

Oersted Medal Lecture 2001: "Physics Education Research—The Key to Student Learning"

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Oersted Medal Lecture 2001: “Physics Education Research—The Key to Student Learning”

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Research on the learning and teaching of physics is essential for cumulative improvement in physics instruction. Pursuing this goal through systematic research is efficient and greatly increases the likelihood that innovations will be effective beyond a particular instructor or institutional setting. The perspective taken is that teaching is a science as well as an art. Research conducted by physicists who are actively engaged in teaching can be the key to setting high (yet realistic) standards, to helping students meet expectations, and to assessing the extent to which real learning takes place. © 2001 American Association of Physics Teachers.
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PREFACE

I would like to thank the AAPT for the 2001 Oersted Medal. The accomplishments recognized by this honor are the result of many contributions over many years by faculty, post-docs, graduate students, K–12 teachers, and undergraduates in the Physics Education Group at the University of Washington. We have had many visitors, long and short term, who have enriched our work. In addition to those who have been directly associated with us, there are many others who have helped to build the field of physics education research. They have done so through direct participation in research, through their use of the results, and/or through their support. I want to emphasize that I view this award as one to our entire community and also as recognition of research on the learning and teaching of physics as a useful field for scholarly inquiry by physicists. I deeply appreciate being selected for the Oersted Medal but I am also overwhelmed by the list of previous recipients. Like many of them, I would like to use this opportunity to share some insights drawn from my experience.

I believe that our group’s most significant achievement in the last two decades has been to demonstrate the value of discipline-based education research. Our investigation of student understanding of one-dimensional kinematics that began in 1973 led to the publication of research papers on velocity (December 1980) and acceleration (January 1981). These were the first of their kind to appear in the *American Journal of Physics*. The situation has changed greatly since then. Today, there are several groups that conduct research in physics education and there is a substantial literature. Rather than attempt to give a representative overview, I will focus on the work of the Physics Education Group because that is what I know best. Although the data, interpretations, and conclusions presented are drawn from the experience of our group, I shall try to identify the features of physics education research that I believe are the most critical and most universally applicable.

I. INTRODUCTION

Physics education research differs from traditional education research in that the emphasis is not on educational theory or methodology in the general sense, but rather on student understanding of science content. For both intellectual and practical reasons, discipline-based education re-

search should be conducted by science faculty within science departments. There is evidence that this is an effective approach for improving student learning (K–20) in physics. The emphasis in the discussion here is on introductory students and K–12 teachers and, to a lesser extent, on graduate students in their role as teaching assistants. However, insights obtained through research have also proved to be a useful guide for instruction in more advanced physics courses.

II. PERSPECTIVES ON TEACHING AS AN ART AND AS A SCIENCE

Many physics faculty think of teaching solely as an art. This traditional view was clearly expressed in 1933 in the first article in the first journal published by the American Association of Physics Teachers.¹ In *Physics is Physics*, F. K. Richtmyer, who considered teaching very important, argued that it is an art and not a science. He quoted R. A. Millikan in characterizing science as comprising “a body of factual knowledge accepted as correct by all workers in the field.” Professor Richtmyer went on to say:

“Without a reasonable foundation of accepted fact, no subject can lay claim to the appellation ‘science.’ If this definition of a science be accepted—and it seems to me very sound—then I believe that one must admit that in no sense can teaching be considered a science.”

Although this definition of science is somewhat limited, we may challenge the implication that it is not possible to build “a reasonable foundation of accepted fact” for the teaching of physics (and, by extension, other sciences). The Physics Education Group treats research on the learning and teaching of physics as an empirical applied science. We adhere, to the extent possible, to the rules of evidence of experimental physics. To this end, we document our procedures and results so that they can be replicated. Beyond its intrinsic interest to us, we believe that physics education research can provide the key to student learning. We conduct systematic investigations on how well students who have studied physics from the introductory to the graduate level understand important concepts and principles. We use the results to guide the development of instructional materials and assess their effectiveness on the basis of what students have learned. The graduate students in our group earn their

Ph.D.'s in physics for this type of research. As is the practice among scientists, we report our results at professional meetings and in peer-reviewed journals.

Results from our research support the premise that teaching can be considered a science. Students in equivalent physics courses with different instructors are remarkably similar in the way they respond to certain kinds of questions, both before and after standard instruction by lecture, textbook, and laboratory. We have found that there are a limited number of conceptual and reasoning difficulties that students encounter in the study of a given topic. These can be identified, analyzed, and effectively addressed through an iterative process of research, curriculum development, and instruction. Although students vary in the way they learn best, learning is not as idiosyncratic as is often assumed.

Student difficulties and effective strategies for addressing them are often generalizable beyond a particular course, instructor, or institution. When the results are reproducible, as is often the case, they constitute a "reasonable foundation of accepted fact." There is by now a rapidly growing research base that is a rich resource for cumulative improvement in physics instruction.² Publicly shared knowledge that provides a basis for the acquisition of new knowledge is characteristic of science. To the extent that faculty are willing to draw upon and to contribute to this foundation, teaching can be treated as a science.

A. Criteria for the effectiveness of instruction

The criteria an individual uses to assess the effectiveness of instruction reflect his or her perspective on teaching. When teaching is considered as an art, the criteria tend to be highly subjective with the personal qualities and style of an instructor having a strong influence on assessments. Instructors frequently judge the success of a new course or innovation by their impression of how much the students have learned or how satisfied they appear to be. An inspiring lecturer can motivate students and kindle their interest. The benefits, however, seldom extend beyond the instructor's own class. Student ratings of a course or instructor are a commonly accepted form of evaluation that is consistent with the view that teaching is an art. In some instances, however, we have found that students whose instructors received low ratings have done better on matched questions than those whose instructors received higher ratings. Moreover, when asked to rate how much they have learned, students are often poor judges. If student learning (as distinct from enthusiasm) is used as the criterion, we have found that effective teaching is not as tightly linked as is often assumed to the motivational effect of the lecturer, to student evaluations of the course and instructor, or to self-assessment of learning by students. Implicit in the perspective of our group that teaching is a science is the belief that the primary criterion for the effectiveness of instruction must be the assessment of student learning in terms of specified intellectual outcomes.

B. Focus on the student as a learner

The focus of our research is on the student as a learner, rather than on the instructor as a teacher. We have conducted investigations among various populations: students enrolled in introductory physics courses, in physics courses for underprepared students, in advanced undergraduate and graduate physics courses, in engineering courses, and in courses for K-12 teachers of physics and physical science. We explore what students can and cannot do and monitor their intellec-

tual state as instruction progresses. We use two primary research methods: individual demonstration interviews that enable us to probe deeply into the way students think and widely administered written tests that provide data on prevalence. We supplement this information through less formal means, such as engaging students in dialogues, examining homework and written reports in detail, and observing in the classroom as students interact with one another and with their instructors. The results are used to guide the development of curriculum. Assessment is an integral part of the process and usually includes a comparison of student performance on post-tests and corresponding pretests.

III. INSIGHTS FROM RESEARCH AND TEACHING EXPERIENCE IN NONSTANDARD PHYSICS COURSES

The Physics Education Group has two major curriculum development projects: *Physics by Inquiry* (Wiley, 1996) and *Tutorials in Introductory Physics* (Prentice Hall, 1998).³ Both owe much to our research and teaching experience in nonstandard physics courses. For more than 25 years, we have been conducting special courses during the academic year and in NSF Summer Institutes to prepare prospective and practicing teachers to teach physics and physical science by inquiry. Another group whom we have been able to teach in relatively small classes are students who aspire to science-related careers but whose prior preparation is inadequate for success in the required physics courses. Close contact with students in these special courses has provided us with the opportunity to observe the intellectual struggles of students as they try to understand important concepts and principles. We have found that students better prepared in physics often encounter the same difficulties as those who are not as well prepared. Since the latter are usually less adept in mathematics, it is easier to identify and probe the nature of common difficulties. Day-to-day interaction in the classroom has enabled us to explore in detail the nature of specific difficulties, to experiment with different instructional strategies, and to monitor their effect on student learning.

A. Research on student understanding: An example from electric circuits

Below, we briefly illustrate the type of research that underlies the development of curriculum by our group. The context is electric circuits. Our investigation of student understanding of this topic has extended over many years and has included individuals whose background in physics has ranged from the introductory to the graduate level.⁴ Since the results are well known by now, only a summary is presented here.

In the question in Fig. 1(a), students are asked to rank the brightness of identical bulbs in three circuits. This question has been used in many different classes over many years. It has been given either before or after the usual treatment of this topic in lecture, textbook, and laboratory. Since the results have been essentially the same before and after standard instruction, they have been combined. As shown in Table I, only about 15% of more than 1000 introductory students have given the correct ranking ($A=D=E>B=C$). Similar results have been obtained from high school physics teachers and from university faculty in other sciences and mathematics. Only about 70% of the graduate teaching assistants have given a correct ranking. Analysis of the responses has re-

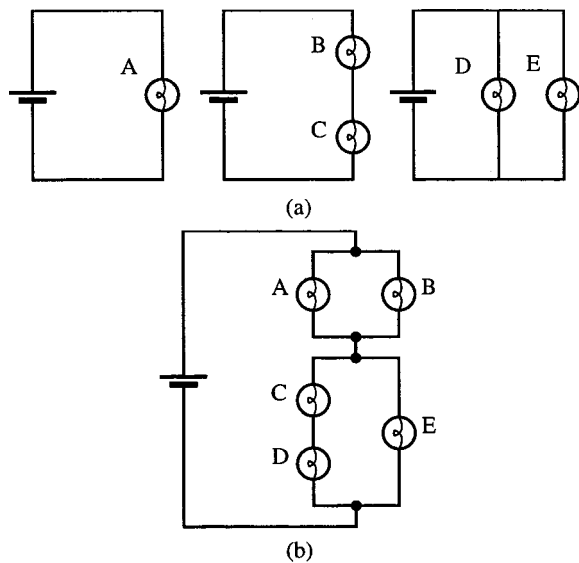


Fig. 1. Circuits used on questions given (a) after standard instruction on electric circuits and (b) after students had studied the material through guided inquiry. Students are asked to rank the bulbs from brightest to dimmest and to explain their reasoning. In both cases, they are told to treat the bulbs as identical and the batteries as identical and ideal.

vealed the widespread prevalence of two mistaken beliefs: the battery is a constant current source and current is “used up” in a circuit. Among all populations, the basic underlying difficulty seems to be the lack of a conceptual model for an electric circuit.

B. Basic instruction by guided inquiry

The nonstandard courses described above have provided the context for the development of *Physics by Inquiry* (PbI). This self-contained, laboratory-based curriculum helps students develop a coherent conceptual framework for important topics. PbI is not like a typical text, in that it does not present information and give explanations. The modules contain carefully structured experiments, exercises, and questions that are intended to engage students actively in the construction of important concepts and in their application to the physical world. The instructional approach can be characterized as guided inquiry. Although expressly designed for the preparation of K–12 teachers, PbI has also proved useful for providing a foundation in physics for underprepared students and nonscience majors.

The *Electric Circuits* module provides an example of how results from research are incorporated in PbI. As the students work through the module, they are guided in constructing a qualitative model for a simple circuit. In the process, specific difficulties identified through research are addressed.

Table I. Results from pretest on electric circuits shown in Fig. 1(a). All percentages are rounded to the nearest 5%.

	Undergraduates $N > 1000$	Precollege teachers $N > 200$	Faculty in other sciences and mathematics $N > 100$	Graduate TAs $N \sim 55$
Correct answer	15%	15%	15%	70%

C. Assessment of student learning

The instructional approach in *Electric Circuits* has proved effective with K–12 teachers at all levels. In Fig. 1(b) is an example of a post-test, given after students have worked through the relevant material. Students are asked to rank the brightness of identical bulbs ($E > A = B > C = D$). Elementary and middle school teachers generally have a weaker mathematical background than students in the introductory calculus-based course. Nevertheless, their post-test performance on this and other relatively complicated resistive circuits has regularly surpassed that of most physics and engineering students.

D. Commentary

We believe that the primary reason for the effectiveness of PbI is that students must go step-by-step through the reasoning needed to overcome conceptual hurdles and build a consistent coherent framework. There are also other features that we think are important. Collaborative learning and peer instruction are integrated into PbI. Students work with partners and in larger groups. Guided by the questions and exercises, they conduct open-ended explorations, perform simple experiments, discuss their findings, compare their interpretations, and collaborate in constructing qualitative models that can help them account for observations and make predictions. Great stress is placed on explanations of reasoning, both orally and in writing. The instructor does not lecture but poses questions that motivate students to think critically about the material. The appropriate response to most questions by students is not a direct answer but a question to help them arrive at their own answers.

IV. INSIGHTS FROM RESEARCH AND TEACHING EXPERIENCE IN STANDARD INTRODUCTORY COURSES

The topic of electric circuits is only one of many in which we have examined student understanding. Our investigations have spanned many topics at several levels of instruction with special emphasis on introductory physics.

A. Need for improvement in student learning

Faculty in introductory courses work hard at preparing lectures in which they give lucid explanations, show demonstrations, and illustrate problem-solving procedures. They expect that, in the process of learning how to solve standard physics problems, students are developing important concepts, integrating them into a coherent conceptual framework, and developing the reasoning ability necessary to apply the concepts in simple situations. It is also assumed that students are learning to relate the formalism of physics to objects and events in the real world. There is ample evidence from research, however, that students do not make nearly as much progress toward these basic goals as they are capable of doing. Few develop a functional understanding of the material they have studied.

The gap between the course goals and student achievement reflects a corresponding gap between the instructor and the students. In teaching introductory physics, many faculty proceed from where they are now or where they think they were as students. They frequently view students as younger

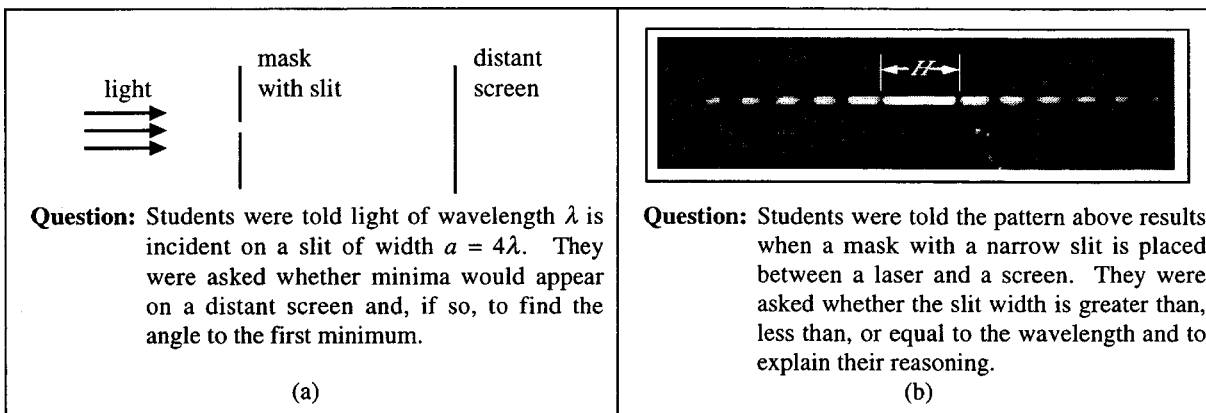


Fig. 2. Questions used to probe student understanding of diffraction after standard instruction in large introductory physics courses: (a) quantitative question and (b) qualitative question.

versions of themselves. This approach is particularly unsuitable for a typical introductory physics course in which fewer than 5% of the students will major in physics. For most, it is a terminal course in the discipline.

A functional understanding of physics connotes the ability to interpret and use knowledge in situations different from those in which it was initially acquired (the degree of difference increasing with educational level). Majors eventually develop this ability. Most students do not. Although faculty hope that they are helping students develop scientific reasoning skills, the type of problem solving that takes place in a typical introductory course is not consistent with this objective. Often the effect is to reinforce the common perception that physics is a collection of facts and formulas and that the key to solving physics problems is finding the right formulas. However, even correctly memorized formulas 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 them is of greater lasting value.

B. Motivation for tutorials

The success of *Physics by Inquiry* with teachers and other students motivated us to try to provide for students in standard introductory courses a modified version of the intellectual experience that this curriculum provides. However, the challenge of securing the mental engagement of students in a typical calculus-based or algebra-based course is much greater. The large size of these classes, the breadth of material covered, and the rapid pace preclude use of a laboratory-based, self-contained curriculum like *Physics by Inquiry*. Therefore, we decided to try to incorporate some of the important features of *PbI* in a curriculum that could be used to supplement the lectures and textbook of a standard calculus-based or algebra-based course. We wanted to produce materials that would be useful not only at our own university but in a wide variety of instructional settings. *Tutorials in Introductory Physics* has been our response to this challenge. Although this project was motivated by a desire to improve student learning in introductory physics, we and others have found that the same instructional approach also works well in more advanced courses.

V. RESEARCH-BASED GENERALIZATIONS ON LEARNING AND TEACHING

Our experience in research, curriculum development, and instruction has led to several generalizations on learning and teaching.⁵ These are empirically based in that they have been inferred and validated through research. The early research and development of *Physics by Inquiry* formed the initial basis for the generalizations. Our later experience with *PbI* and *Tutorials in Introductory Physics* confirmed their validity and provided additional insights that broadened their applicability. The generalizations serve as a practical model for curriculum development by our group. Below we present several that have proved especially useful. The illustrative examples are from our investigation of student understanding in physical optics.⁶ This long-term study involved undergraduates in introductory and more advanced courses, as well as physics graduate students.

A. Research-based generalizations on student learning

Examples from our research are given below as evidence for a few of the generalizations on student learning. Others are supported more broadly from our research base.

1. Facility in solving standard quantitative problems is not an adequate criterion for functional understanding.

Although experienced instructors know that there is a gap between what they teach and what is learned, most do not recognize how large the gap can be. The traditional measure for assessing student understanding is performance on standard quantitative problems. Since a significant portion of a typical class receives grades of A or B, instructors may con-

Table II. Results from quantitative and qualitative questions on single-slit diffraction shown in Fig. 2.

Undergraduate students		Graduate TAs
Quantitative question $N \sim 130$	Qualitative question $N \sim 510$	Qualitative question $N \sim 95$
70% correct with correct angle	10% correct with correct explanation	55% correct with correct explanation

clude that students have understood the material at an acceptable level. However, the ability of students to obtain correct answers for numerical problems often depends on memorized algorithms. Liberal awarding of partial credit also may conceal lack of understanding.

Questions that require qualitative reasoning and verbal explanation are essential for assessing student learning. The importance of qualitative questions is demonstrated by all of our research. As illustrations, we consider some examples from physical optics. As part of our investigation, we tried to determine what students who have studied physical optics in a standard course can and cannot do. The two questions below pose essentially the same problem.

a. Quantitative question on single-slit diffraction. The question in Fig. 2(a) was given on an examination to about 130 students. They were told that light is incident on a single slit of width $a=4\lambda$. The students 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 $\theta = \sin^{-1}(0.25) \approx 14^\circ$.

Approximately 85% of the students stated that there would be minima. About 70% determined the correct angle for the first minimum. (See the first column in Table II.)

b. Qualitative question on single-slit diffraction. For the question in Fig. 2(b), students were shown a single-slit diffraction pattern with several minima. 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 by referring to the equation for the angle θ to the first diffraction minimum. Since minima are visible, the angle to the first minimum is less than 90° and $a \sin \theta = \lambda$. Therefore, since $\sin \theta < 1$, $a > \lambda$.

About 510 students, including the 130 who had been given the quantitative question, were asked this question after they had completed standard instruction on single-slit diffraction.

Performance was poor. About 45% of the students made a correct comparison. Only 10% gave a correct explanation. (See the second column of Table II.) This same question was also posed in a graduate teaching seminar ($N \sim 95$). About half of the participants responded correctly with correct reasoning. (See the third column of Table II.)

c. Comparison of results from qualitative and quantitative questions. The difference in the way that the introductory students treated the two questions above provides some insight into what they typically can and cannot do. As can be seen from Table II, the success rate on the qualitative question was much lower than on the quantitative question. The 130 students who had previously been given the quantitative question performed at about the same level as those who had not had this experience. Apparently, the ability to solve numerical problems is not a reliable indicator of conceptual understanding.

2. Connections among concepts, formal representations, and the real world are often lacking after traditional instruction.

The ability to use and interpret formal representations (algebraic, diagrammatic, and graphical) is critical in physics. The responses to the qualitative question on single-slit diffraction demonstrate that many students could not relate the formula that they had memorized (or had available) for the location of diffraction minima to the diffraction pattern. Two examples that provide additional evidence of a failure to make connections between the phenomena and formalism of physical optics appear under the next generalization.

3. Certain conceptual difficulties are not overcome by traditional instruction. (Advanced study may not increase understanding of basic concepts.)

Research has shown that certain conceptual difficulties persist in spite of instruction. The two examples below indicate deep confusion about the different models for light and the circumstances under which a ray, wave, or particle model applies. All the students involved had received explicit instruction on at least the ray and wave models but seemed to have great difficulty in interpreting the information.

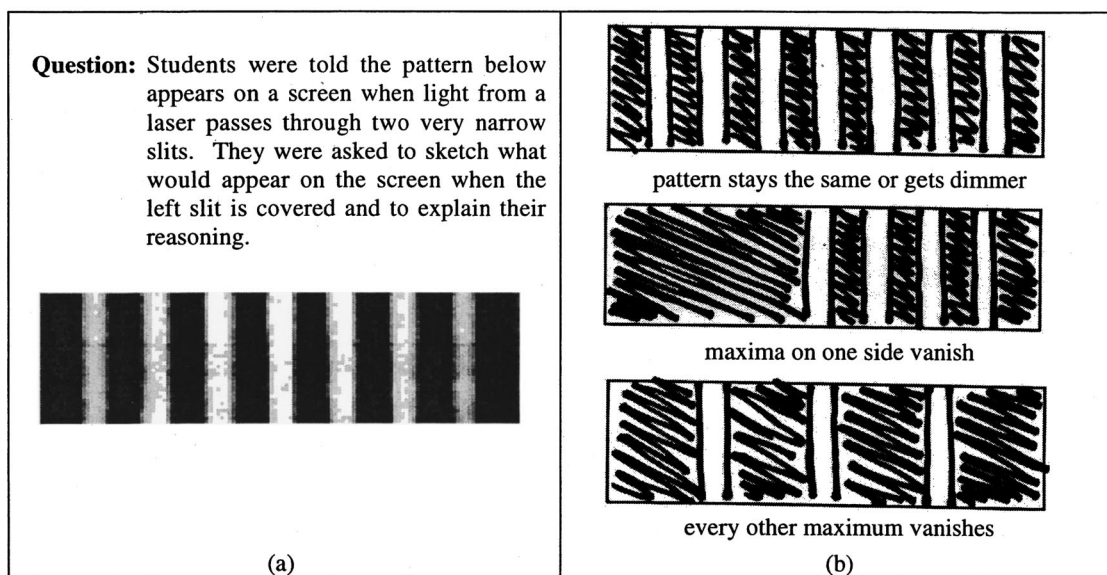


Fig. 3. (a) Question used to probe student understanding of double-slit interference. (b) Common incorrect diagrams drawn by students in response to the written question.

a. *Qualitative question on double-slit interference.* 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. 3(a).] They 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 line source. After the left slit is covered, the interference minima would vanish and the screen would be (nearly) uniformly bright.

This question was asked in several lecture sections of the calculus-based course ($N \sim 600$) with similar results before and after standard instruction. No more than about 40% of the students answered correctly. 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. [See Fig. 3(b).]

b. *Individual demonstration interview on single-slit diffraction.* In addition to the written questions on single-slit diffraction, we conducted individual demonstration interviews. Of the 46 students who participated, 16 were from the introductory calculus-based course and 30 from a sophomore-level modern physics course. All were volunteers and had earned grades at or above the mean in their respective courses.

During the interviews, students were shown a small bulb, a screen, and a small rectangular aperture. They were asked to predict what they would see on the screen as the aperture is narrowed to a slit. Initially, the geometric image of the aperture would be seen. Eventually, a single-slit diffraction pattern would appear.

In responding to this and other questions, students from both courses often used hybrid models with features of both geometrical and physical optics. For example, some students claimed that the central maximum of the diffraction pattern is the geometric image of the slit and that the fringes are due to light that is bent at the edges. Another difficulty of both introductory and more advanced students was the tendency to attribute a spatial extent to the wavelength or amplitude of a wave. Many considered diffraction to be a consequence of whether or not light would “fit” through the slit. Some of the introductory students claimed that if the width of the slit were greater than the amplitude of the wave, light would be able to pass through the slit, but that if the slit width were less, no light could emerge. [See Figs. 4(a) and 4(b).] Some modern physics students extended these same ideas to photons distributed along sinusoidal paths. (See Fig. 5.) Their diagrams indicated that the photons would not get through the slit if the amplitude were greater than the slit width. In physical optics and other topics, we have found that study beyond the introductory level does not necessarily overcome serious difficulties with basic material. Unless explicitly addressed in introductory physics, these difficulties are likely to persist.

4. A coherent conceptual framework is not typically an outcome of traditional instruction.

Many students emerge from introductory physics without having developed a coherent conceptual framework for important basic topics. As has been discussed, our research on student understanding of electric circuits supports this generalization. The examples from physical optics that have been used as illustrations provide additional evidence.

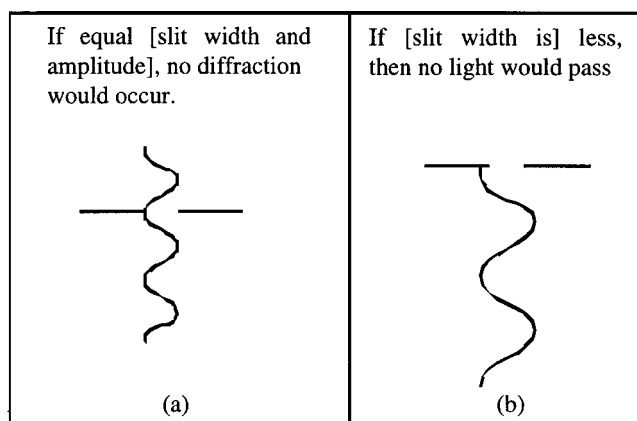


Fig. 4. Diagrams drawn by introductory students during interviews on single-slit diffraction to illustrate their belief that diffraction depends on the amplitude of the light wave: (a) amplitude less than or equal to the slit width and (b) amplitude greater than slit width.

Analysis of the results from the written questions and interviews on physical optics revealed the presence of a number of conceptual difficulties. Among these were: (1) the use of a hybrid model with features of both geometrical and physical optics, (2) a tendency to attribute to the amplitude or wavelength a spatial extent that determines whether light can “fit” through a slit, and (3) lack of recognition that an interference pattern results from two or more slits. Underlying these and other specific difficulties was one of fundamental importance: the failure of students to relate diffraction and interference effects to differences in path length (or phase). They had not developed a basic wave model that they could use to account for the diffraction and interference of light in the far-field limit.

Having a wave model for light would seem to be a prerequisite for understanding the wave nature of matter. Thus, there are clear implications for reform efforts directed toward introducing topics from modern physics into the introductory course. Results from research indicate that difficulties with advanced physics often have their roots in elementary material.

5. Growth in reasoning ability often does not result from traditional instruction.

An important factor in the difficulties that students have with certain concepts is an inability to do the qualitative reasoning that may be necessary for applying these concepts. Students often do not recognize the critical role of reasoning, nor understand what constitutes an explanation in physics. Our research has provided many illustrations. For example,

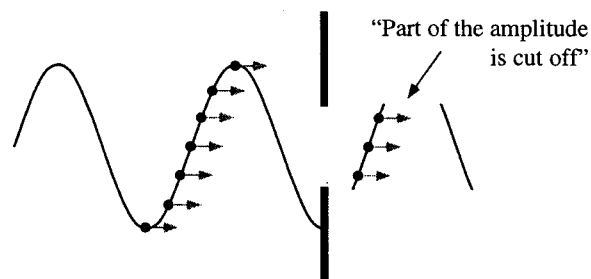


Fig. 5. Diagram drawn by a student in a modern physics course during interview on single-slit diffraction. The student tries to use the idea of photons to account for diffraction.

on the quantitative question on single-slit diffraction discussed earlier, many students used the single-slit diffraction formula to give a correct response for the location of the first diffraction minimum. Yet on the qualitative problem, many of these same students could not do the reasoning necessary to conclude that the presence of diffraction minima in the photograph implied that the slit width must be greater than the wavelength.

6. Teaching by telling is an ineffective mode of instruction for most students.

This generalization is based on results from our investigations of student understanding in mechanics, electricity, magnetism, electromagnetic waves, geometrical and physical optics, hydrostatics, and thermodynamics. In all of these topics, we have found that on certain types of qualitative questions student performance is essentially the same: before and after standard instruction by lecture and textbook, in calculus-based and algebra-based physics, with or without demonstrations, with or without a standard laboratory, in large and small classes, and regardless of the popularity of the instructor as a lecturer.

B. Research-based generalizations on teaching

The generalizations on student learning have implications for teaching. Our experience in developing curriculum and testing its effectiveness with students has led to a corresponding set of research-based generalizations on teaching. Below, the generalizations on student learning are repeated. Each is followed by one on teaching [in bold italics].

1. 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 and are an effective strategy for helping students learn.***

As has been discussed, the traditional forms of instruction seem to be inadequate for helping most students develop a functional understanding of basic topics in physics. Hearing lectures, reading textbooks, solving quantitative problems, seeing demonstrations, and doing experiments often have surprisingly little effect on student learning. We have found that an effective instructional approach is to challenge students with qualitative questions that cannot be answered through memorization, to help them learn how to respond to such questions, and to insist that they do the necessary reasoning by not supplying them with answers.

2. Connections among concepts, formal representations, 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.***

Most instructors recognize that students need help in relating the concepts and formal representations of physics to one another and to physical phenomena. However, illustrative examples and detailed explanations are often ineffective. Analogies obvious to instructors are often not recognized by students. For example, in developing our curriculum on physical optics, we found that many students needed explicit guidance in transferring their experience with two-source interference in water to double-slit interference in light.

3. Certain conceptual difficulties are not overcome by traditional instruction. (Advanced study may not increase understanding of basic concepts.) ***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 gradu-

ally disappear as the course progresses. Others are highly resistant to instruction. Some are sufficiently serious that they may impede, or even preclude, development of a functional understanding. For example, the belief that the amplitude of a light wave has a spatial extent or that the wave is a carrier of photons makes it impossible to develop a correct wave model for light. (See Figs. 4 and 5.)

Our experience indicates that warning students not to make particular errors is ineffective. For most students, assertions by an instructor make no difference. Avoiding situations likely to evoke errors by students, or providing algorithms that they can follow without thinking, may conceal latent difficulties that will surface at some later time. If faulty reasoning is involved, merely correcting an error is useless. Major conceptual change does not take place without a significant intellectual commitment by students.

An instructional strategy that we have often found effective for securing the mental engagement of students can be summarized as: *elicit*, *confront*, and *resolve*. The first step is to create a situation in which the tendency to make a known common error is exposed. After the students have been helped to recognize a resultant inconsistency, they are required to go through the reasoning needed to resolve the underlying difficulty. Since single encounters are seldom sufficient for successfully addressing serious difficulties, it is necessary to provide students with additional opportunities to *apply*, *reflect*, and *generalize*.

A word of caution is necessary because frequent use of the terms “misconceptions” and “misconceptions research” has trivialized the intellectual problem. The solution is not a matter of identifying and eradicating misconceptions. The intellectual issues are much deeper. Misconceptions are often symptoms of confusion at a fundamental level.

4. 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.***

Among the goals of a physics course is the development of physical concepts and an understanding of their relationships to one another and to the real world. Helping students develop a sound conceptual understanding is not simply a matter of defining concepts, presenting models, and illustrating their application. Often students cannot identify the critical elements or recognize inconsistencies with their ideas. A spiral approach in which models are continually refined is helpful but may not necessarily lead to coherence. Serious conceptual difficulties that preclude development of a consistent model must be addressed.

We have found that an effective strategy for helping students understand the relationships and differences among concepts is to engage them actively in the model-building process. As has been discussed in the context of electric circuits, this approach also provides some direct experience with the nature of scientific inquiry.

5. 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. Hence, instruction should address both concurrently. The *Electric Circuits* module in PBI is an example. The physical optics tutorials to be discussed later are another. In both instances, students go through the reasoning necessary for developing the concepts.

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

All of the generalizations on learning and teaching support this last set. The extent to which these hold is often not adequately appreciated by faculty. Meaningful learning requires the active mental engagement of the learner. 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 their thinking for them. The students must do it for themselves. Some are reluctant to do so; others do not know how. For most students, the study of physics is a passive experience.

It seems to be a natural instinct for instructors to believe that if the explanations they give are sufficiently clear and complete, students will learn. To this end, lecturers work at perfecting their presentations. Our experience has been, however, that the effort involved does not result in significant gain for most students. If they learn, it seems to be primarily because they have been willing and able to tackle the material with intellectual intensity. Both *Physics by Inquiry* and *Tutorials in Introductory Physics* are designed to engage students at a sufficiently deep intellectual level for meaningful learning to occur.

VI. APPLICATION OF RESEARCH-BASED GENERALIZATIONS TO THE DEVELOPMENT OF CURRICULUM

The development of all instructional materials by our group is the result of an iterative cycle that has three components: research on student understanding, use of the findings to guide the development of curriculum, and assessment of student learning. Research and curriculum development for PbI and for the tutorials are mutually reinforcing. Research motivated by one of the projects enriches the other. Similarly, instructional strategies that work well in one curriculum often, with some modification, work well in the other. To ensure applicability beyond our own university, all of our instructional materials are also tested at pilot sites. Some have environments similar to ours; others have different instructional settings. Experience at our university and at pilot sites has shown that certain conditions are necessary for the successful implementation of curriculum. The discussion here is limited, however, to those intellectual aspects that bear directly on student learning.

A. Description of the tutorials

Tutorials in Introductory Physics is designed for use in the small-group sections often associated with large lecture courses. The word *tutorial* was chosen to distinguish the type of instruction in the tutorials from more traditional recitation, discussion, quiz, or problem-solving sections. The usual procedure in such sections is for the instructor or TA to work problems, ask students to solve problems, or respond to questions (often with a mini-lecture). The tutorials are very different in purpose and in structure. They incorporate some of the critical features that we believe have contributed to the effectiveness of PbI.

The tutorials provide a context for our ongoing research and curriculum development at the introductory level and beyond. They address the questions: Is the standard presentation of an important topic in textbook and lecture adequate

to develop a functional understanding? If not, what can be done? 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 provide experience in learning through guided inquiry. Less detailed and thorough than PbI, they are better able to fit the constraints of large-scale instruction. The tutorials target critical concepts and skills that are essential for developing a functional understanding of important topics and that are known through research and teaching experience to present difficulty to students.

Each tutorial consists of four components: pretest, worksheet, homework, and post-test. The sequence begins with a pretest (so named because it precedes the tutorial although the material has usually been covered in lecture). The pretests have several purposes that include: to alert students to what they need to know and be able to do, to set the stage for the associated tutorial, and to inform the course lecturers and tutorial instructors about the intellectual state of the students. Pretests are not returned to the students. They are expected to be able to answer the questions by working through the tutorials and related homework.

During the tutorial sessions, about 20–24 students work collaboratively in groups of three or four. The structure is provided by tutorial worksheets that contain questions that try to break the reasoning process into steps of just the right size for students to stay actively involved. If the steps are too small, little thinking may be necessary. If too large, the students may become lost unless an instructor is by their side. The tutorial instructors do not lecture or give answers but assist students by posing questions to guide them through the necessary reasoning. Tutorial homework assignments help reinforce the ideas developed during the tutorial. A significant portion of every course examination requires the kind of qualitative reasoning and verbal explanations that characterize the tutorials.

B. Preparation of tutorial instructors

The tutorials require ongoing preparation in both the subject matter and instructional method of the tutorial instructors (mostly graduate Teaching Assistants but also undergraduates and volunteer post-docs). Although they can provide assistance with end-of-the-chapter problems, TAs generally have not thought deeply enough about the concepts nor gone carefully enough through the required chain of reasoning to be able to help introductory students develop a functional understanding of the material. Results from research indicate that study beyond the introductory level does not necessarily lead to a deeper understanding of basic topics. We have found that advanced students not only have conceptual difficulties with special relativity and quantum mechanics but also with topics in introductory physics.

Like most teachers, TAs tend to teach as they were taught. If they are to help undergraduates learn physics by guided inquiry, they need to experience this instructional approach and reflect upon the rationale. This opportunity is provided 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. The TAs take the same pretests as the introductory students. Their performance provides us with a measure of their level of understanding and helps set a reasonable goal for a tutorial. We consider a tutorial to be

successful when the post-test performance of the introductory students matches, or exceeds, the pretest performance of the TAs.

C. Supplementary instruction by guided inquiry: Example from physical optics

The research-based generalizations discussed above and others drawn from experience have proved valid and useful for our continuing development of curriculum. We illustrate their application in the context of physical optics. Other topics could serve equally well.⁷

Underlying the specific conceptual difficulties in physical optics was the failure of students to recognize the role of the difference in path length (or phase) in determining the maxima and minima of diffraction and interference patterns. To address this fundamental difficulty and others that are more specific, we developed a series of tutorials that guide students through the development of a simple wave model that they can use to account for diffraction and interference effects. A more complete discussion of these tutorials and of the rationale that guided their development can be found in previously published papers.

The series 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 wave fronts 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. We found, however, that the analogy often eludes students. Consequently, the tutorials were modified to provide explicit help in making the connection between water waves and light waves. In later tutorials, the students extend their wave model to interference from more than two slits, single-slit diffraction, and combined interference and diffraction.

D. Assessment of student learning

As mentioned earlier, our primary means of assessment of student learning is through comparison of student performance on post-tests and corresponding pretests. These also provide the detailed feedback needed for the development of curriculum. The pretests and post-tests consist mostly of qualitative questions for which explanations are required. As has been illustrated, such questions are often a better test of student understanding than more difficult problems that can be solved by manipulation of formulas. Moreover, the feedback provided by numerical problems is often not very useful for improving instruction. Multiple-choice and true-false questions (whether quantitative or qualitative) have this same disadvantage.

The post-tests may or may not be similar to the pretests. Our research has shown that prior experience with a pretest has virtually no effect on student performance on a post-test. The post-tests require an understanding of the concepts and are designed so that (like the pretests) they cannot be answered on the basis of memorization.

The pretest and post-test below have been used in assessing the tutorial on multiple-slit interference. However, since

learning is cumulative, the effect of each tutorial cannot be isolated from the preceding ones in the series.

1. Pretest on multiple-slit interference

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. 6(a).] A point on the first interference maximum, 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 . Thus point B will still be a point of maximum constructive interference and will be brighter than before. [See Fig. 6(b).]

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. About 30% of the students have responded correctly with fewer than 5% using correct reasoning. Most students have failed to consider path length differences and superposition. About 60% of the participants in the graduate teaching seminar have answered correctly with about 25% giving correct explanations. (See the third column of Table III.)

2. Post-test on multiple-slit interference

In one post-test question, students are shown the same double-slit interference pattern as was used for the pretest. [See Fig. 6(a).] 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. Therefore, the intensity at point B decreases. [See Fig. 6(c).] 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 cannot 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, a criterion that we have set for a successful tutorial.

E. Effectiveness of the tutorials

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. The post-test performance of the undergraduates has often matched (and sometimes surpassed) that of the graduate students on the pretests. In spite of less time devoted to quantitative problem solving, students who have worked through the tutorials do

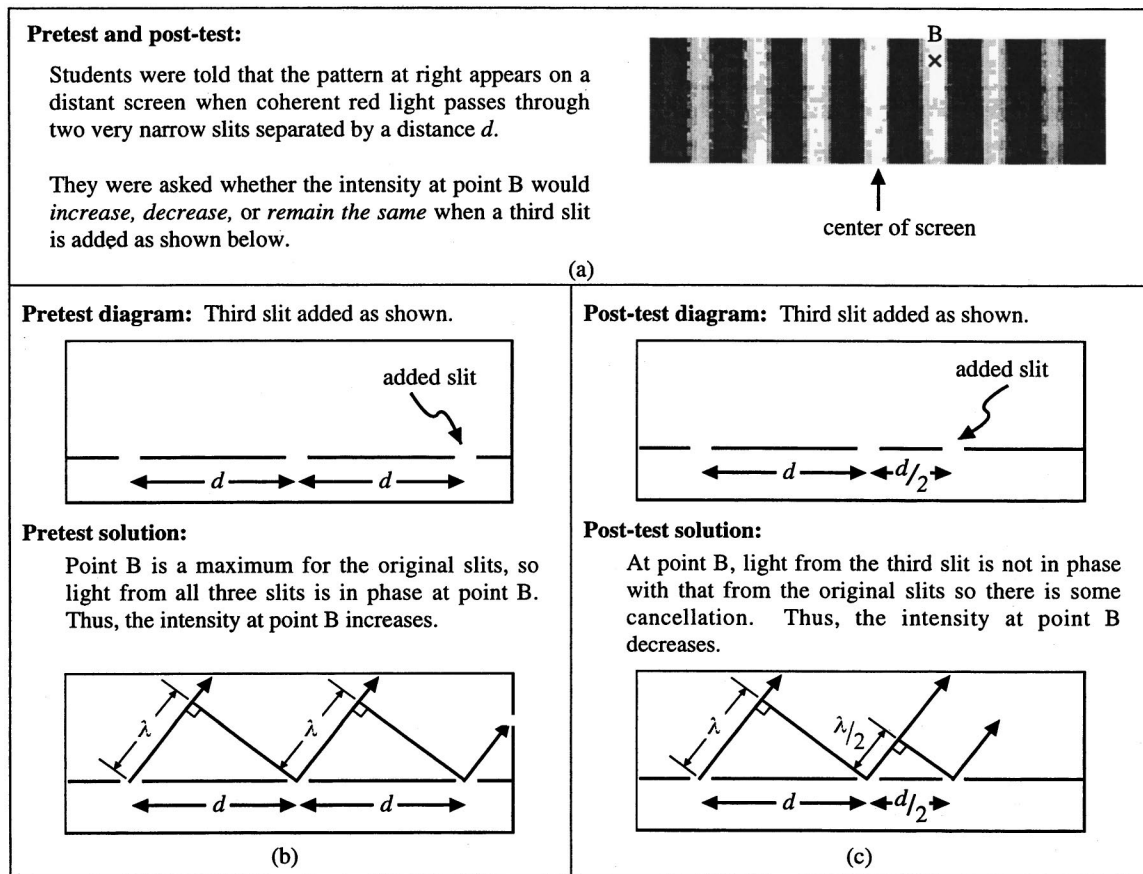


Fig. 6. (a) Basic question for pretest and post-test on multiple-slit interference. (b) Pretest diagram and solution. (c) Post-test diagram and solution.

somewhat better on standard numerical problems than those who have not had this experience. On quantitative problems that require understanding of the concepts, tutorial students have done much better than similar nontutorial students. Moreover, there is evidence that the type of intellectual effort demanded by the tutorials leads to a higher retention rate than that from standard instruction.

The particular instructional approach incorporated in the tutorials is only one of several that can be used to engage students actively in learning physics. *Physics by Inquiry*, in which all instruction emphasizes conceptual understanding and reasoning ability, is even more effective. The tutorials,

however, require relatively little modification of the traditional mode. They have proved to be practical, flexible, and sustainable.

F. Commentary

Careful assessment of student learning should be an integral part of the development of all printed and computer-based materials. It is difficult to develop curriculum that yields reliable results when used by different instructors. Therefore, unless instructors can devote a long-term effort to the design, testing, and refinement of new materials, it is best to take advantage of existing curriculum that has been thoroughly evaluated. It is important to know what has been accomplished and not expend resources in recreating what has been done well.

VII. CONCLUSION

Research in physics education can provide a guide for setting standards for student learning that are more rigorous than the generally accepted criterion of success in solving quantitative problems. It is possible to help students meet higher standards than most instructors often tacitly accept. As already mentioned, there is considerable evidence that time spent on developing a sound qualitative understanding does not detract from, and often improves (sometimes significantly), the ability to solve quantitative problems. Students should be expected to develop a coherent conceptual framework that enables them to determine in advance the

Table III. Results from pretest and post-test for tutorial on multiple-slit interference shown in Fig. 6. In both cases, a third slit was added to a mask containing two slits a distance d apart. On the pretest, the third slit was added a distance d to the right of the rightmost slit; on the post-test the third slit was added a distance $d/2$ to the right.

	Undergraduate students		Graduate TAs
	Pretest (d) $N \sim 560$	Post-test ($d/2$) $N \sim 405$	Pretest (d) $N \sim 55$
Correct without regard to reasoning	30%	80%	60%
Correct with correct reasoning	<5%	40%	25%

type of answer that they should obtain in a quantitative problem. Therefore, the types of intellectual goals that have been set forth, both explicitly and implicitly, do not represent a “dumbing down” of standards, a charge often levied at attempts to modify traditional physics instruction. On the contrary, an increased emphasis on qualitative reasoning means that we are setting *much higher* standards.

Research can be the key to student learning. Without a sound base for informing the development of curriculum, we lack the knowledge necessary to make cumulative progress in improving instruction. We need to increase our understanding of how students think about traditional and contemporary topics. This information can provide a basis for designing instruction to achieve the specific goals of physics courses. Research on how students learn can also lead to insights about how to promote the development of some more general intellectual goals. We would like to help students understand the nature of scientific models and the scientific method through which they are developed. We want them to know the difference between what is and what is not a scientific explanation and to be able to distinguish between explanations based on scientific reasoning and arguments based on personal belief or popular opinion. Students need to recognize the kinds of questions that they must ask themselves to determine whether they understand a concept or line of reasoning and, if they do not, to formulate questions that can help them improve their understanding. Being able to reflect on one’s thinking and to learn on one’s own is a valuable asset that transcends the learning of physics. The study of physics offers many opportunities to cultivate the ability to engage in scientific, critical, and reflective thinking. Thus, research can be the key to setting higher (yet realistic) standards, to helping students meet expectations, and to assessing the extent to which the goals for student learning are met.

We can be greatly encouraged by the positive change that has occurred in the physics community within the last decade. Research in physics education has had an increasing influence on the way physics is taught. Faculty have drawn upon the results in producing new textbooks and revised versions of established texts. Research has also had a direct impact on the development of innovative instructional materials that have been shown to be effective. The results have been reported at professional meetings and in readily accessible journals. At meetings of professional organizations, sessions on research are well attended.

Many departments currently devote seminars and colloquia to physics education and, in particular, to research on the learning and teaching of physics. Faculty have been receptive and interested. Today, there are several universities in which graduate students can earn a Ph.D. in physics for research in this area. The rate of publication is increasing. The evolution in climate is reflected in the actions of physics-related professional organizations. In May 1999, the Council of the American Physical Society passed a resolution in support of physics education research as an appropriate field for scholarly inquiry by faculty in physics departments. In December 1999, the American Institute of Physics, the American Physical Society, and the American Association of Phys-

ics Teachers (along with others) endorsed a statement urging physical science and engineering departments to become actively engaged in the preparation of K–12 teachers. We have come a long way and, with research as a guide, can look forward to continued progress in physics education.

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¹F. K. Richtmyer, “Physics is Physics,” *Am. Phys. Teach.* **1** (1), 1–5 (1933).

²For an overview, see L. C. McDermott and E. F. Redish, “Resource Letter: PER-1: Physics Education Research,” *Am. J. Phys.* **67**, 755–767 (1999). The Resource Letter emphasizes research conducted among university students and contains relatively few entries below the college level.

³L. C. McDermott and the Physics Education Group at the University of Washington, *Physics by Inquiry* (Wiley, New York, 1996); 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).

⁴L. C. McDermott and P. S. Shaffer, “Research as a guide for curriculum development: An example from introductory electricity. I. Investigation of student understanding,” *Am. J. Phys.* **60**, 994–1003 (1992); Printer’s erratum to Part I **61**, 81 (1993); and P. S. Shaffer and L. C. McDermott, “Research as a guide for curriculum development: An example from introductory electricity. II. Design of instructional strategies,” *ibid.* **60**, 1003–1013 (1992). In addition to the examples given in these papers, reference is made to some of the research reported in L. C. McDermott, P. S. Shaffer, and C. P. Constantinou, “Preparing teachers to teach physics and physical science by inquiry,” *Phys. Educ.* **35** (6), 411–416 (2000).

⁵L. C. McDermott, “Guest Comment: How we teach and how students learn—A mismatch?,” *Am. J. Phys.* **61**, 295–298 (1993). The discrepancy between teaching and learning is also discussed in L. C. McDermott, “Millikan Lecture 1990: What we teach and what is learned—Closing the gap,” *ibid.* **59**, 301–315 (1991), as well as in other articles by the Physics Education Group.

⁶B. 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**, 146–155 (1999); 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). In addition to the specific examples in these papers, reference is made to some of the research reported in B. S. Ambrose, P. R. L. Heron, S. Vokos, and L. C. McDermott, “Student understanding of light as an electromagnetic wave: Relating the formalism to physical phenomena,” *Am. J. Phys.* **67**, 891–898 (1999); S. Vokos, B. S. Ambrose, P. S. Shaffer, 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).

⁷See Ref. 2. The Resource Letter includes references that report on work done by our group in the context of a broad range of topics. These articles provide evidence that the results for other topics are consistent with those in the cited articles on electric circuits and physical optics.