

IDENTIFYING AND ADDRESSING STUDENT CONCEPTUAL DIFFICULTIES: AN EXAMPLE FROM INTRODUCTORY PHYSICS

Paula R.L. Heron, Peter S. Shaffer, and Lillian C. McDermott

Department of Physics, University of Washington
Seattle, Washington

Systematic investigations over the past few decades have demonstrated that many students emerge from introductory physics courses without having developed a functional understanding of the concepts and principles they were taught.¹ Discipline-based education research can help improve student learning by guiding the development of instructional materials that target specific conceptual and reasoning difficulties. In this paper we illustrate this process in the context of physics, but analogies can be made to other disciplines.

I. CONTEXT FOR RESEARCH AND CURRICULUM DEVELOPMENT

The Physics Education Group at the University of Washington (UW) conducts a coordinated program, in which research, curriculum development, and instruction are tightly linked in an iterative cycle. Our two major NSF-funded curriculum development projects are *Physics by Inquiry* and *Tutorials in Introductory Physics*.^{2,3} The first is designed to prepare prospective and practicing K-12 teachers to teach science as a process of inquiry. The second, which is the focus of this paper, is intended to supplement traditional instruction in large-enrollment courses.

The calculus-based physics course in the UW Physics Department provides the context in which we have been developing the *Tutorials*. At any one time there are about 1000 students enrolled in this course, which is required for physics majors and most engineering majors. Instruction takes place primarily in lectures in which a great deal of material is covered quickly.

In addition to the large number of students, there is the additional complication that all three academic quarters of this course - mechanics, 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 three years. There are about 45 laboratory and 45 tutorial sections. In both structure and content the course is similar to many others in colleges and universities throughout the U.S. Therefore the setting is well-suited for the development and assessment of curriculum that can be adopted at other institutions.

III. TUTORIALS: AN INSTRUCTIONAL APPROACH FOR ADDRESSING STUDENT DIFFICULTIES IN LARGE COURSES

We were faced with the challenge of securing the intellectual engagement of students in a large course in which resources are limited and in which the selection of topics is essentially fixed. Moreover, although our faculty are very conscientious instructors, our Department is strongly research oriented. Therefore an approach 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*.

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 employed. 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. Homework assignments provide students the opportunity to *apply* the relevant concepts in related but different contexts, to *reflect*, and to *generalize*.

The overall instructional philosophy underlying the tutorials is guided by generalizations from physics education research that are consistent with the findings of educational research conducted from different perspectives.⁴ In particular, it is well known that teaching by telling is ineffective. Therefore the structure of each tutorials is provided by a worksheet containing a series of questions and suggested experiments that help guide students through the reasoning needed to construct, interpret and apply concepts for themselves. Teaching assistants, usually physics graduate students, are expected to ask additional questions that help students arrive at the answers for themselves. Each tutorial is designed on the basis of specific research on how students learn the topic in question.

A. Description of the tutorial system at UW

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 3 or 4 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. Approximately one-fourth of every course examination requires qualitative reasoning and verbal explanations.

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 TA's, or faculty to be able, without preparation, to teach by questioning in a way that promotes development of reasoning skills. Preparation of the tutorial instructors takes place on a weekly basis in a required graduate teaching seminar. The seminar is conducted on the same material and in the same manner that the tutorial instructors are expected to teach.

Variations of this system are in place in dozens of colleges and universities that have adopted the *Tutorials*. The institutions represent a wide range in terms of class size and student background. In all cases that we are aware of, careful attention is paid to tutorial instructor preparation and tutorial-related material is included on course examinations.

B. Example of a tutorial: *Light and Shadow*

In a study that spanned several years, we examined whether university students could use their knowledge of the rectilinear propagation of light to account for the bright region produced on a screen when light is incident on an aperture.⁵ 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 hundreds of students in the introductory calculus-based course. (See Fig. 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 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. Since the bulbs are closely spaced, the images overlap substantially. The resulting image is a vertical rectangle terminating at the top in a triangle. [See Fig. 1(b).]

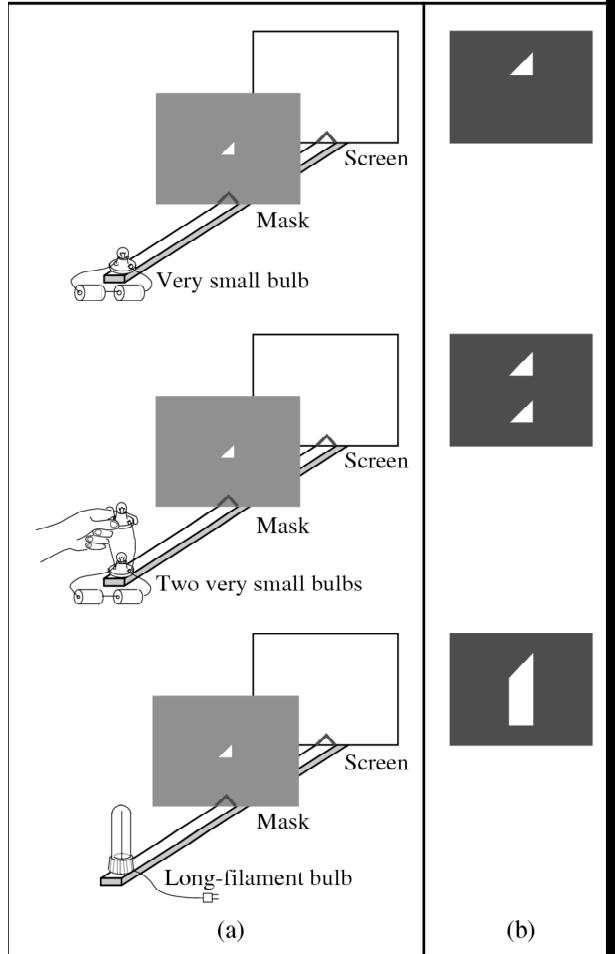


Figure 1. A written question on basic ideas in geometrical optics. (a) Students were asked to sketch what they would see on the screen. (b) Correct answer. The same apparatus is used in the tutorial *Light and Shadow*.

Although the amount of instruction varied from class to class, the results did not.⁶ 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.⁷ (See Table I.) About 70% predicted that the image would be triangular.

	Students in calculus-based course		Participants in graduate teaching seminar
	Pretest before tutorial (N ≈ 1215)	Post-tests after tutorial (N ≈ 360)	Pretest before tutorial (N ≈ 110)
Correct or nearly correct response	20%	80%	65%
Incorrect response: image that mimics shape of hole in mask	70%	10%	30%

TABLE I. Results from pretests and post-tests administered in introductory physics courses and a graduate teaching seminar. The pretest question is the one shown in Fig. 1 involving a long-filament bulb. An example of a post-test is shown in Fig. 2. The table contains only data from the part of each test pertaining to an extended light source.

With results from the investigation briefly described above as a guide, we designed a tutorial based on the apparatus in Fig. 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.

IV. EVIDENCE OF EFFECTIVENESS

Assessment of the impact on student learning plays an integral role in the development of each tutorial. In this section we give an example in the context of the Light and Shadow tutorial. We also summarize some results obtained from assessments conducted at other universities where the tutorials have been adopted.

Conceptual understanding

The primary goal of the tutorials is to help students apply concepts and principles to situations they have not seen before. By administering pretests and post-tests that require qualitative reasoning we are able to gauge the extent to which this goal has been met. In some cases we give comparable pre-tests and post-tests to the same group of students. In other cases we give the same problem to two groups: one prior to the tutorial; the other after it has been completed. Below we give an example of the former.

In Fig. 2(a) is an example of a post-test for the tutorial on *Light and Shadow*. The correct answer appears in Fig. 2(b). 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 prior to the tutorial.^{8,9} Only 10% drew images the same shape as the aperture, in sharp contrast to the 70% who made this error prior to the tutorial. [See Table I.]

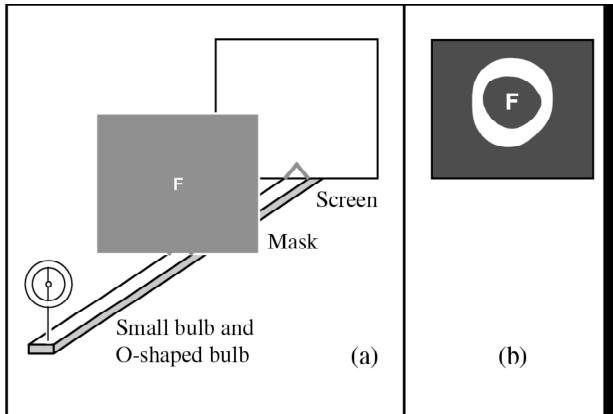


Figure 2. An example of a post-test. (a) Students were asked to sketch what they would see on the screen. (b) Correct answer.

We consider the pretest performance of physics graduate students to be a reasonable post-test goal for introductory students. The last column of Table I shows the pretest results on the long-filament bulb for 110 TA's and post-docs. About 65% have given a *correct or nearly correct* response. About 30% have drawn a triangular image.

Comparison of the post-test performance of the introductory students with the pretest performance of the graduate students indicates that our goal has been achieved.

Pretesting and post-testing using qualitative problems like those in the above example has also been conducted by physics faculty at other institutions where the tutorials are being used. The results indicate that the tutorials can be effectively used by instructors not involved in their development.¹⁰

At some universities, faculty adopting the tutorials have also given multiple-choice tests like the Force Concept Inventory (FCI), which is widely used to gauge student learning of Newtonian mechanics.¹¹ The ease with which multiple-choice tests like the FCI can be administered and scored, and the availability of data for comparison purposes, have led to their popularity in physics. Finkelstein and Pollock at the University of Colorado administered the FCI at the beginning and end of each semester in a course

using the tutorials. They report much higher gains than are typical for large introductory physics courses.¹⁰

Pretest and post-test comparisons can also be used to assess the degree to which learning gains demonstrated in a semester persist after the course ends. Francis *et al* at Montana State University investigated the retention of understanding of the concepts of Newtonian Physics by administering the FCI to student volunteers up to three years after they had completed an introductory course that used the tutorials.¹² By comparing the results to those obtained from the same students at the beginning and end of the physics course, the authors showed that there was little or no decreases in scores despite the passage of months or years.

Broad assessments like the FCI have also been used as the basis for large-scale investigations of the conceptual learning of sub-groups within the population of students who take introductory physics. For example, Lorenzo *et al* at Harvard documented a “gender gap” in scores on the FCI between male and female students enrolled in an introductory course.¹³ They looked at the effect on this gap of switching the focus of the course from lecture-and-textbook mode to emphasize interaction between among students. The authors report that the gender gap was significantly reduced in “partially interactive” classes (ones in which students discussed conceptual questions in lecture and indicated their responses using a personal response system) while the gap was eliminated in some “fully interactive” classes (ones with the addition of *Tutorials* in small sections).

Quantitative Problem Solving

In most physics courses, the ability of students to solve quantitative problems remains one of the most important measures of effectiveness. In some courses in which

the *Tutorials* have been adopted, the increase in emphasis on qualitative reasoning came at the expense of demonstrations of quantitative problem-solving by faculty or TAs. Therefore it is essential to assess the impact on student ability to solve such problems. In one university in which tutorials had been adopted in some sections of the introductory course, a quantitative examination problem was used in both a section that had tutorials and one that did not. The tutorial students performed much better, despite having devoted less class time to similar problems.¹⁴

Student Attitudes

The attitudes that students express towards physics courses, and their beliefs about learning, have been the subject of increasing attention in the PER community. Adams *et al* at the University of Colorado developed the Colorado Learning About Science Survey (CLASS) to examine the evolution of student attitudes.¹⁵ Finkelstein and Pollock administered this survey in a course using *Tutorials*.¹⁰ They reported that while they saw no shift toward favorable attitudes, neither did they observe the kind of shift toward unfavorable attitudes that has been widely reported in introductory physics.

Broader Impact

To date, more than 75,000 copies of *Tutorials in Introductory Physics* have been used at more than 50 institutions in the United States. Translations into Spanish, Greek and German are complete. The publication of the *Tutorials* has also had an impact on the field of physics education research. In the past few years dozens of publications and conference presentations have examined student learning in the context of courses using the *Tutorials*. Astronomers and geologists have been inspired by the tutorials to develop materials in the same spirit for introductory courses in their own disciplines.

IV. NEXT STEPS

As remarked earlier, at least one study has demonstrated that student mastery of concepts did not appear to decay after the end of a course using *Tutorials*. We believe that it would also be important to examine the degree to which such mastery influences learning in subsequent courses. We have made a modest start investigating this issue and found that student performance in engineering mechanics courses was stronger for students who had participated in the tutorials but the large number of uncontrolled variables prevents us from drawing a firm conclusion. We believe that further research in this direction is important.

We also focused above on the ability of students to solve qualitative and quantitative physics problems. However, the tutorials are also intended to help students develop scientific reasoning skills that transcend the subject matter of introductory physics. We recently published results related to student difficulties in designing and interpreting controlled experiments.¹⁶ However, we believe it is important to conduct additional detailed assessments of student abilities to apply important scientific reasoning skills.

IV. 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.

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

The research and curriculum development described represent a collaborative effort by many members of the Physics Education Group, present and past. Major contributions were made by Karen Wosilait. We are grateful to the National Science Foundation for the support that has enabled the group to conduct a coordinated program of research, curriculum development, and instruction.

1. For a comprehensive review of the literature in physics education research, see L.C. McDermott and E.F. Redish, "Resource Letter: PER-1: Physics Education Research," *Am. J. Phys.* **67**, 755 (1999).
2. L.C. McDermott and the Physics Education Group at the University of Washington, *Physics by Inquiry*, Vols. I and II (Wiley, New York, 1996).
3. L.C. McDermott, P.S. Shaffer, and the Physics Education Group at the University of Washington, *Tutorials in Introductory Physics*, First Edition (Prentice Hall, Upper Saddle River, NJ, 2002).
4. For a discussion of these generalizations and the research on which they are based, see L.C., McDermott, "Millikan Lecture 1990: What we teach and what is learned - Closing the gap," *Am. J. Phys.* **59**, 301 (1991); L.C. McDermott, "Guest Comment: How we teach and how students learn - A mismatch?," *Am. J. Phys.* **61**, 295 (1993) and L.C. McDermott, Oersted Medal Lecture 2001: "Physics Education Research: The Key to Student Learning," *Am. J. Phys.* **69**, 112 (2001).
5. This investigation is described in greater detail in K. Wosilait, P.R.L. Heron, P.S. Shaffer, and L.C. McDermott, "Development and assessment of a research-based tutorial on light and shadow," *Am. J. Phys.* **66**, 906 (1998) and P.R.L. Heron and L.C. McDermott, "Bridging the gap between teaching and learning: Examples from geometrical optics," *Optics and Photonics News*, **9**, (9) 30 (1998).
6. Other examples in which student performance on certain questions is essentially the same before or after standard instruction can be found in Ref. 1, as well as in other reports of research by our group.
7. 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.
8. 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.
9. Each group took only one post-test. The results are presented only for those students who attended the tutorial session. Although the classes for whom the pretest and post-test 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 post-test performance.
10. N. D. Finkelstein and S. J. Pollock, "Replicating and understanding successful innovations: Implementing tutorials in introductory physics," *Phys. Rev. ST Phys. Educ. Res.* **1**, 010101 (2005).

- 11 D. Hestenes, M. Wells, and G. Swackhamer, “Force Concept Inventory,” *Phys. Teach.* **30**, 141-158 (1992). For a discussion of typical results, see R.R. Hake, “Interactive-engagement versus traditional methods: A six-thousand-student survey of mechanics test data for introductory physics courses,” *Am. J. Phys.* **66** (1) 64-74 (1998)
12. G.E. Francis, J.P. Adams, and E.J. Noonan, “Do they stay fixed?,” *Phys. Teach.* **36**, 488 (1998).
- 13 M. Lorenzo, C.H. Crouch, and E. Mazur, “Reducing the gender gap in the physics classroom,” *Am. J. Phys.*, **74**, 118-122 (2006).
14. B.S. Ambrose, P.S. Shaffer, R.N. Steinberg, and L.C. McDermott, “An investigation of student understanding of single-slit diffraction and double-slit interference,” *Am. J. Phys.* **67** (2) pp. 146-155 (1999). For other examples in which the shift to qualitative reasoning has not adversely affected quantitative problem solving ability, see B. Thacker, E. Kim, K. Trefz and S.M. Lea, “Comparing problem solving performance of physics students in inquiry-based and traditional introductory physics courses,” *Am. J. Phys.* **62**, 627 (1994); and E. Mazur, *Peer Instruction, A User's Manual* (Prentice Hall, Upper Saddle River, NJ, 1997).
15. W. K. Adams, K. K. Perkins, N. Podolefsky, M. Dubson, N. D. Finkelstein and C. E. Wieman, “A new instrument for measuring student beliefs about physics and learning physics: the Colorado Learning Attitudes about Science Survey,” *Phys. Rev ST: Phys. Educ. Res.* **2** (1) 010101 (2006).
16. A. Boudreaux, P.S. Shaffer, P.R.L. Heron, and L.C. McDermott, “Student understanding of control of variables: Deciding whether or not a variable influences the behavior of a system,” *Am. J. Phys.* **76** (2008).