

BRIDGING THE GAP BETWEEN TEACHING AND LEARNING: THE ROLE OF PHYSICS EDUCATION RESEARCH IN THE PREPARATION OF TEACHERS AND MAJORS¹

(Aproximando ensino e pesquisa: o papel da pesquisa em ensino de Física na preparação de professores e bacharéis)

Lillian C. McDermott [lcmcd@phys.washington.edu]
Department of Physics, Box 351560
University of Washington
Seattle Washington 98195 U.S.A.

Abstract

Research can play a critical role in the development of instructional materials for precollege teachers, for students at the introductory level, and for students in more advanced physics courses. Examples from introductory physical optics are used to illustrate the use of research in identifying student difficulties, in developing instructional strategies to address these difficulties, and in assessing student learning. The implications for the design of instruction extend beyond the topic of physical optics and beyond introductory physics.

Key-words: physics education research; preparation of physics teachers; physical optics.

Resumo

A pesquisa pode ter um papel crítico no desenvolvimento de materiais instrucionais para professores pré-universitários, para estudantes em cursos introdutórios de Física bem como em cursos mais avançados. Exemplos em ótica física introdutória são aqui apresentados para ilustrar dificuldades dos estudantes, no desenvolvimentos de estratégias para ajudá-los a superar tais dificuldades, assim como na avaliação da aprendizagem. Contudo, as implicações para o planejamento do ensino vão além do tópico ótica física e além da física introdutória.

Palavras-chave: pesquisa em ensino de Física; preparação de professores de Física; ótica física.

Introduction

The Physics Education Group at the University of Washington has been engaged for many years in preparing elementary and secondary teachers to teach physics and physical science by inquiry.² We are also deeply involved in the calculus-based introductory course that is required for students majoring in physics, other sciences and engineering.³ In addition, we participate in the instruction

¹ Invited paper. Plenary talk presented at the VII Interamerican Conference on Physics Education, Porto Alegre, (Canela), Brazil, July 3-7, 2000.

² See, for example, L.C. McDermott, P.S. Shaffer, and C.P. Constantinou, "Preparing teachers to teach physics and physical science by inquiry," *Phys. Educ.* **35**(6) (November 2000); L.C. McDermott and L.S. DeWater, "The need for special science courses for teachers: Two perspectives," an invited chapter in *Inquiring into Inquiry Learning in Teaching and Science*, J. Minstrell and E.H. van Zee eds., Washington, D.C., AAAS (2000), pp. 241–257; and L.C. McDermott "A perspective on teacher preparation in physics and other sciences: The need for special courses for teachers," *Am. J. Phys.* **58** (8) 734–742 (1990).

³ See, for example, L.C. McDermott, P.S. Shaffer, and M.D. Somers, "Research as a guide for teaching introductory mechanics: An illustration in the context of the Atwood's machine," *Am. J. Phys.* **62** 46–55 (1994); L.C. McDermott and P.S. Shaffer, "Research as a guide for curriculum development: An example from introductory electricity. Part I: Investigation of student understanding," *Am. J. Phys.* **60** 994–1003 (1992) and printer's erratum to Part I, *Am. J. Phys.* **61**, 81 (1993); and P.S. Shaffer and L.C. McDermott, "Research as a guide for curriculum development: an example from introductory electricity, Part II: Design of instructional strategies," *Am. J. Phys.* **60** 1003–1013 (1992).

of more advanced courses.⁴ All of these efforts are an integral part of the Physics Education Group's comprehensive program in research, curriculum development, and instruction. Our research focuses on investigations of student understanding in physics.⁵ We try to identify specific difficulties that students encounter in studying a particular topic and use the results to guide the design of instructional materials for precollege teachers, for students at the introductory level, and for students in more advanced physics courses.⁶

We are currently developing two types of curriculum, both of which are nationally distributed. *Physics by Inquiry* is a self-contained, laboratory-based curriculum designed for use by faculty to prepare precollege (*i.e.*, pre-university) teachers.⁷ *Tutorials in Introductory Physics* is intended to supplement the lectures, laboratory experiments, and textbooks that characterize instruction in a standard university physics course.⁸ Both sets of instructional materials are research-based.

In this paper, we discuss the role of research in the development of curriculum by the Physics Education Group. The discussion is based on results from a long-term, investigation of student understanding of geometrical and physical optics.^{9,10} (Other topics could have served the same purpose.) To give a sense of the scope of the curriculum in introductory physical optics, the examples used as illustrations have been drawn from different sub-topics (single-slit diffraction, double-slit and multiple-slit interference).

The results from the part of the investigation discussed in this paper involved undergraduate and graduate students at our university. The undergraduates came from several courses: introductory calculus-based and algebra-based physics, sophomore-level modern physics, and junior-level quantum mechanics. The latter two groups consisted mostly of physics majors. The graduate students were enrolled in a weekly teaching seminar required for all teaching assistants in our physics department. Although none of the data were expressly collected from precollege teachers, some prospective high school teachers were included in almost all of the groups. Results from other topics indicate that their responses tend to be similar to those of science and engineering majors.¹¹

⁴ See, for example, S. Vokos, P.S. Shaffer, B.S. Ambrose, and L.C. McDermott, "Student understanding of the wave nature of matter: Diffraction and interference of particles," *Phys. Educ. Res., Am. J. Phys. Suppl.* **68** S42–S51 (2000) and R.N. Steinberg, G.E. Oberem, and L.C. McDermott, "Development of a computer-based tutorial on the photoelectric effect," *Am. J. Phys.* **64** 1370–1379 (1996).

⁵ There is a growing body of research on the learning and teaching of physics at all levels of instruction. The references in this paper are all directly related to research and curriculum development by the Physics Education Group. For articles that report on other research at the university level, see L.C. McDermott and E.F. Redish, "Resource Letter: PER-1: Physics Education Research," *Am. J. Phys.* **67**, 755–767 (1999).

⁶ For an overview of how research guides the development of curriculum by the Physics Education Group, see L.C. McDermott, "Millikan Lecture 1990: What we teach and what is learned—Closing the gap," *Am. J. Phys.* **59** 301–315 (1991) and "Guest Comment: How we teach and how students learn—A mismatch?" *ibid.* **61** 295–298 (1993).

⁷ L.C. McDermott and the Physics Education group at the University of Washington, *Physics by Inquiry, Vols. I and II* (John Wiley & Sons, Inc., New York, N.Y., 1996).

⁸ L.C. McDermott, P.S. Shaffer, and the Physics Education group at the University of Washington, *Tutorials in Introductory Physics, Preliminary Edition* (Prentice Hall, Upper Saddle River, N.J., 1998).

⁹ For articles by our group on geometrical optics, see P.R.L. Heron and L.C. McDermott, "Bridging the gap between teaching and learning in geometrical optics: The role of research," *Opt. & Phot. News* **9** (9), 30–36 (1998); 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**, 906–913 (1998); F.M. Goldberg and L.C. McDermott, "Student difficulties in understanding image formation by a plane mirror," *Phys. Teach.* **24** 472–480 (1986); and F.M. Goldberg and L.C. McDermott, "An investigation of student understanding of the real image formed by a converging lens or concave mirror," *Am. J. Phys.* **55** 108–119 (1987).

¹⁰ For articles by our group on physical optics, see B.S. Ambrose, P.S. Shaffer, R.N. Steinberg, and L.C. McDermott, "An investigation of student understanding of two-source interference and single-slit diffraction," *Am. J. Phys.* **67** 146–155 (1999) and K. Wosilait, P.R.L. Heron, P.S. Shaffer, and L.C. McDermott, "Addressing student difficulties in applying a wave model to the interference and diffraction of light," *Phys. Educ. Res., Am. J. Phys. Suppl.* **67** S5–S15 (1999).

¹¹ See, for example, the second article in Ref. 9 and the second article in Ref. 3.

Identification of what students can and cannot do

To be able to improve instruction in an efficient and cumulative manner, a systematic approach is necessary. Just as physicists do in any investigation, we focus attention on the phenomenon being studied. Extrapolating on the basis of one's own ideas and experience can be very misleading. The proper place to begin is to determine what students can and cannot do. This approach is illustrated by the examples that follow.

Single-slit diffraction

The first two questions on diffraction described below were administered on examinations in the introductory calculus-based physics course at the University of Washington. The questions pose essentially the same problem. The difference in the way that many students treated the questions provides some insight into what they typically can and cannot do. The third question was posed in interviews with students to probe their understanding in greater depth than is possible in written questions.

Quantitative question

The following quantitative question was given to about 130 students on an examination in the introductory calculus-based course. [See Fig. 1(a).] The question was posed after standard lecture instruction on diffraction. The students were told that light is incident on a single slit of width 4λ . They were asked to state if any minima would appear on a screen and, if so, to calculate the angle to the first minimum. Since the slit width is larger than the wavelength, minima would occur. The required angle can be obtained by using the equation $a \sin \theta = \lambda$, which yields $\theta = \sin^{-1}(0.25) = 14^\circ$.

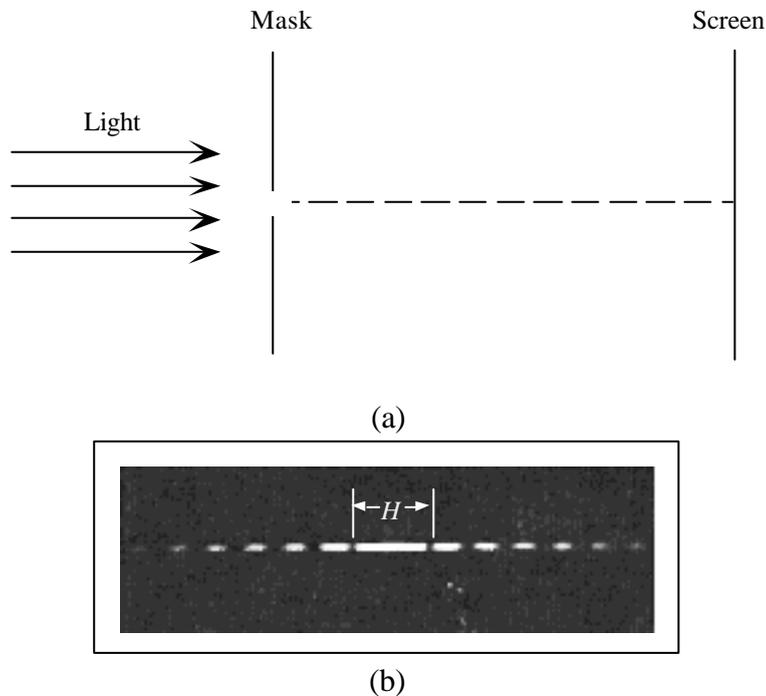


Figure 1: (a) Diagram from quantitative question on single-slit diffraction. Students are told that the slit width D is equal to 4λ . They are asked whether minima would appear on the screen and, if so, to calculate the angle to the first minima. (b) Diagram used in qualitative question on single-slit

diffraction. Students are asked whether the slit width is greater than, less than, or equal to the wavelength.

Approximately 85% of the students stated that there would be a first minimum. About 70% determined the correct angle. (See the first column in Table I.) However, the evidence given below indicates that success on this question was not commensurate with a functional understanding (i.e., the ability to do the reasoning necessary to apply concepts to situations that have not been memorized).

Table I: Results from quantitative and qualitative questions on single-slit diffraction posed after standard instruction in introductory calculus-based courses. On the quantitative question, students are asked whether any minima would occur for the situation shown in Fig. 1(a) and, if so, to calculate the angle to the first minimum. On the qualitative question, students are asked whether the slit that produced the diffraction pattern in Fig. 1(b) has width greater than, less than, or equal to the amplitude.?

	Students in introductory calculus-based course		Graduate Students
	Quantitative question	Qualitative question	Qualitative question
	After standard instruction (N = 130)	After standard instruction (N = 510)	(N = 95)
Minima exist (quantitative question)	85%	45%	80%
$a < \lambda$ (qualitative question)			
Correct angle (quantitative question)	70%	10%	55%
Correct reasoning (qualitative question)			

Qualitative questions

In order to probe student understanding in depth, we administered written questions and conducted individual demonstration interviews. We were particularly interested in the reasoning that the students used to support their answers.

Written question

On one written question, the students were shown a single-slit diffraction pattern with several minima. [See Fig. 1(b).] They were told that the pattern results when a mask with a single vertical slit is placed between a laser (wavelength λ) and a screen. They were asked to decide whether the slit width is greater than, less than, or equal to λ and to explain their reasoning. They could answer this question by using the equation that describes the angle θ to the first diffraction minimum, $a \sin \theta = \lambda$, where a is the width of the slit. Since minima are visible, the angle to the first minimum is less than 90° . Therefore, $\sin \theta < 1$ and λ/a is less than 1.

About 510 students in calculus-based physics have been asked this question after completing traditional instruction on single-slit diffraction. As shown in the second column of Table I, performance was poor. About 45% of the students made a correct comparison with only 10% giving a correct explanation. This same question was also posed in the graduate teaching seminar ($N \sim 95$). About half of the participants responded correctly with correct reasoning. (See the third column of Table I.)

Individual demonstration interviews

In addition to written questions, we conducted individual demonstration interviews in which similar questions were asked. Of the 46 students who participated, 16 were from the introductory calculus-based course and 30 from the modern physics course. All were volunteers and they came from several lecture sections. They had earned grades at or above the mean in their respective courses. The interviews with the introductory students took place during the last week of the academic quarter after all instruction on the interference and diffraction of light had taken place. In the modern physics course, the students had reviewed this material and covered similar topics in the context of matter waves. The interviews, from 3/4 to 1 hour in length, were videotaped.

The students were shown a small bulb, a screen, and a mask with a rectangular aperture 1 cm wide and 3 cm tall. (See Fig. 2.) They were asked to predict what they would see on the screen and how this would change as the aperture is gradually narrowed to become a slit. Initially, the geometric image of the aperture would be seen. Eventually, a single-slit diffraction pattern would appear.¹²

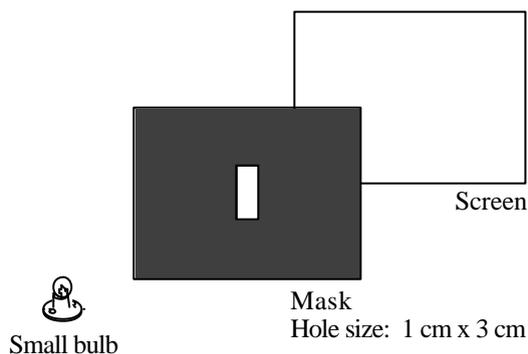


Figure 2: Apparatus used in individual demonstration interviews. Students are asked to predict what they would see on the screen: (1) for the situation shown, (2) for the situation in which the bulb is moved farther and farther from the mask, and (3) for the situation in which the slit is made narrower and narrower.

Identification of difficulties

The difficulties revealed by the written questions and interviews were similar. Among the introductory students, there was a tendency to use a hybrid model with features of both geometrical and physical optics. For example, some students seemed to believe that light passing through the center of the slit forms a geometric image, while light striking the edges of the slit is bent to form

¹² The investigator tried to ensure, either tacitly or overtly, that certain simplifying assumptions would be made. If the students seemed to think of the bulb as an extended source, they were told to treat it as a point source. If they recognized that the light would be composed of many colors, they were told to imagine a red bulb.

other bright regions on the screen. [See Fig. 3(a).] Some modern physics students expressed a similar belief but used a hybrid model that incorporated photons. [See Fig. 3(b).] Their exposure to more advanced material seems to have introduced additional difficulties.

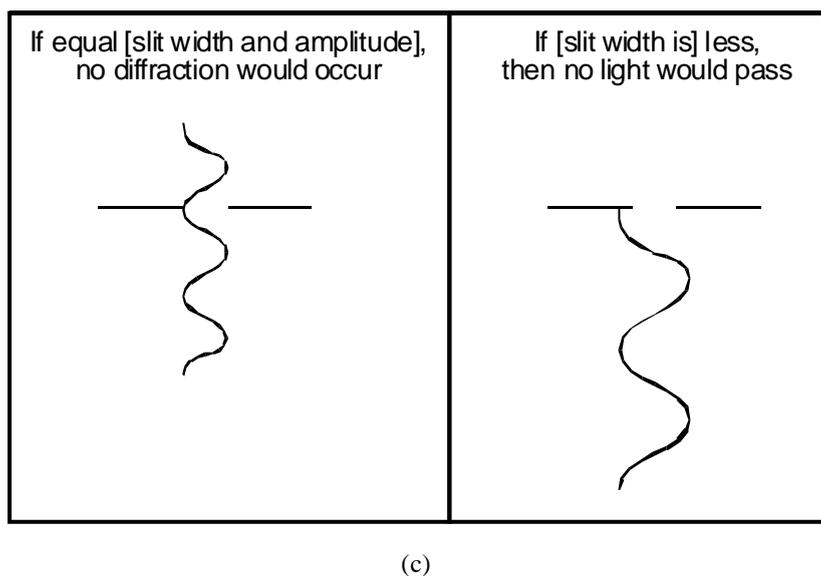
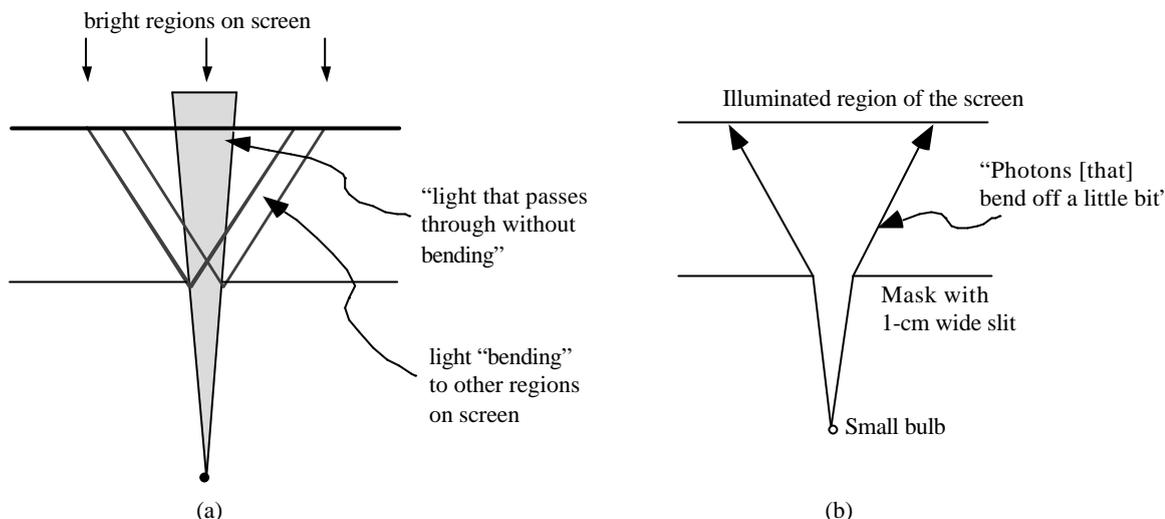


Figure 3: (a) Sketch by student who treated central bright region as geometric image and diffraction fringes as resulting from light bending at edges of slit. (b) Sketch by a modern physics student who believed that photons travel on straight paths that “bend” near the edges of a slit. (c) Sketch by student who treated light as a wave with an amplitude that is a spatial quantity.

Students often misused comparisons between slit width and wavelength or amplitude. Many considered diffraction to be a consequence of whether or not light could “fit” though the slit. Among the introductory students, some claimed that if the slit *width* were greater than the wave *amplitude*, light would be able to pass through the slit but that if the slit width were less, no light could emerge. [See Fig. 3(c).] For these students, the amplitude of a wave had a spatial extent. The modern physics students carried some of the same ideas a step further by introducing photons distributed along sinusoidal paths. [See Fig. 4(a) and 4(b).] The diagrams that they drew indicated that the photons would not get through the slit if the amplitude of the wave were greater than the slit width.

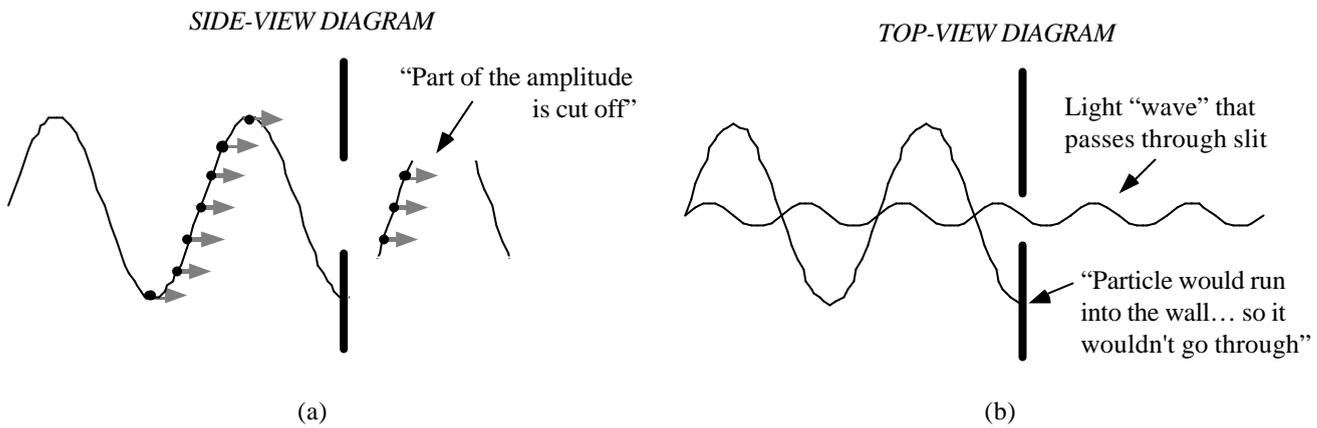


Figure 4: Sketches by modern physics students treating photons as traveling along sinusoidal paths.

Underlying the specific difficulties illustrated above was a more basic difficulty. Students often failed to relate diffraction effects to differences in path length (ΔD) or phase ($\Delta \phi$). They had not developed a basic wave model that they could use to account for the diffraction of light through a narrow slit in the far-field limit.

Comparison of performance on quantitative and qualitative questions

As can be seen from Table I, student performance on the qualitative question was much poorer than on the quantitative question. Even the students ($N \sim 130$) who had previously been given the quantitative question had difficulty with the qualitative question. When explanations were ignored, the success rate was about 45%. When explanations were considered, this percentage dropped to approximately 10%. These results support the following generalizations related to learning and teaching (in italics).¹³

? Facility in solving standard quantitative problems is not an adequate criterion for functional understanding. *Questions that require qualitative reasoning and verbal explanation are essential for assessing student learning.*

Double-slit interference

Double-slit interference provided another context for exploring student thinking about wave phenomena. Qualitative questions revealed that many students did not recognize that two slits are necessary to produce a double-slit pattern. Below is an example.

Qualitative question

The students were shown a photograph of the central portion of a double-slit interference pattern, in which all the maxima are of similar intensity. (See Fig. 5.) The students were asked to sketch what would appear on the screen if the left slit were covered. To respond correctly, they needed to recognize that the minima are due to destructive interference of light from the two slits and that each slit can be treated as a point source. After the left slit is covered, the interference minima would vanish and the screen would be (nearly) uniformly bright.

¹³ The generalizations on learning and teaching in this paper are discussed in greater detail in the second article in Ref. 6.

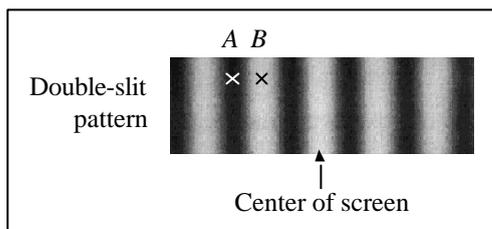


Figure 5: Diagram used in written questions on double-slit and multiple-slit interference.

Identification of difficulties

This question was asked in several lecture sections of the calculus-based course ($N \sim 600$) with similar results before and after standard instruction. In the section with the best results, about 40% of the students answered correctly. (See Table II.) Overall, about 45% gave answers reminiscent of geometrical optics. Many claimed that the pattern would be the same, but dimmer. Others predicted that the maxima on one side would vanish, leaving a dark region, or that every other maximum would vanish. In the graduate teaching seminar ($N \sim 50$), about 55% of the participants stated that the screen would be uniformly bright. About 25% claimed that a single-slit diffraction pattern with minima would appear. However, since the interference maxima are of similar intensity, it can be inferred that the fringes lie within the central maximum of the diffraction pattern.

Table II: Results from question on double-slit interference based on Fig. 5, in which students were asked to sketch what would appear on the screen if one slit were covered.

	Students in introductory calculus-based course	Graduate Students
	After standard instruction ($N \sim 600$)	($N \sim 50$)
Correct: Screen is essentially uniformly bright	~40%	55%
Incorrect: Interference minima remain when one slit is covered.	45%	--
Diffraction minima appear on screen	--	25%

Questions on multiple-slit interference yielded similar results. Analysis of student responses for double and multiple slits led to the identification of two prevalent difficulties: (1) a failure to interpret the pattern as resulting from the interference of light from two (or more) slits and (2) a

tendency to use ideas from geometrical optics to account for interference effects. At a still more fundamental level, the basic underlying difficulty was the failure of students to relate interference effects to differences in path length (ΔD) or phase ($\Delta \phi$). As with single-slit diffraction, the students had not developed a wave model that can account for the interference of light.

Implications for the design of instruction

The results discussed in the preceding section are consistent with those from other studies by our group. They support several sets of generalizations on learning and teaching that have constituted a model for curriculum development by our group.¹³ These generalizations are empirically based in that they have been inferred and validated through research. A few are listed below. Each set is followed by a short commentary.

? A coherent conceptual framework is not typically an outcome of traditional instruction. *Students need to participate in the process of constructing qualitative models and applying these models to predict and explain real-world phenomena*

There is by now ample evidence that many students emerge from introductory physics without having developed a coherent conceptual framework for some basic topics. Helping students build a sound conceptual understanding is not simply a matter of presenting them with the proper models. Often they do not understand how to interpret the important features. We have found that an effective approach for helping students understand the relationships and differences among concepts is to engage them actively in the model-building process. Not only does this approach promote conceptual development, it also provides some direct experience with the nature of scientific inquiry.

? Growth in reasoning ability often does not result from traditional instruction. *Scientific reasoning skills must be expressly cultivated.*

Conceptual models in physics are often inseparably linked with particular lines of reasoning. We believe that conceptual models and the chain of reasoning through which they are developed and applied must be learned concurrently. A critical element in the development of a functional understanding is that students be given the opportunity to go step-by-step through the reasoning involved in the development and application of important concepts. We have found that when they do so, they can significantly deepen their understanding of even very difficult material.

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

Some difficulties that students have in learning a body of material are addressed through standard instruction or gradually disappear as instruction progresses. However, research has shown that certain conceptual difficulties are persistent and highly resistant to instruction. For most students, explanations by an instructor are inadequate. They need a different type of assistance to bring about a significant change in their thinking.

? Teaching by telling is an ineffective mode of instruction for most students. *Students must be intellectually active to develop a functional understanding.*

We have found in a variety of topics that on certain types of questions, student performance in traditional courses is essentially the same: before and after instruction, in calculus-based and algebra-based physics, with and without a standard laboratory, with and without demonstrations, in large and small classes, and irrespective of the lecturer. The role of the lecturer is clearly important. He or she is the one who motivates the students and the one to whom they look for guidance about what they need to learn. The lecturer, however, cannot do the students' thinking for them. They

must do it for themselves. Regardless of how lucid explanations are, significant conceptual change does not take place without a major intellectual commitment by the students.

Development of a research-based curriculum

To illustrate the approach that our group takes to curriculum development, we give a brief description of *Tutorials in Introductory Physics*.¹⁴ The emphasis in the tutorials is on constructing concepts, developing reasoning skills, and relating the formalism of physics to the real world, not on transmitting information and solving standard problems.

Instructional context

Each tutorial sequence consists of a pretest, worksheet, homework assignment, and one or more examination questions. The 10-minute pretest helps focus student attention on the topic to be addressed in the tutorial. The pretest serves to *elicit* specific conceptual and reasoning difficulties that have been identified by research or teaching experience. During the subsequent 50-minute tutorial sessions, students work collaboratively in groups of 3 or 4. The structure is provided by worksheets that consist of carefully sequenced questions and exercises that guide students through the reasoning necessary to develop a functional understanding of important concepts. In designing the worksheets, we strive to ensure that the steps in reasoning are neither too small nor too large to engage the students productively. The worksheets also help the students to *confront* and to *resolve* specific difficulties and to *apply* the concepts in different contexts. Tutorial homework assignments help students reinforce and extend what they have learned during the tutorial sessions. Besides providing additional practice in applying the concepts, the homework gives students the opportunity to *reflect* and to *generalize*. Questions based on the tutorials are included on every course examination and serve as post-tests.

During the sessions, graduate and undergraduate teaching assistants help the students by questioning, not by telling. Preparation of the tutorial instructors takes place in the required weekly seminar, in which the teaching assistants take the same pretests and work through the same tutorials as the students. We consider a tutorial to be reasonably successful when the achievement of the introductory students on post-tests matches (or surpasses) that of the graduate students on the corresponding pretests.

Tutorial sequence

The tutorials on physical optics guide students through the process of constructing a qualitative wave model that can account for interference and diffraction effects. The series of tutorials begins with interference in the context of water. Waves in a ripple tank are much less abstract than light waves. This environment forms a visual representation of wavefronts and provides a framework in which students can derive the mathematical relationships for locating the maxima and minima of an interference pattern. We knew from previous research that students often do not apply the principle of superposition properly. By investigating what happens when water waves combine under different conditions, we hoped that they might be better able to apply superposition to light.

After working through the tutorial on two-source interference in water, the students are guided in making an explicit analogy between water waves and light waves. Like other analogies that are obvious to physicists, we have found that this one often eludes students. Our experience supports the following generalizations.¹³

¹⁴ A more complete description of the tutorials and the tutorial system can be found in the articles in Refs. 3, 4, and 10. See also the first two articles in Ref. 9.

? Connections among concepts, formal representations (algebraic, diagrammatic, graphical, *etc.*) and the real world are often lacking after traditional instruction. *Students need repeated practice in interpreting physics formalism and relating it to the real world.*

The tutorials on double-slit interference are followed by tutorials on multiple-slit interference and on single-slit diffraction. The series culminates with a tutorial on the combined interference and diffraction pattern produced on a distant screen by two slits of finite width. A more detailed discussion of the tutorials on physical optics and of the rationale that guided their development can be found in previously published papers.¹⁰

Assessment of student learning

The primary means of assessment of the tutorials has been through pretesting and post-testing, mostly with qualitative problems. Our experience indicates that simple, conceptually-based questions are often a better test of student understanding than more difficult problems that can be solved through direct application of formulas or algorithms.

Student performance on post-tests is compared to the results from the corresponding pretests. The post-tests may or may not be similar to the pretests. We have found that prior experience with a pretest has virtually no effect on student performance on a similar post-test. (Pretests are not returned to the students. They are expected to be able to answer the questions by working through the tutorials.) The post-tests require an understanding of the concepts covered in the tutorials. However, they are designed so that they cannot be answered on the basis of problems that students have memorized.

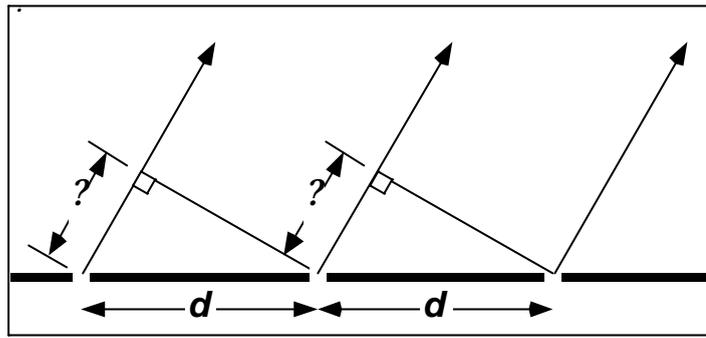
In this paper, the data on student performance in introductory physics are from the calculus-based course. Results from the algebra-based course are similar. The pre- and post-test data from our university are supplemented by information obtained from pilot sites. This feedback helps us determine the effectiveness of the tutorials in different instructional settings and guides us in modifying the curriculum accordingly.

Multiple-slit interference

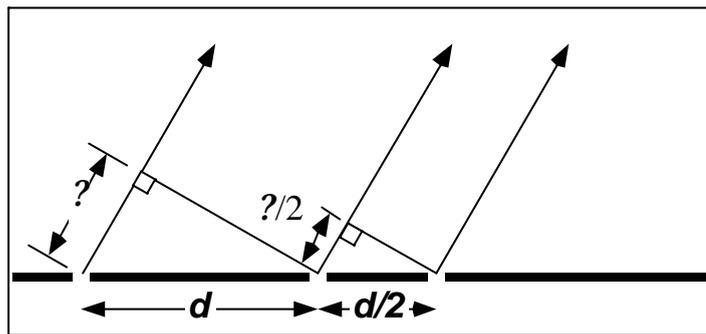
Ever since tutorials were introduced in the calculus-based physics course at the University of Washington, all examinations have included qualitative problems related to topics from the tutorials. Student performance on these problems has been the most common form of assessment. Below we describe a set of pretest and post-test questions to assess the tutorials on double-slit and multiple-slit interference.

Pretest

On the pretest, the students are shown the central portion of the pattern formed by light incident on a mask with two very narrow slits separated by a distance d . (See Fig. 5.) A point of maximum intensity, B , is marked. The students are told that the two-slit mask is replaced by a three-slit mask with the same separation d between adjacent slits. They are asked whether point B would still be a point of maximum constructive interference. This question requires application of the ideas of path length difference and superposition. From the pattern, it can be seen that light from two slits a distance d apart is in phase at point B . Since the distance between adjacent slits in the three-slit mask is also d , light from all three slits is in phase at point B . [See Fig. 6(a).] Thus point B will still be a point of maximum constructive interference but brighter than before. This question was given to about 560 students, either before or after lecture instruction. Since the results were similar, the data have been combined in the first column of Table III.



(a)



(b)

Figure 6: Arrangement of slits in (a) pretest and (b) post-test for multiple-slit interference. The diagrams show a ray from each slit to a distant point B , which was a maximum for the two left slits before the third was added. The differences in distance from adjacent slits to point B are marked.

About 30% of the students have answered this question correctly. However, fewer than 5% have given correct reasoning. Most of the students have failed to consider path length differences and to reason in terms of superposition. About 60% of the participants in the graduate teaching seminar ($N = 55$) have given the correct response. About 25% have given correct explanations. (See column 3 of Table III.)

Post-test

In one of the post-test questions, students are shown the same double-slit interference pattern as was used for the pretest. (See Fig. 5.) In this case, however, they are asked how the intensity at point B changes when a third slit is added a distance $d/2$ to the right of the rightmost slit. The students need to recognize that the waves from the original two slits are in phase at point B . When the third slit is added, the waves from this slit are 180° out of phase with the waves from both of the other slits. [See Fig. 6(b).] Therefore, the intensity at point B decreases. This question requires students to extend their thinking to a situation beyond their experience, *i.e.*, when the slits are not evenly spaced.

The results of the post-test question are shown in the second column of Table III. About 80% of the students ($N = 405$) have stated that the intensity at point B decreases when the third slit is added. About 40% have given correct reasoning. The improvement indicates that the tutorial helps students learn how to take into account the path length (or phase) difference in a situation in which they could not resort to a formula. As shown in Table III, the introductory students did better on the post-test than the teaching assistants on the pretest, one of our criteria for a successful tutorial.

Table III. Results on pretest and post-test questions on multiple-slit interference. Students are asked what will happen at a maximum (Point *B*) on a double-slit pattern when a third slit is added to the right of the rightmost slit in the following ways: (1) with the original slit separation, d (pretest) or (2) with half the original slit separation, $d/2$ (post-test). [See Figs. 2 and 7(a) and 7(b).]

	Students in introductory calculus-based course		Graduate students
	Pretest before tutorial (N = 560)	Post-test after tutorial (N = 405)	Pretest (N = 55)
<i>distance between second and third slits</i>	d	$d/2$	d
Point B (maximum for two slits)			
correct	30%	80%	60%
with correct reasoning	< 5%	40%	25%

Effectiveness of the tutorials

Physics examinations at our university consist mostly of quantitative problems. The inclusion of qualitative problems in the calculus-based introductory course has been largely due to the implementation of tutorials. As illustrated above, the tutorials have had a very positive effect on the ability of students to solve qualitative problems of the type illustrated. For most students, the post-tests have shown marked improvement over the corresponding pretests, with the undergraduates often matching (and sometimes surpassing) the graduate students on the pretests.

There is considerable evidence that time spent on developing a sound conceptual understanding does not detract from the ability of students to solve quantitative problems. In spite of less time devoted to practice on quantitative problem solving, students who have worked through the tutorials have done somewhat better on standard numerical problems than those who have not had this experience. On quantitative problems that cannot be solved by substitution in formulas but require understanding of the concepts, students who have worked through the tutorials have done much better than others. When we have been able to match performance on quantitative problems by tutorial and non-tutorial students, the tutorial students have done somewhat better (and sometimes much better), despite spending much less time on such problems.¹⁵ Moreover, there is evidence that the type of intellectual effort demanded of students by the tutorials leads to a higher retention rate than that resulting from standard instruction.¹⁶

For the tutorials to be useful beyond our university, the results must be reproducible in other instructional settings. Several other universities and two-year and four-year colleges serve as pilot-sites at which we can assess effectiveness. In all instances for which we have data, the results have been consistent with those from our university.

¹⁵ For a specific example that documents this statement, see the second article in Ref. 10.

¹⁶ See, for example, the first article in Ref. 2, the third article in Ref. 3, and G.E. Francis, J.P. Adams, and E.J. Noonan, "Do they stay fixed?" *Phys. Teach.* **36** (8), 488–490 (1998.)

Conclusion

The results from the research discussed in this paper indicate that many students who have studied physical optics at the introductory and more advanced levels do not develop a coherent wave model that they can apply to account for the diffraction and interference of light. We have also identified similar difficulties about the wave nature of matter among students in more advanced courses.¹⁷ For these and other topics, we have found that advanced study does not necessarily overcome serious conceptual and reasoning difficulties with basic material.¹⁸ Unless these are explicitly addressed at the introductory level, they are likely to persist even after instruction in more advanced courses. The tutorials discussed in this paper have been developed in response to this need. They are one example of how, within a small allotment of time, a research-based curriculum can help students learn to do the kind of qualitative reasoning that can make physics meaningful to them and establish a sound basis for quantitative problem-solving.

Meaningful learning connotes the ability to interpret and use knowledge in situations that differ from those in which it was initially acquired. Even when formulas and procedures are successfully memorized, they are likely to be forgotten after the course ends. An understanding of important physical concepts and the ability to do the reasoning necessary to apply these in a variety of situations is of greater lasting value. To this end, students need to learn to ask themselves the types of questions necessary to determine if they do or do not understand a concept. They also need to recognize what types of questions they must ask in order to develop to a functional understanding. Insights gained from research on the learning and teaching of physics can help achieve this goal, which is important for all students but especially for teachers and majors.

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¹⁷ See the first article in Ref 4.

¹⁸ Although graduate students do considerably better than introductory students on the tutorial pretests, their responses indicate that many have not resolved some serious conceptual difficulties. (Although these often do not prevent them from solving quantitative problems successfully, these difficulties can interfere with their effectiveness as instructors.) See, for example, the articles in Refs. 3 and 4 and the first two articles in Ref. 9. See also, T. O'Brien Pride, S. Vokos, and L.C. McDermott, "The challenge of matching learning assessments to teaching goals: An example from the work-energy and impulse-momentum theorems," *Am. J. Phys.* **66**, 147–157 (1998).