Studio optics: Adapting interactive engagement pedagogy to upper-division physics

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The use of interactive engagement strategies to improve learning in introductory physics is not new, but have not been used as often for upper-division physics courses. We describe the development and implementation of a Studio Optics course for upper-division physics majors at Kansas State University. The course adapts a three-stage Karplus learning cycle and other elements to foster an environment that promotes learning through an integration of lecture, laboratories, and problem solving. Some of the instructional materials are described. We discuss the evaluation of the course using data collected from student interviews, a conceptual survey, an attitudinal survey, and the instructor's reflections. Overall, students responded positively to the new format and showed modest gains in learning. The instructor's experiences compared favorably with the traditional course that he had taught in the past. © *2011 American Association of Physics Teachers.*
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I. INTRODUCTION

Research has shown that students learn better through interactive engagement.[1] A variety of interactive engagement models have been used in introductory level physics courses such as Studio Physics,[2] Tools for Scientific Thinking,[3] Workshop Physics,[4] Peer Instruction,[5] Socratic Dialog Laboratories,[6] and the New Studio method developed at Kansas State University.[7] All of these models have focused on the introductory level. Application of similar models to upper-division classes is much less explored, although there are some notable examples such as Paradigms in Physics,[8] where the junior-senior curriculum for physics majors was revamped and tutorials developed for upper-division physics theory courses.[9]

In this paper we describe an interactive course in optics at the junior-senior and first year graduate student level that incorporates the methods of interactive physics instruction. Similar efforts have recently been reported by others.[10] We describe our efforts to infuse interactivity in the upper-division optics course by incorporating into the lecture short laboratory experiences which we call lab-demos.

II. THE STUDIO OPTICS CONCEPT

The optics studio course, Physics 651, is the first 15 week semester of our three-semester optics curriculum. The textbook is *Optics* by Hecht. The course schedule is 2 h on Monday and Wednesday and 1 h on Friday. The total of five course hours equals the time available in previous course offerings before the studio model was implemented, but the way in which the time is allocated between lecture and experiment different.

The course topics are elementary waves and electromagnetism, Fresnel equations, dispersion theory, geometric optics and instruments, polarization, interference, and diffraction. The second and third semesters, which have not yet been adapted to the studio format, include Fourier optics, coherence theory, holography, scattering, lasers, nonlinear optics, ultrafast optics, and fiber optics.

Implementation of the studio/workshop concept has several important components. The lectures, experiments, and discussion occur in the same room with 1200 ft^2 of space, with five 4×6 ft optical tables for the students, and one 4×8 ft optical table for the instructor. Students work in groups of up to four, so a total of 20 students can be accommodated. Two whiteboards are at the front for the instructor to use for lectures as well as for students to talk and share information as they work in small groups on the experiments. At the front of the room is a wide TV screen to display PowerPoint slides or information from the internet. This layout allows a seamless integration and transitions between the lectures and experiments. It also puts the students together for interaction and peer instruction, and the instructor has easy access to all the groups for facile teacher-student interaction.

Another key component of the studio/workshop concept is the close temporal connection between the lecture and hands-on experimentation. We typically follow a three-ministep approach consistent with Karplus's learning cycle[11] or Schwartz and Bransford's "time for telling" strategy.[12]

Step 1: Miniexploration, $\approx$5 min: This step is a brief familiarization with the topic where the students "mess around" with equipment and think qualitatively about ideas that will be discussed in the minilecture. The duration of this step is curtailed to not lose focus.

Step 2: Minilecture, $\approx$5–20 min: The instructor lectures on the subject in the usual manner, including concepts, derivations, and terminology, in bite-sized units that students can assimilate and apply. This idea is borrowed from Paradigms.[8] We do not want the lecture to go too long before students apply their knowledge. Rather they do so immediately in the minilaboratory. In a 2 h studio period, two to three minilectures/minilaboratories are taught. In some cases the minilecture is taught first with the minilaboratory verifying the lecture as well as amplifying and cementing the concepts. In other cases the minilaboratory precedes the theory discussed in the lecture, and the students are guided to discover principles to be subsequently discussed in the minilecture.

A limitation of this approach is that students do not have an adequate opportunity to perform careful extended data taking and analysis. However, our discussions with the instructor who has mentored some of our students when they become graduate student researchers in his research laboratory indicate that they do not appear to have deficiencies in their ability to analyze research data.

Step 3: Minilaboratory, ≈10–30 min: Students make quantitative measurements to verify and apply what they have learned in the minilecture. Some of the minilaboratories also involve group problem solving. Many of the assigned homework problems can be related to the minilaboratories, thus giving reality to the problems. Comparison of numerical results obtained from relevant homework with experimental results instills a sense of experimental uncertainty which varies widely in optics.

A novel feature of the minilaboratory is the use of laboratory demos. The lab-demos are short hands-on activities that have both experimental and demonstrational components in the spirit of lecture demonstrations. This style was successfully implemented several years ago for our calculus-based physics course.[7] The optics lab-demos quickly demonstrate the main idea or ideas of the minilecture and integrate readily with both the lecture material and assigned problems. For example, 20 min of forming images with lenses gives reality to ray diagrams and the paraxial formula. A total of 46 lab-demos have been developed.

The development of the lab-demos was modeled after our development of lab-demos for our introductory physics course.[7] A professor, who had taught optics six times, reviewed the course topics and suggested the relevant lab-demos. These ideas were given to a graduate student assistant to try them. This tryout ranged from simply grabbing a few lenses and rehearsing image formation to designing and prototyping new equipment. Once a lab-demo worked well enough, six copies of the equipment were made and/or purchased, often with the aid of our machine shop. The professor wrote brief, noncookbook descriptions of the lab-demos and assembled them into the Optics Studio Manual. Materials were purchased with the aid of an NSF grant and totaled ≈\$80,000. Some examples from our studio manual are shown in the Appendix.

As mentioned, relevant experimentation with optical equipment immediately follows the minilecture. At minimum this one-two punch of the same subject matter helps the students' retention through repetition. But the immediate juxtaposition of lecture (that is, theory) and experiment is much richer. In this way the lecture material immediately takes form as real phenomena and relations. Students interact with the phenomenon and explore it with other students and the professor. This setting of lively interaction is very conducive for learning.

III. EVALUATION

After the activities had been developed and before the Studio Optics course was offered, we conducted interviews with 12 students to determine how they would respond to learning using the studio optics activities. Eight of the students were physics majors in their sophomore or junior year who had all completed 1 yr of calculus-based physics. The other four were beginning graduate students who had completed an undergraduate optics course. Our goal was to ascertain the issues that students might have regarding the studio laboratory format. In particular, we were interested in the clarity of the instructions for the experiments. How do students proceed and reason through the experiment?

Each student was interviewed twice, with each interview session about a week apart. Each session was about 50 min long. The interview topics were single slit diffraction in the first session and circular diffraction and Poisson's spot in the second session. In each session the student was provided with the laboratory instructions, the equipment for the laboratory, and a large sheet of paper on which to record data as they worked through the laboratory exercise. Students were asked to work through the experiment as they would do in a real course. The interviewer was mainly an observer, and did not provide assistance, but asked them to explain what they were writing. If the students were off track, the interviewer provided cues so that the student would make observations pertinent to the experiment goal. The interviewer also asked students to defend their explanations of the observations. All interviews were videotaped and transcribed. The transcripts were analyzed for patterns of student behavior and reasoning and not as much for details about the correctness of the physics concepts related to the particular laboratory.

Our analysis of student work through the laboratory exercises indicated that the instructions were clear to all of the students. However, most students were uncomfortable with the philosophy of "messing around." Nine out of the 12 students tended to revert to using a traditional experimental procedure even without being asked to do so. Students also had difficulties with the physics as evinced by their reliance on equations rather than qualitative reasoning and inability to recognize incorrect results (for example, when they calculated the wavelength of the laser in millimeters instead of nanometers). Overall, students' expectations of what they should be doing in a laboratory appeared to constrain the exploratory mode of the studio laboratories.

A conceptual test was administered during the first offering of Studio Optics. To assess student learning we administered the conceptual test three times in the course: first as a pretest, then as a midtest with a subset of the questions addressing topics that were covered in the course, and finally as a post-test with the remainder of the test questions. The questions were adapted from Ref. 13 and were based on what the instructor indicated would be covered during the semester and included questions on ray optics, polarization, interference, and diffraction. There were short answer questions as well as multiple-choice questions that also asked students to explain the reasoning for their answer.

The short answer and reasoning questions were graded on a scale of 0–4 based on correctness: "0" was for no answer, "1" indicated an incorrect answer, and points 2–4 were assigned depending on the reasoning. After multiple attempts, we were able to build consistency in using the scoring rubric to 97%.

Table I shows the data from the conceptual test. Only those students who were present for all three evaluations are included for statistical purposes, a total of 15, and the values in the table are averages for these participants. Table I shows

Table I. The normalized gain (Ref. 1) and effect size on each of the test items between the pretest and midtest or between the pre- and post-test. The shaded cells indicate significant gains with an effect size greater than one.

	Pretest to midtest		Pretest to post-test	
Q No.	Normalized gain	Effect size	Normalized gain	Effect size
1	⋯	⋯	0.17	−0.37
2	0.0	0.16	−0.14	−0.55
3	−0.26	0.72	0.14	0.33
4	−0.08	0.29	0.41	1.13
5	0.14	0.35	0.29	0.88
6	⋯	⋯	0.16	0.34
7	⋯	⋯	0.29	0.88
8	⋯	⋯	0.0	0.26
9	⋯	⋯	0.11	0.53
10	⋯	⋯	0.32	0.76
11	0.47	1.15	0.29	0.63
12	0.57	0.75	0.49	0.70

the normalized gain[6] for the score on each test item as well as the effect size for both pretest to midtest comparisons and pretest to post-test comparisons.

The normalized gain is given by

$$\langle g\rangle = \begin{cases} \dfrac{\text{post\%} - \text{pre\%}}{100 - \text{pre\%}} & \text{if post\%} > \text{pre\%} \\ \dfrac{\text{post\%} - \text{pre\%}}{\text{pre\%}} & \text{if post\%} \leq \text{pre\%}. \end{cases} \quad (1)$$

Equation (1) is a ratio of the actual pretest to post-test increase (or decrease) in score on a question to the maximum possible pretest to post-test increase (or decrease), yielding a maximum possible normalized gain of 1 (if post% = 100%) and a minimum possible normalized gain of −1 (if post% = 0%).

The effect size is given by

$$r = \frac{\text{post\%} - \text{pre\%}}{\text{Standard Deviation}}. \quad (2)$$

Equation (2) is the ratio of the actual pretest to post-test increase (or decrease) in score on a question to the pooled standard deviation from both pretest and post-test scores on that question. Although there are no set standards, effect sizes greater than 0.8 are usually considered a large effect, whereas those near 0.2 are often regarded as a small effect.

From Table I we see that gains on only two of the questions are significant (effect size greater than 0.8): Q4 from pretest to post-test and Q11 from pretest to midtest.

Many of the gains are negative, particularly from pretest to midtest. Students seem to have forgotten about the concepts they had learned prior to the midtest when they took the post-test. Forgetting might be expected when the course covers a vast amount of content and students do not revisit what they had learned earlier in the course. Thus, some of the misconceptions that students had when they entered the course, such as their belief that a part of an image will disappear when a lens is covered,[14] persisted even after they had completed the course. Further work is needed to develop ways for students to overcome these misconceptions.

An online survey was administered toward the end of the course. The survey had Likert-scale questions with space for students to provide further comments. A summary of student responses on the Likert-scale questions is shown in Table II. For the first, third, and fourth sets of questions we collapsed the strongly agree and agree responses into a single positive category. Similarly, we collapsed the strongly disagree and disagree responses into one negative category. The second set of questions, which inquired about the adequacy of time spent, differed from the other sets of questions and was collapsed into three categories: less than adequate, adequate, and more than adequate. The actual percentage of students in each collapsed category is a more accurate representation of the data than the means and standard deviations of the Likert-scale rankings.

The first set of questions was on whether the studio activities were closely related to the lecture material, how they helped build understanding of optics, and how keeping a laboratory notebook helped them. Most of the student responses were positive, with the only negative responses coming from questions on laboratory notebooks.

The second set of questions was on the time allotted for completing the studio activities. The responses in Table II indicate that most students believe that the time spent on the studio activities was adequate. It appears that students preferred coverage of the topics in a brief lecture before the activities. For example, one student commented, "It would be better to spend more time after the activities to relate what we did to the book material. This way, the concept is presented at the beginning of class, we do something physically to visualize it and then the concept is repeated to tie up any loose ends." Another student remarked, "Perhaps dedicating a little bit more time to follow up would be nice, as sometimes, even with the hands-on activities, I don't really understand the concept or material." These suggestions are related to the reason why some students did poorly on the post-test, especially on items related to material covered before the midtest. Due to a lack of time that the students spent on each topic, they were unable to foster a deep conceptual understanding of the material.

The third set of questions asked students about the equipment and technology that was used during the studio activities. The results are positive, but as with questions in the second set, there are more neutral responses than positive responses. A typical student comment is "I would like to see more quantitative activities infused into this class; perhaps something similar to what we would encounter in research." Several responses indicated frustration with a lack of equipment such as optics bolts, set screws, posts and post holders, and protractors.

The final set of questions was aimed at determining students' opinions of the Studio Optics course and its comparison with a more traditional laboratory course. The responses were overall positive, with few negative responses. Students appeared to have enjoyed the studio format compared to the traditional laboratory and would overwhelmingly choose the studio format over the traditional laboratory. Students were unanimous in their view that they learned more from the studio format than from the traditional lecture.

The course instructor was experienced in teaching the optics course in the traditional format before he began teaching the Studio Optics course. The instructor did not participate in the development of Studio Optics, and thus his perspective is similar to that of an experienced instructor who would be asked to teach the class in the revised format. The instructor is also an active researcher in nonlinear optics. A few of the

Table II. Results of the attitudes survey.

Studio activities	Negative (%)	Neutral (%)	Positive (%)
1. The studio activities relate closely to what we are talking about in lecture.		38	62
2. Keeping a laboratory book helps me to better understand the studio activities.	20	32	48
3. Keeping a laboratory book helps me understand how the activities relate to the material.	20	32	48
4. The studio activities help me understand the principles of optics	9	9	82
5. The studio activities help me relate the theory to what is really happening.		34	66
6. The studio activities clearly relate to what we are discussing in lecture.	27	46	27
Time spent in studio	Less than adequate (%)	Adequate (%)	More than adequate (%)
7. How would you describe the time allotted for completing the studio activities?		56	44
8. How would you describe the time spent covering a topic before the activity?		36	64
9. How would you describe the time spent covering a topic after the activity?	24	52	24
Studio equipment	Negative	Neutral (%)	Positive (%)
10. The studio equipment is sufficient for completing the studio activities.		54	46
11. The studio equipment is being used to its full potential.		8	92
12. The course appropriately makes use of available technology.			100
General opinions	Negative (%)	Neutral (%)	Positive (%)
13. I enjoy the studio format.		8	92
14. I enjoy the studio format more than the typical laboratory format.	18	24	56
15. If traditional form and studio format were offered, I would choose the studio.	9	9	82
16. I believe I have learned more from the studio format than a traditional lecture.			100

students who took this class, both graduates and undergraduates, went on to conduct research in this professor's research laboratory. Thus, the course instructor could offer his commentary on the extent to which the Studio Optics laboratory experiences prepared students for optics research.

We interviewed the instructor for about 30 min in an unstructured format. The interview began with the overarching question: What are your overall impressions as instructor of the Studio Optics course? During the conversation the interviewer asked follow-up questions that asked the instructor to elaborate on the similarities and differences between the two formats as well as the advantages and disadvantages of each. In the following we describe some of the emergent themes from the instructor interview.

Student access to equipment: When the course was taught in the lecture format with a separate laboratory, students had to wait until they went to the laboratory to use the equipment and do the experiments to test the ideas introduced in the lecture. In the studio format, the students were able to learn the new ideas through concrete experience.

Combating student boredom: Previously, during the 50 min lecture, students often became bored and lost interest. The attendance was sparse. Missing an occasional class did not hurt the good students, because they were able to learn the material by themselves. However, the poor students struggled. In the studio format students were more active. They moved around, engaged in experiments. The minilectures were short enough that students did not get bored, because as soon as the minilectures were completed the students were engaged in the hands-on activities.

Multiple representations of new concepts: In the traditional lecture students were unable to interact with a new concept in any other way; that is, the only way they learned the concept during class time was by listening to the lecturer.

In the studio students were able to revisit a new concept by observing its implications using real equipment. For example, students would not have had a feeling for what is a milliradian. With the appropriate equipment they were able to gauge what a milliradian is.

Preparation for future learning: The studio laboratory experience was closer to a real research laboratory experience. Not only did students use the same equipment in the studio laboratory that they used in their research laboratory, they also played with the equipment in a way similar to a research laboratory. Previously, students who had not taken Studio Optics were often scared as they entered the research laboratory. Students who had completed Studio Optics were much more confident when they entered the research laboratory. The lack of explicit instructions and directions appeared to have better prepared these students to learn how to do research later.

Students' expectations of what they should be doing in a laboratory appeared to constrain the exploratory mode of the studio laboratories. More needs to be done to make students comfortable with the loosely structured nature of the studio laboratories. Student performance on the written conceptual test showed that students improved significantly from the pre- to post-test on only some of the items. They also regressed on some of the items that had been learned before the midtest. More attention needs to be paid to the number of different concepts and how often they are revisited in the course. Students also expressed the need for better integration of the vast number of concepts across the course to facilitate their conceptual understanding of the material. This result is consistent with the lack of conceptual understanding demonstrated on some items of the conceptual assessment. The instructor also observed that the interactive style of the course improved student enthusiasm and alleviated their boredom. These and other intangible benefits are not measurable by conceptual assessments and attitudinal surveys.

IV. SUMMARY

The studio format allows for seamless spatial and temporal integration of lecture and laboratory activities. The immediate juxtaposition of theory and experiment allows students to interact with the phenomenon and explore it with other students and the professor. The lab-demos in the minilaboratory demonstrate the main idea or ideas of the minilecture topic and integrate readily with both lecture material and assigned problems.

The Studio Optics course is based on the assumption that interactive engagement is superior to traditional lectures. Our evaluation of the course indicates that students respond positively to the overall format of the course, but more needs to be done to improve the course and its impact on student learning. We need to better prepare the students in the course so that they become more comfortable with the open-ended nature of some of the minilaboratories. Another change would be to reduce the number of topics so that students have the opportunity to develop a deeper conceptual understanding of the material covered in the course.

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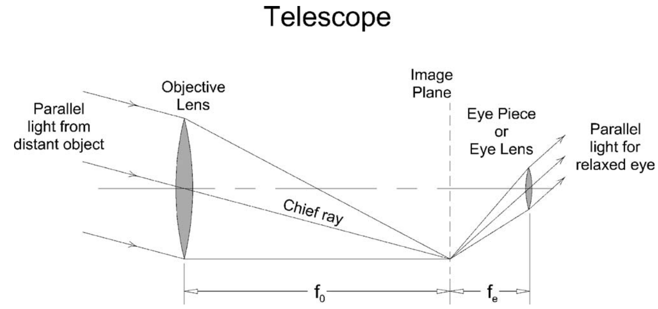

Fig. 1. Diagram of a telescope.

APPENDIX: EXAMPLES OF LAB-DEMOS FROM THE STUDIO MANUAL

Lab-demo 14. Lenses. Set up a luminous object, a lens, and an observation screen.

- Form an image of the object on the screen using a positive lens. Measure the image and object distances. Compare to the paraxial formula. Vary your object distances from much greater than the focal length f to twice the focal length (the "2f point," an important point of symmetry) to f. Closer than f, what happens? Draw a ray diagram and show consistency with both the calculation and the measurement for your situations. Measure the image and object size and compare to calculation and your ray diagram.
- Mess around with a negative lens. Can you form a real image? Can you ever magnify (enlarge) with such a lens?

Lab-demo 17. Telescopes. Make a telescope using two positive lenses, see Fig. 1. A focal ratio of about 5 to 1 works well for this demo. Test your telescope by looking at a distant object. What is the lens separation for a distant object? Verify that the final image is inverted. Calculate the magnification of your telescope. Estimate the experimental magnification by looking through your microscope with one eye, looking at the object with your other eye and allowing your eyes to relax—your brain will overlap the images. Measure the magnification using the clear aperture and the exit pupil. Change the orientation of the lenses and see which leads to the least image distortion. Why do things look smaller when you look the "wrong way" through your telescope?

A Galilean telescope uses an eye lens with a negative focal length. Make one. Is the image erect or inverted? What is the spacing between the lenses when focused at infinity? Compare this to the telescope with two positive lenses. Also compare both telescopes' fields of view.

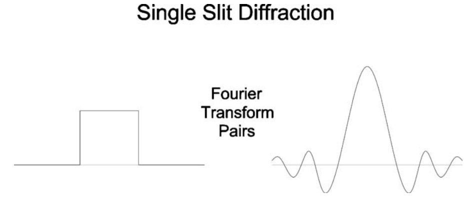

Fig. 2. The square pulse and its Fourier transform.

Lab-demo 31. Single-slit Fraunhofer diffraction. Shine a laser onto a closed adjustable slit. Slowly open the slit until the interference pattern appears on a distant ($\sim$1 m) screen or wall. Observe and sketch how the pattern changes with varying widths and qualitatively explain. Calculate the wavelength of the laser based on the interference pattern that appears and the width of the slit, and compare this to the known wavelength of the laser. (Use a magnifying glass and machinist's ruler to measure the slit width.) Note that you can also try to recreate the diffraction pattern by "squeezing" the laser beam with your thumb and index finger. Figure 2 illustrates the connection between the slit and its diffraction pattern.

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