students gives a measure of the difference in learning gains for the different student groups, regardless of initial student conceptual understanding. For group A, the average gain, *g*-factor, was 0.66 ± 0.09 while for group B, the control group, the *g*-factor was 0.40 ± 0.08.

Kinematics lab

The kinematics lab on acceleration we used was based on *Workshop Physics*, 'Unit 4: One-Dimensional Motion II—A Mathematical Description of Constant Acceleration' [1, pp 75–108] and *RealTime Physics*, 'Lab 2: Changing Motion' [2, pp 2-1 to 2-30]. This laboratory relies on graphs of position, velocity and acceleration versus time obtained by a motion detector. It uses these plots to guide the students through the development of a mathematical description of acceleration as well as a measurement of acceleration due to gravity of objects in free fall. The lab requires more predictions and explanations coupled with observations than a traditional lab does. Again, we embedded questions in the lab instructions and gave the modified lab instructions to two groups: a test group (group A) and a control group (group B). For measuring student conceptual gains, we used a subset of eight multiple choice questions from the Force and Motion Conceptual Evaluation (FMCE) Questions 22–29 as our pre- and post-test [8].

The biggest difference in the two test groups was the size. Group A, which incorporated our method, was two lab sections of 15 and 20 students, while group B, the control group, was one lab section of 27 students. Unfortunately, we cannot control the laboratory sizes because they are determined by student schedule conflicts.

As shown in table 1, for both classes the pre-test average score was around 1 question correct out of 8. The post-test averages for the two classes were significantly different. Group B, the control group, improved to an average of 2.6 out of 8 correct and a corresponding average g-factor of 0.25 ± 0.13. Group A, in which the lab groups were paired for discussion, improved to an average of 4.5 out of 8 correct with a g-factor of 0.50 ± 0.17.

Discussion

For both experiments, both lab groups experienced learning gains from the laboratory activity itself, but group A, using our technique, showed significant learning gains in comparison with group B, the control group. We are aware that this is a small data sample. Nevertheless, this preliminary result shows clearly that this technique does indeed increase student learning. Lazarowitz and Tamir have indicated that it is very difficult to obtain statistics that demonstrate the effectiveness of laboratory work [9]. Thus, we find these preliminary results quite striking.

For comparison, note that for traditionally taught classes, the overall gain in conceptual understanding for the course (not for one particular topic as we tested) is Gain (g-factor) $\simeq 0.25$, while more interactive courses have gain values in the range 0.36–0.68 [4, p 46]. So the values of the Gain (g-factor) we see when our method is used are comparable to learning gains in interactive courses (as expected for laboratory work).

Improved communication skills

These data show that our technique can improve student gains on pre- and post-tests involving concepts. Although harder to measure directly, our own experiences indicate that this improves critical thinking and communication skills of the students as well. For example, a class culture of discussion can arise from this technique. Because the instructors had used our techniques in previous labs, a culture of discussion developed in the sections of group A labs. The instructors in those sections would often suggest pairings of groups for discussion, but even without suggestions from the instructor, the groups would themselves initiate discussion with other groups. The instructors would find them engaged in meaningful discussions that went to the heart of challenging conceptual issues of the laboratory material. Even though students had to stop doing the experiment to talk with other groups (which they might have felt kept them in the lab longer), the students voluntarily engaged in discussion about physics (and not the latest campus gossip!), improving both their communication and critical thinking skills along the way.

Transfer of conceptual understanding

In an attempt to determine why group A consistently outperformed the control group, we examined the student responses, question by question, on the optics lab pre- and post-test and found some evidence to suggest that our method helps to develop critical thinking skills, particularly the ability to transfer conceptual understanding. Several questions involved applying concepts that should have been learned in lab to different situations (questions #1, #2 and #4). These three questions involve transfer of conceptual understanding. The other seven pre/post-test questions came almost directly from questions already asked or diagrams already seen in the lab.

Group A did the same or better than group B on each of the ten questions. However, the improvement on two of the questions (#2 and #4) was dramatic. For question #2, on the pre-test 4 of the 34 students in group A chose the correct response, yet on the post-test 20 out of the 34 students chose the correct response. In comparison, in group B, 2 out of 31 students chose the correct response on the pre-test, but only 3 out of 31 students chose the correct response on the post-test. Similarly, on question #4, 10 of the group A students were correct on the pre-test with an improvement to 31 of the 34 students choosing the correct response on the post-test. For group B, 6 of the students were correct on the pre-test with an improvement to only 11 of the 31 students choosing the correct response on the post-test. Furthermore, these were two of the three questions that involved transfer of conceptual understanding to a novel situation.

Question 2 (Appendix A) asks the student to identify the location of the focal point of a lens with a given ray diagram. The diagram shows one ‘standard’ ray from ray diagrams (this experiment teaches students to draw ‘standard’ rays) and another ray that is not one of the ‘standard’ rays. To successfully answer this question, students must understand the difference between focal point and image point adequately to analyse a diagram that has a ray that is different from the ones drawn in the lab. Question 4 (Appendix A) shows converging rays that do not intersect on the diagram. To locate the image, students must extend the rays in the ray diagram. In the lab, all the ray diagrams showed rays extending to the image location. In both questions, students needed to transfer their concept of image formation and focal point to these diagrams. Evidently using BeyondQuestion coupled with peer discussion helped students to form a better understanding of these concepts.

On the other hand, on the questions that came almost directly from the laboratory, both groups showed similar gains. For example, for question 9, 33 of the 34 students in group A and 28 of the 31 students in group B got the answer correct on the post-test. This was an exact copy of a question embedded in the laboratory, and whether or not students discussed it with other lab groups they learned which ray in a ray diagram passes through the focal point. This is also probably one of the simpler concepts. So, although this is a small data set, our results indicate that while students do learn material as a result of the laboratory exercises, the peer discussion seems to help students understand the concepts well enough to do a better job of transferring this conceptual understanding to novel situations.

To have a better understanding of how this technique leads to increased student understanding, more data and wider testing would be helpful since this is a small sample. It would also be useful to explore how much the increase in learning can be attributed to each of our modifications. Specifically, how much the increase in learning is due to students sending the answers to the embedded questions (since students know the instructor is ‘watching’ their answers come in on the computer) and how much is due to the collaborative grouping and peer instruction. It would also be useful to see whether this method leads to similar learning gains in laboratory exercises in other sciences.

Conclusions

We have developed and tested a method that enhances student learning in the laboratory as measured by pre- and post-tests. We found that the group that submitted answers on the computer and discussed answers with other lab groups had a g-factor of 0.66 ± 0.09 and 0.50 ± 0.17 on two different labs while the control group had a g-factor of 0.40 ± 0.08 and 0.25 ± 0.13. Furthermore, we have anecdotal evidence suggesting that our method enhances communication in the laboratory as well as tentative results from the pre- and post-test differences between the two groups to suggest that critical thinking skills are also enhanced. All these results are based on a relatively small data sample, but they do show that embedding questions in the laboratory, asking students submit these answers in real time to the instructor and then occasionally pairing groups across the lab enhances student learning.

Appendix.
Optics: Pre- & Post-test questions

1. Light rays are coming into the mirror in the box. Two of these are drawn. Where is the image located? (See figure 1)

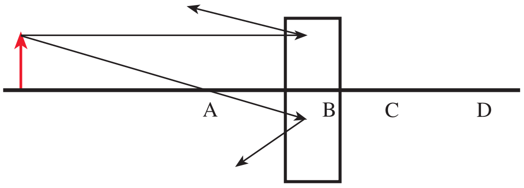

Figure 1.

2. Light rays are coming into the lens. Two of these are drawn. Where is the focal point of the lens? (See figure 2)

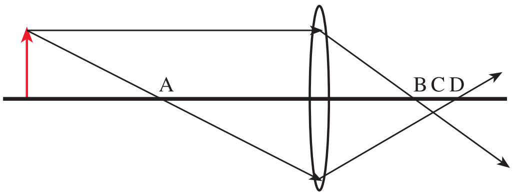

Figure 2.

3. An object placed 3 m in front of a lens with a focal length of 2 m forms an image that is

6 m on the other side of the lens. This image will be

A. bigger than the object
B. the same size as the object
C. smaller than the object
D. the ratio of sizes depends on the size of the object

4. An object is placed slightly beyond the focal point f of the concave mirror. The ray diagram given below (figure 3) is drawn correctly. When a screen is placed so that the object is clearly focused on the screen, the screen will be located

A. at the focal point
B. closer to the mirror than the focal point
C. further from the mirror than the focal point
D. the distance depends on the size of the object
E. there will be no clear image no matter where the screen is placed
F. none of the above

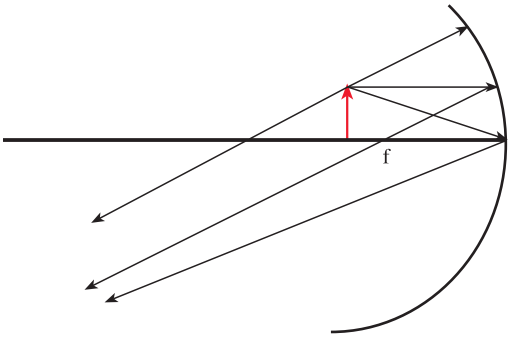

Figure 3.

5. Which of the following is the correct ray diagram (and the correct location of the image): (see figure 4)
6. Which one is the correct ray diagram for the convex mirror below? (See figure 5)
7. Which of the following is the correct ray diagram? (See figure 6)
8. A laser beam is hitting a shiny round metal ball and bouncing off. Which way does the beam bounce off? The laser beam is the thick, black line, and some possible choices for the way the light may bounce off are given with thin lines. Please circle the one that you feel

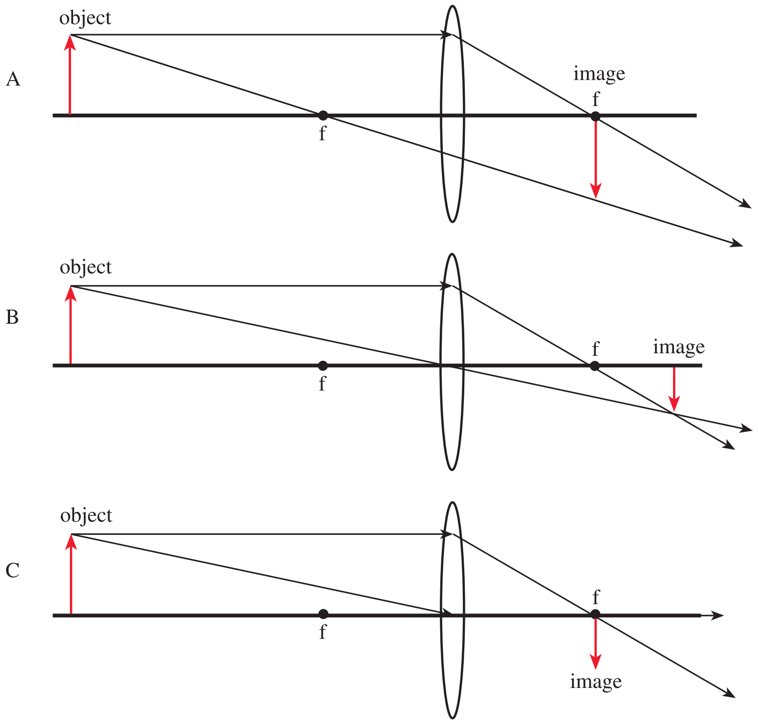

Figure 4.

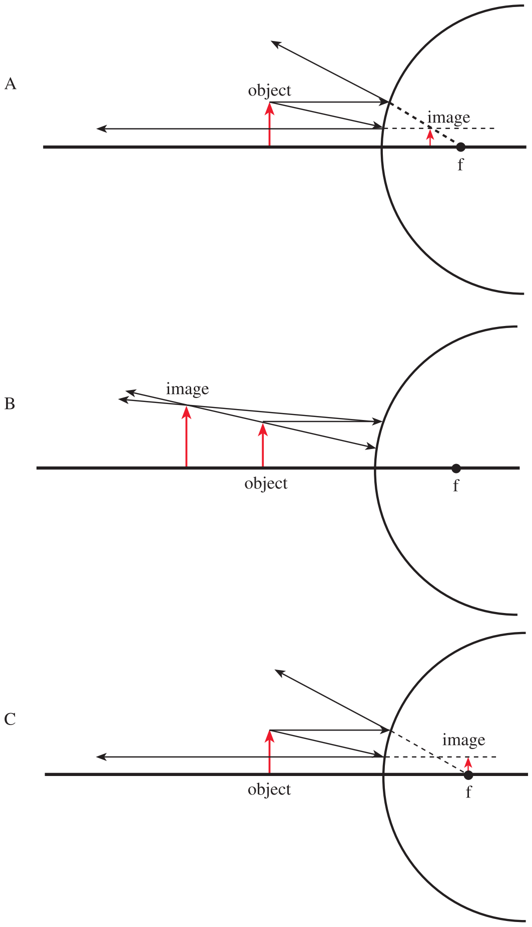

Figure 5.

is closest to the way it will actually occur. The ball acts like a spherical mirror and both the centre of the ball, C, and its focal point, f, are marked on the diagram (figure 7).

9. Which of the following light rays (going from the tip of the object arrow to the mirror) will bounce off the mirror parallel to the horizontal axis (please circle the ray)? The centre of curvature and focal point of the mirror are both shown on the diagram (figure 8).
10. For the diagram above (figure 8), where will the image of the object be located?
    - A. to the right of the mirror
    - B. at the focal point
    - C. at the centre of curvature
    - D. there will be no clear image of the object
    - E. none of the above

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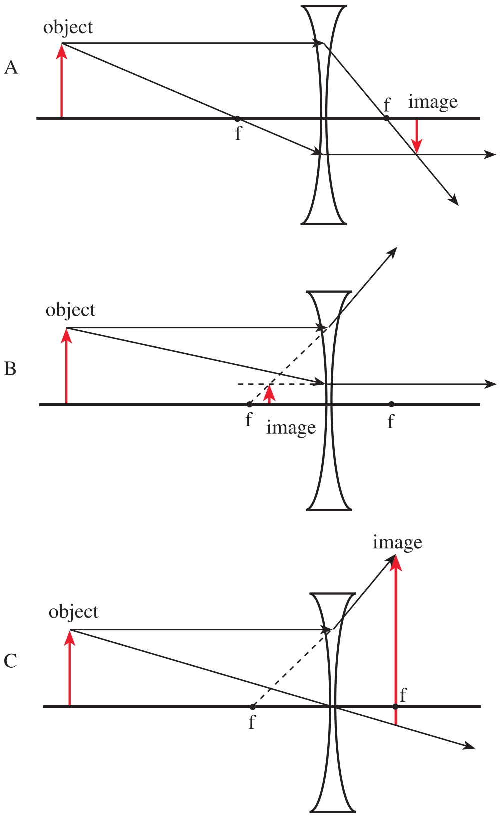

Figure 6.

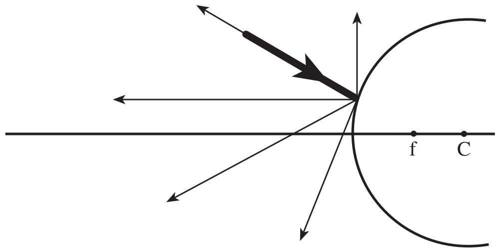

Figure 7.

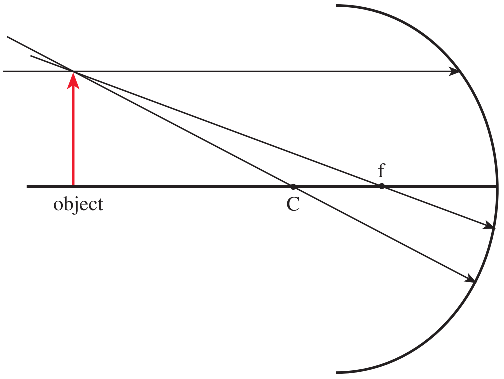

Figure 8.

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