Research as a Guide to Improving Student Learning: An Example from Introductory Physics

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The view among many faculty that teaching is an art and not a science has prevented the cumulative progress that characterizes the sciences. Often, new instructors start from scratch, trusting that personal charisma, intuition, and experience gained through trial and error are sufficient for effective teaching. This approach sometimes works quite well, especially when the primary measure of success is based on student perceptions. When student learning is used as a criterion, however, the outcome is often quite disappointing. Systematic investigations have demonstrated that the gap between what is taught and what is learned is often greater than many instructors realize (1–5). This chapter illustrates how discipline-based research on learning and teaching can help bridge this gap. The context is physics, but analogies can be made to other disciplines.

Context for Research and Curriculum Development

The Physics Education Group at the University of Washington consists of physics faculty, postdoctoral research associates, and graduate students. The graduate students earn a PhD in physics for research on the learning and teaching of physics. We conduct a coordinated program, in which research, curriculum development, and instruction are tightly linked in an iterative cycle. Our two major curriculum development projects are *Physics by Inquiry* (6) and *Tutorials in Introductory Physics* (7). The first is designed to prepare prospective and practicing K-12 teachers to teach science as a process of inquiry. The second is intended to supplement traditional instruction in the introductory course.

Investigation of Student Understanding

Our group is very pragmatic in our efforts to improve instruction. We recognize that the physics community is deeply embedded in a common culture. Therefore, we work within the traditional curriculum by asking the following questions: "Is the standard presentation of a basic topic in the textbook or lecture adequate to develop a functional understanding? If not, what gaps need to be filled?" By functional understanding, we mean the ability to apply what has been learned in one context to another.

We use two basic research methods. One is the individual demonstration interview, in which a simple demonstration provides the basis for a dialogue between an investigator and a student. We also make classroom observations, engage students in informal discussions, and analyze student responses to quizzes and examinations. These methods are illustrated here in the context of geometrical optics (8,9).

In a study that spanned several years, we examined whether students could use their knowledge of the rectilinear propagation of light to account for the *geometric image*, the bright region produced on a screen when light is incident on an aperture. A written problem based on a simple optical system consisting of a light source, a mask with a small triangular hole (~1 cm), and a screen has been given to almost 5,000 students in the introductory calculus–based course (Figure 1). In the first part, the light source is a very small bulb. The students are asked to sketch the appearance of the image. The same task is then posed for two other light sources: two very small bulbs (one above the other) and a long-filament bulb that is essentially a line source.

To give a correct response, students must recognize that 1) light travels in a straight line and 2) a line source can be

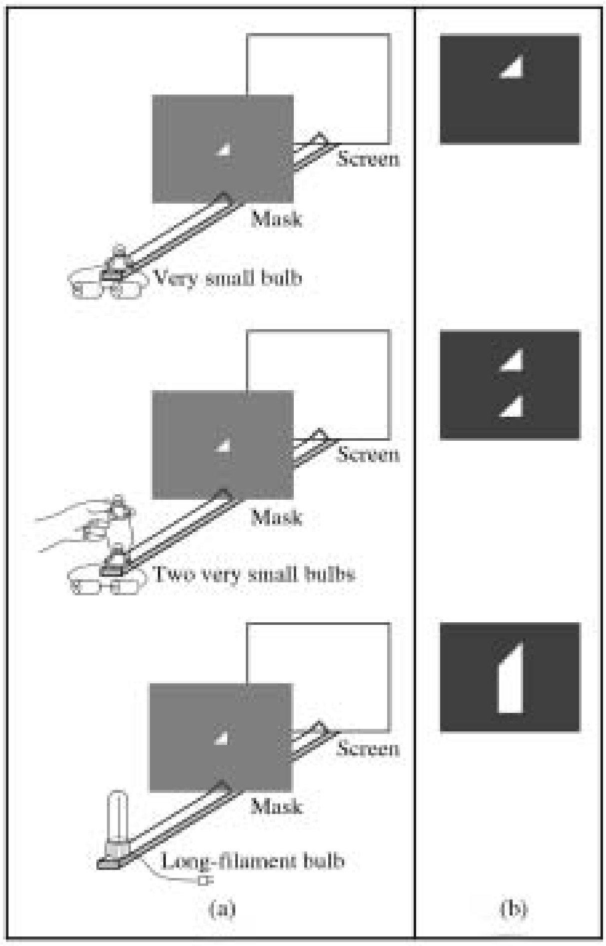

Figure 1. A written question on basic ideas in geometrical optics. A: Students were asked to sketch what they would see on the screen. B: Correct answer. The same apparatus is used in the tutorial Light and Shadow.

treated as a series of point sources. For the single small bulb, the image on the screen is triangular. With a second bulb, a second triangular image appears. If the bulbs are sufficiently close to each other, the images overlap. The image due to the long-filament bulb can be found by treating it as a string of many closely spaced small bulbs, each of which produces a triangular image. Because the bulbs are closely spaced, the images overlap substantially. The resulting image is a vertical rectangle terminating at the top in a triangle (Figure 1B).

Although the amount of instruction varied from class to class, the results did not.[1] Almost all of the students correctly predicted a single triangular image for the single small bulb. About 60% gave a correct response for the two bulbs. The most common error was to show a triangular image. Only about 20% of the students answered the question on the long-filament bulb correctly[2] (see Table 1). About 70% predicted that the image would be triangular.

These results illustrate the following generalization, which is based on numerous similar observations:

- **Certain conceptual difficulties are not overcome by traditional instruction.** *Persistent conceptual difficulties must be explicitly addressed by multiple challenges in different contexts.*

  There is by now evidence from many such investigations that on certain types of qualitative questions, student performance is essentially the same: before and after standard instruction, in the calculus-based and algebra-based course, with and without a standard laboratory, with and without demonstrations, in large and small classes, and regardless of the students' perception of the effectiveness of the lecturer. These findings lead to the following generalization:
- **Teaching by telling is an ineffective mode of instruction for most students.** *Students must be intellectually active to develop a functional understanding.*

  Intellectual engagement is difficult to secure in typical introductory physics courses. Instruction takes place primarily in lectures in which a great deal of material is covered quickly. The presentation tends to be theoretical and abstract. Instructors expect students to develop skill in problem-solving and in scientific reasoning. However, results from research indicate that most students do not develop the ability to reason qualitatively nor do they understand what is meant by a physical explanation. They tend to view physics as a collection of facts and formulas and to believe that the key to solving a physics problem is finding the right formula. This perception becomes more firmly entrenched as the course progresses (10).

Tutorials: An Instructional Approach for Addressing Student Difficulties in Large Courses

At any one time in our Physics department, there are about 2,000 students enrolled in the introductory courses. Almost 1,000 are taking calculus-based physics. In addition to the large number of students, there is the additional complication that all three academic quarters of this course—mechanics,

Table 1. Results from Pretests and Posttests Administered in Introductory Physics Courses and a Graduate Teaching Seminar

	Students in calculus-based course		Participants in graduate teaching seminar
	Pretest before tutorial	Posttests after tutorial	Pretest before tutorial
N	1,215	360	110
Correct or nearly correct response	20%	80%	65%
Incorrect response: image that mimics shape of hole in mask	70%	10%	30%

The pretest question is the one shown in Figure 1 involving a long-filament bulb. An example of a posttest is shown in Figure 2. The table contains only data from the part of each test pertaining to an extended light source.

electricity and magnetism, and waves and optics—are taught concurrently. There are eight lecture sections with eight different instructors. Faculty rotate through the course on a cycle that varies from one academic quarter to 3 years. There are about 45 laboratory and 45 tutorial sections.

We were faced with the task of securing the mental engagement of students in this context. Although our faculty are very conscientious instructors, the department is strongly research oriented. A system was needed that would be practical, flexible, and sustainable. The result is a tutorial system, the core of which is provided by *Tutorials in Introductory Physics* (7). The emphasis in the tutorials is on constructing concepts, on developing reasoning skills, and on relating the formalism of physics to the real world, not on transmitting information and solving standard problems.

The tutorials target critical ideas and skills that are known through research and teaching experience to present difficulty to students. A variety of instructional strategies are used. One that has proved particularly effective can be summarized as a sequence of steps: *elicit, confront,* and *resolve.* The first step is to *elicit* a known difficulty by contriving a situation in which students are likely to make an error that exposes that particular difficulty. If the difficulty is sufficiently serious and not addressed, it may remain latent and arise in other contexts. It is therefore the responsibility of the instructor to insist that students *confront* and *resolve* underlying difficulties. Tutorial homework assignments provide students the opportunity to *apply* the relevant concepts in related but different contexts, to *reflect,* and to *generalize.*

Description of the tutorial system

Each tutorial sequence begins with a pretest (so named because it precedes the tutorial, although the material may have already been covered in lecture). The pretests help set the stage for the associated tutorial and inform the course lecturers and tutorial instructors about the intellectual state of their students. During the tutorial sessions, about 20–24 students work collaboratively in groups of three or four on carefully structured worksheets. The worksheets contain questions that try to break the reasoning process into steps of just the right size for students to become actively involved. Tutorial instructors ask additional questions intended to help the students arrive at the answers for themselves. At least one-fourth of every course examination requires qualitative reasoning and verbal explanations.

Preparation of teaching assistants and other tutorial instructors

The tutorial system would not work without ongoing preparation of the tutorial instructors in both the subject matter and the instructional method. Most of us teach as we were taught. It is unrealistic to expect peer instructors, graduate teaching assistants (TAs), or faculty to be able, without preparation, to teach by questioning in a way that promotes

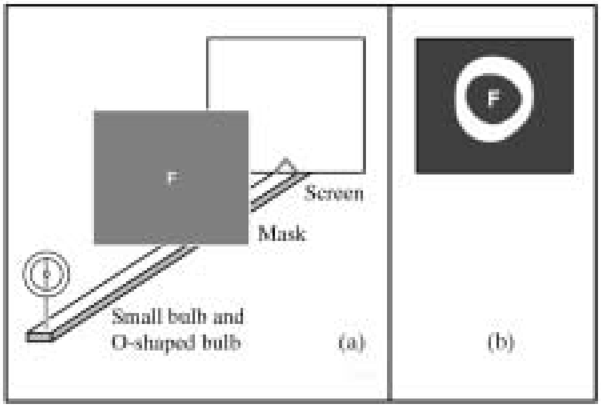

Figure 2. An example of a posttest. A: Students were asked to sketch what they would see on the screen. B: Correct answer.

development of reasoning skills. Preparation of the tutorial instructors takes place on a weekly basis in a required graduate teaching seminar led by our group. The seminar is conducted on the same material and in the same manner that the tutorial instructors are expected to teach. Because the TAs take the same pretests as the introductory students, we have a measure of their level of understanding. Although they can generally solve the end-of-chapter problems, we find that many do not have a sufficiently strong command of the material for the type of teaching by questioning that the tutorials require.

Example of a tutorial: *Light and Shadow*

With results from the investigation briefly described above as a guide, we designed a tutorial based on the apparatus in Figure 1. The tutorial begins by having students predict the images formed by point and line sources with apertures of various sizes and shapes. After the students have made predictions and explained their reasoning to one another, they observe what actually happens and try to resolve any discrepancies with their predictions. They are then asked to predict and explain up-down and left-right inversions of images produced by asymmetric sources. These and other exercises help students recognize that the size and shape of the source, the size and shape of the aperture, and the distances involved all can have an effect on the image. The students note that whether a light source can be treated as a point, a line, or an extended source also depends on a variety of factors.

Assessment of effectiveness at the University of Washington. Throughout the development of the tutorial, assessment of the effect on student learning played a critical role. Figure 2A shows an example of a posttest. The correct answer appears in Figure 2B. This question and several similar ones were administered on different examinations to about 360 students who had worked through the tutorial. The percentage of *correct* or *nearly correct* responses was 80%, an increase from 20% on the pretest given before the tutorial.[3,4] Only 10% drew images the same shape as the aperture, in sharp contrast to the 70% who made this error before the tutorial (Table 1).

We consider the pretest performance of physics graduate students to be a reasonable posttest goal for introductory students. The last column of Table 1 shows the pretest results on the long-filament bulb for 110 TAs and post-docs. About 65% have given a *correct* or *nearly correct* response. About 30% have drawn a triangular image. Comparison of the posttest performance of the introductory students with the pretest performance of the graduate students indicates that our goal has been achieved.

Assessment of effectiveness at pilot sites. We believe that a crucial part of the curriculum development process is to assess the impact of instructional materials not only at the institution at which they have been developed, but at others as well. The tutorials have been pilot-tested at a number of institutions, ranging from large research-oriented universities to community colleges. Responses on pretests demonstrate that difficulties with basic concepts in geometrical optics are widely prevalent among introductory physics students. Results from posttests indicate that the types of instructional strategies in *Light and Shadow* can be effectively used by instructors not involved in the development of the tutorial.

An example is provided by our experience with one of our pilot sites. An earlier version of the tutorial *Light and Shadow* was used in a calculus-based course at a private university. A pretest was given to about 100 students in four different classes before any instruction in geometrical optics. The students took a version of the pretest in which first a single small bulb and then a long-filament bulb is placed in front of a mask with a triangular hole. (There was no intermediate question involving two small bulbs.) Only two students (<5%) correctly answered the question about the extended source. About 90% said that the image would be triangular, the same shape as the hole in the mask.

The posttest shown in Figure 2 was given on an examination after students had worked through the tutorial. About 65% of the students gave a correct or nearly correct response for the extended source. Only about 30% claimed that the image would have the same shape as the aperture. Thus, the tutorial seems to have helped students in a different context from that in which it had been developed and one in which none of the developers was present.

Conclusion

Results from research indicate that most students in a traditional introductory course cannot do the qualitative reasoning necessary to apply concepts to situations not expressly memorized. Our experience has shown that this ability can be developed if students are given practice in solving qualitative problems and in explaining their reasoning. If students go through the reasoning involved in the development and application of important concepts, they can significantly deepen their understanding of even very difficult material. We and others have found that time spent on developing a sound qualitative understanding often improves student ability to solve quantitative problems, often despite reduced emphasis on such problems in class (4,11,12). Retention of concepts is often improved. In one study, students performed at a very high level on a standard multiple-choice test in a course in which the tutorials were used; when tested again three years later, their scores were essentially unchanged (13). To date, more than 75,000 copies of the tutorials have been used at more than 50 institutions. Translations into Spanish and Greek are complete; translation into German is underway. The tutorials are one example of how, within a relatively small time allotment, a research-based curriculum can help students learn to do the type of qualitative reasoning that can make the subject matter meaningful to them.

Acknowledgments

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Endnotes

1. Other examples in which student performance on certain questions is essentially the same before or after standard instruction can be found in Refs. 3, 4, and 8, as well as in other reports of research by our group.

2. Responses were counted as nearly correct if students either treated the extended source as a discrete series of point sources or if they generalized that the image was basically the same shape as the source. The variation in intensity due to the differing degree of overlap among the individual triangular images was ignored in our analysis of student responses.

3. In the case of the O-shaped bulb, the F-shaped hole results in an image that is not precisely circular. However, we considered as correct or nearly correct all student diagrams showing a circular ring.

4. Each population took only one posttest. The results are presented only for those students who attended the tutorial session. Although the classes for whom the pretest and posttest data are reported are not all the same, the results can be compared because there is typically little variation from class to class on pretest or posttest performance.