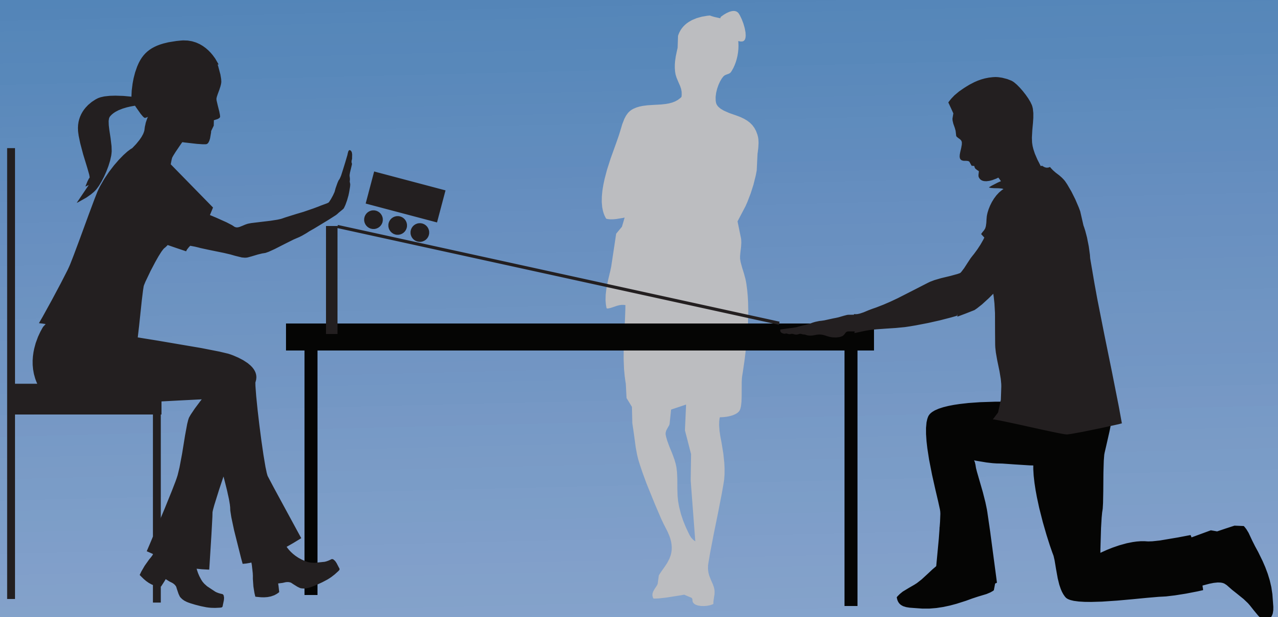
Teacher Education in Physics

Research, Curriculum, and Practice



Physics
Teacher
Education
Coalition

Edited by David E. Meltzer and Peter S. Shaffer

Teacher Education in Physics
Research, Curriculum, and Practice

David E. Meltzer, Arizona State University, Editor

Peter S. Shaffer, University of Washington, Associate Editor

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Reprints

PhysTEC Preface

No one would have any trouble discerning the differences between how experimental physics was done a hundred years ago and how it is done today. Nor has physics itself stood still, with knowledge building with each experiment. Now step into a physics classroom of a century ago and one today and compare the two environments: The contrast is less stunning, to say the least.

One could chalk it up to the idea that we had it pretty much perfect back then – so why change? Unfortunately, the evidence doesn't support this idea; recently published results have demonstrated that there are, in fact, much better ways to educate students that improve not only their understanding of physics, but also their attitudes toward the discipline and about the nature of science.

Although physics education research (PER) is a comparatively new field, with only a few hundred peer-reviewed publications to date, it is beginning to change the scene you encounter in many classrooms today. A large fraction of PER has focused on undergraduate education and, in particular, on the introductory physics curriculum. Prior to the solicitation of papers for publication of this volume, very little research had been published in the United States that was specifically focused on physics teacher education. The goal of the Physics Teacher Education Coalition (PhysTEC) in publishing this collection is to help inspire a broadening of the scholarship that PER is already bringing to undergraduate physics to include more work in the area of teacher education. Integrated in this goal is the desire to bring recognition to faculty members who devote a portion of their professional lives to educating teachers, and to understanding how best to improve the teacher education processes that exist in universities today. Our hope is to help build for teacher education the type of foundation enjoyed in experimental physics today that distinguishes it so readily from the physics of a century ago.

PhysTEC was launched in 2000 as a response to probably the most significant crisis facing physics education and the physics community in the United States: a pervasive and acute shortage of well prepared high school physics teachers. PhysTEC was sponsored initially by the American Physical Society (APS), American Association of Physics Teachers, and American Institute of Physics, and funded by the National Science Foundation and individual and corporate donations to the APS's Campaign for the 21st Century. Today, more than a decade later, the project has demonstrated significant success in advancing model teacher education efforts at more than twenty institutions nationwide.

This book was conceived in 2005 as one of several related efforts of the PhysTEC project to build recognition of, and to inspire and disseminate scholarship centered on teacher education efforts. The project hopes that the community will continue to recognize and value the need for increased scholarship and improvement of practice so that as time proceeds, we will see real differences in how teachers are educated and supported as they prepare the scientifically literate citizenry of future generations.

The PhysTEC project would like to publicly thank this work's editor Professor David Meltzer, his associate editor Professor Peter Schaffer, and the book's Editorial Board for their hard work and diligence in pursuing the details of this volume and in establishing and maintaining the high standards that scholarship of this type must embody to provide appropriate recognition within the community. We would also like to thank the National Science Foundation and numerous private donors for supporting PhysTEC and, consequently, this effort.

Finally, we acknowledge the tremendous effort by the many professionals in the field who spend a good fraction of their professional life educating future teachers. Their devotion to educating teachers and to building the scholarship of teacher education, while often neither recognized nor appropriately rewarded, is an inspiration to us all. Thank you.

Theodore Hodapp
Director of Education and Diversity
American Physical Society
PhysTEC Project Director

Editors' Preface

This book came about due to an increasing national recognition of a need for improved preparation of physics and physical-science teachers. Although there is an extensive and growing body of research and research-based practice in physics teacher education, there has been no single resource for scholarly work in this area. In response, the Physics Teacher Education Coalition (PhysTEC), a project of the American Physical Society (APS) and American Association of Physics Teachers (AAPT), decided in 2007 to publish a compendium of research articles on the preparation of physics and physical-science teachers. The PhysTEC project management selected Editors and an Editorial Board for the book based on recommendations from the physics education community. The editorial group worked to devise a set of guidelines regarding submission of manuscripts. This resulting book includes new reports that reflect cutting-edge research and practice, as well as reprints of previously published seminal papers. Printed copies have been distributed to chairs of all physics departments in the United States. The book is also freely available online at www.PhysTEC.org.

Overview of this book

The papers included in this book address physics and physical-science teacher preparation, with a focus on physics education research and research-based instruction and curriculum development. The primary audience is physics department chairs and faculty members at physics-degree-granting institutions in the United States. However, the book is also envisioned to be useful for faculty in colleges of education who are engaged in physics teacher preparation.

The book has three primary objectives: (1) to provide a resource for physics departments and faculty members who wish to develop and/or expand efforts in teacher preparation; (2) to encourage scholarly documentation of ongoing research and practice, in a form accessible to a broad audience of physicists; and (3) to encourage recognition of teacher preparation as a scholarly endeavor appropriate for faculty in physics departments. In keeping with these themes, it was specified that prospective manuscripts should treat topics that are of general interest and applicability.

To help ensure the highest level of scientific quality and editorial review, all manuscripts that were considered for inclusion in this book were required to be accepted for publication by either the *American Journal of Physics* (AJP) or *Physical Review Special Topics–Physics Education Research* (PRST-PER). Five of the eleven papers were written in response to a call for papers for this project. They are supplemented by reprints of six additional papers that are consistent with the book guidelines. Each of the original and reprinted papers is accompanied by a brief Summary that serves as an introduction to and overview of the key findings of that paper; the Summaries are collected in a separate section.

A review paper introduces this volume. It provides a brief survey of research in physics teacher education with a specific focus on research conducted in the United States. It is an attempt to place the other papers into perspective, and to indicate both their individual significance and the part they play in adding to the body of world literature in this field.

Several years of research, writing, editing, and review were required to bring this book project to fruition. We are confident that the final product represents a significant addition to the world literature on physics teacher education.

Development of this book

The development of this book has extended over more than four years. When the Editors and Editorial Board were selected in 2007, they quickly began working to establish a detailed set of editorial guidelines and procedures. These were published in September of that year. Prior to submitting any manuscripts, prospective authors were required to submit an outline/prospectus for preliminary review. Pre-submission discussion with the book editors was recommended. By March 2008, 33 initial submissions had been received. The Editors carefully reviewed and made extensive comments on all of these submissions and recommended either that a second, revised prospectus be submitted or suggested to the submitting authors that the intended paper would be better suited for other publication venues.

In the second round of review, 18 revised prospectuses were submitted and again carefully reviewed by the Editors. Further review of each prospectus was carried out by at least two members of the Editorial Board supplemented occasionally by independent reviewers solicited by the Editors. A final consensus review reflecting the judgments and comments of the Editors and Editorial Board was then provided to each submitting author, with suggestions as to whether the intended manuscript might be suitable for the book and, if so, what further revisions and additions might be necessary before publication would be possible. It was made clear that authors had the prerogative to submit their manuscripts for journal publication independent of and without prejudice from any editorial consideration regarding publication in the book. This phase of the process was completed in July 2009. Authors were asked to submit their full manuscripts to one of the journals by November 2009.

Ultimately, 10 of the second-round prospectuses resulted in submission of full manuscripts to one of the two targeted journals, AJP and PRST-PER. At that point, all submitted manuscripts went through the standard journal review process with reviewers selected by the journal editors. The journal editors and reviewers either decided against further consideration of the manuscripts or, in all other cases, required the authors to submit revised versions; in some of those cases, multiple revisions were required. Papers that were considered acceptable or potentially acceptable by the journal reviewers and editors went through yet another stage of review by the book editors to decide on suitability for the book and adherence to the published book guidelines. In all cases, additional revisions were required to bring the papers into full conformity with the guidelines.

The final result was that five of the original set of prospectus submissions ultimately resulted in papers that were accepted by and published in one of the journals and also accepted by the book editors for publication in this book. The five papers were published in the journals during 2010 and the first half of 2011. These have been supplemented by reprints of six additional papers that had previously been published either in AJP or PRST-PER. The reprints were selected by the Editors and Editorial Board based on their relevance to the book's theme and their consistency with the book guidelines. The Summaries were written either by the Editors or by the original authors, but in all cases reviewed and approved by the authors.

Acknowledgments

It is a pleasure to express our gratitude to Dr. Theodore Hodapp, Director of Education and Diversity of the American Physical Society. It was his vision and drive that ensured that this book project would eventually be realized. We are also grateful to Prof. Steven J. Pollock (University of Colorado, Boulder) and Prof. Bradley S. Ambrose (Grand Valley State University, Michigan) for assistance during the editorial review process.

David E. Meltzer, Arizona State University
Editor

Peter S. Shaffer, University of Washington
Associate Editor

October 14, 2011

Review Paper: Research on the Education of Physics Teachers

Research on the education of physics teachers

David E. Meltzer[a)]
Mary Lou Fulton Teachers College, Arizona State University, 7271 E. Sonoran Arroyo Mall, Mesa, Arizona 85212

The focus of this review is on physics teacher education in the United States. Research on "pedagogical content knowledge" in physics addresses the understanding held by prospective and practicing teachers regarding students' ideas in physics, effective teaching strategies for specific physics concepts, and methods of assessing students' physics knowledge. Courses designed for physics teachers focus on probing and strengthening knowledge of research results regarding students' physics ideas, and of ways to apply that knowledge to effective instruction. Programs for practicing ("in-service") physics teachers have been prevalent since the 1940s; the few relevant research reports suggest that some of these programs may improve teachers' physics knowledge and teaching enthusiasm. More recent research indicates that some current in-service programs lead to significant improvements in learning by students taught by participants in these programs. Research on programs for prospective ("preservice") physics teachers is a more recent phenomenon; it indicates that those few programs that incorporate multiple courses specifically designed for physics teachers can strengthen participants' potential or actual teaching effectiveness. The broader implications of worldwide research on programs for physics teacher education are that several program characteristics are key to improving teaching effectiveness, including (1) a prolonged and intensive focus on active-learning, guided inquiry instruction; (2) use of research-based, physics-specific pedagogy, coupled with thorough study and practice of that pedagogy by prospective teachers; and (3), extensive early teaching experiences guided by physics education specialists.

I. INTRODUCTION: THE CHALLENGE OF RESEARCH IN PHYSICS TEACHER EDUCATION

The focus of this review is on physics teacher education in the United States. We begin with a discussion of the disparity between research on physics teacher preparation in the U.S. and research done abroad, followed by an exploration of the specific challenges that make research in this field particularly difficult. In Section II there is a general discussion of research that has been done on helping teachers develop skill in teaching physics, as opposed to developing physics content knowledge or general skill in teaching. (This type of content-specific skill is termed "pedagogical content knowledge.") In Section III there is a description of the research that has been conducted on specific courses for physics teachers, as distinct from other research related to more extensive teacher preparation programs that generally include multiple courses and program elements. The focus in Section III is on courses developed in the United States, but also included is a brief survey of such courses that have been developed elsewhere. In Section IV we examine programs for practicing (in-service) physics teachers in the United States; such programs have been a distinctive feature of the educational landscape for more than 50 years. In Section V, we review research reports on programs for prospective (preservice) physics teachers in the United States. We conclude in Section VI with a brief overview of the major insights gained from research on the education of physics teachers, as well as implications of this work for future advancements in the field.

A. Physics teacher education in the United States and the world

Several hundred research papers dealing with the education of physics teachers have been published in English-language journals worldwide. However, only a small fraction deal with the education of preservice (prospective) or in-service (practicing) high school physics teachers in the United States. There are several related reasons. First, the nature and role of secondary-school physics education in the United States is quite different from that in many other countries. For example, physics has typically been taught as a one-year course in the U.S. by teachers who primarily teach courses other than physics.[1] In many other countries physics is (or has been) taught as a multi-year sequence of courses by teachers who specialize in physics. In those countries, the need for research to inform and support the preparation of such specialist teachers has long been recognized and encouraged. Moreover, outside the United States, many or most physics teacher preparation programs are led by research faculty who specialize in physics education and who often have extensive high school teaching experience; this is not the case in the U.S. In addition, very few U.S. teacher preparation programs incorporate courses or major activities that focus *specifically* on the teaching of physics. In many other countries, by contrast, the course of study includes a specific focus on physics pedagogy.[2] These specialized courses and programs have provided a fertile ground for research by non-U.S. physics education faculty. Consequently, most physics research faculty who focus on teacher education are located outside of the U.S. and it is they who originate the majority of research investigations related to physics teacher education. In the U.S., most physics education researchers have necessarily focused on other areas of interest.

An example of recent research on physics teacher education outside the U.S. is a paper by Eylon and Bagno on an Israeli program for in-service teachers. It is reprinted in this book because, although the context is quite different from that in the U.S., the researchers provide detailed descriptions and documentation of physics-specific practices that have substantial potential for effective adaptation with physics teachers in the United States.[3] Although general principles both of pedagogy and of science teaching are also relevant to physics teachers, these do not deal with the specific pedagogical issues arising from physics as a distinct area of study. It is those physics-specific issues that are the focus of this review and of this book.

B. Practical challenges to research in physics teacher education

Many of the obstacles to effective research in this field are inherent in the nature of the field itself, that is: most projects and activities aimed at improving physics teacher education are treated as practical, applied problems and not as research projects *per se*. (This holds true both for U.S. and non-U.S. work, although research aspects are generally given greater weight in work done outside the U.S.) Any research that is done is generally considered secondary to the primary objective of near-term improvements in program outcomes, however those might be defined. The focus is usually on overall program effectiveness, not on close examination of individual program elements. Assessment and evaluation—such as there are—tend to be on broad program measures. Multiple and mutually influencing elements of courses or programs are often simultaneously introduced or revised, making assessment of the effectiveness of any one particular measure difficult or impossible. Program revisions are generally based on practical experience, interpretations of the literature, and plausible hypotheses, and not on tested or validated research results. Documentation of changes in practice or outcomes is often unreported and rarely very thorough; even more rarely is there documentation of tests of the effectiveness of these changes.

The reasons for this "practical" orientation—in contrast to one that might be more closely tied to research—are diverse, albeit interconnected. An important consideration is that most teacher educators are practitioners whose primary interest is in improving practice and not necessarily in carrying out research on that practice. Research is viewed as time-consuming, costly, and inconclusive, and generally as offering fewer prospects for practical improvements than work based on intuition, experience, and sound judgment. Those who provide funding for teacher education seem to share this viewpoint, since funding for innovative teacher education projects generally does not envision nor allow for a substantial research effort to be incorporated in the program design. Since the costs of careful research in this field are often felt to be prohibitively high, it is generally conceded that evaluation efforts should be serious but not necessarily extensive, long-term, or in-depth. A major consideration is time: multiple cycles of testing are often impractical when a project extends over a two- or three-year period as is frequently the case. Furthermore, enrollments in courses targeted specifically at pre- or in-service physics teachers are usually low, making it difficult to draw conclusions that have high levels of statistical significance.

It may be helpful to consider what sorts of elements are required to make a research report on teacher education most useful for others who wish either to put into practice or to test independently some of the findings claimed by the researchers. In order for other practitioners or investigators to reproduce effectively the work being assessed, detailed descriptions of the instructional activities would have to be provided, including specific information regarding the tasks given to the students and the methods employed for accomplishing those tasks. Samples of curricular materials would need to be provided in the report or made available elsewhere, the instructor's role would have to be made clear, and samples of student responses to typical quiz, homework, or exam questions would be needed. In order to assess whether the educational objectives have been met, those objectives would have to be explicitly identified and benchmarks specified that could indicate whether and to what extent the objectives had been achieved.

Despite the large number of published reports regarding physics teacher education around the world, few of them include all of the desirable elements identified in the previous paragraph. This is largely true for reports originating from outside the United States, as well as for reports of U.S. work. In any case, since important contextual factors often differ significantly from one institution or region to another, even clear and detailed reports of programs in one nation might have only limited applicability in another nation's context. Consequently, those who are responsible for implementing teacher education in physics must attempt to synthesize results from a large number of studies and draw from them the appropriate implications regarding their own local situation.

Despite these various challenges to research in physics teacher education, the published literature does provide substantial guidance in defining important themes and outlining key findings in the field. The remainder of this review will provide a brief sketch of these themes and findings. It is intended to help place the papers in this book within a context that allows their significant contribution to be more readily apparent. The focus will be on peer-reviewed research related directly to physics teacher education in the United States. As will become evident, almost all of this research relates to evaluations and assessments of specific teacher preparation programs or courses. An extensive bibliography that includes relevant books, reports, and other non-peer-reviewed materials related to this topic may be found in the Report of the National Task Force on Teacher Education in Physics.[4] For the most part, the multitude of published reports regarding physics teacher education programs outside the U.S. will not be discussed in this review apart from mention of several exemplars. Nonetheless, some attention to the non-U.S. work is essential for providing an adequate perspective on the full scope of work in this field.

We continue this review by focusing on those aspects of pedagogical expertise that are specific to the field of physics; this form of expertise has come to be called "pedagogical content knowledge" in physics. Then we turn to courses that have been developed specifically for the benefit of prospective or practicing physics teachers. These courses incorporate various elements of pedagogical content knowledge, as well as physics subject matter taught in a manner intended to be particularly useful to teachers of physics. Finally we examine research on broader programs of physics teacher education in the U.S.; these programs generally incorporate multiple courses or program elements that are designed with a specific focus on the education of physics teachers.

II. DEVELOPMENT AND ASSESSMENT OF "PEDAGOGICAL CONTENT KNOWLEDGE" IN PHYSICS

This section addresses research that has been done in relation to physics teachers' knowledge and skills insofar as they relate explicitly to the teaching of physics. Research on the development of physics teachers' general physics content knowledge is usually discussed in reports on courses, or programs of courses, that have been designed for and targeted at prospective and practicing physics teachers; these courses and programs are reviewed in Sections III-V below.

A. Definition of Pedagogical Content Knowledge (PCK)

In 1986 Lee Shulman introduced the term "Pedagogical Content Knowledge" (PCK) to the education literature and this idea has had particularly strong resonance among science and mathematics educators. PCK in science refers to an awareness of, interest in, and detailed knowledge of learning difficulties and instructional strategies related to teaching *specific* science concepts, including appropriate assessment tools and curricular materials. It refers to the knowledge needed to teach a *specific topic* effectively, beyond general knowledge of content and teaching methods. As described by Shulman, this includes *"… the ways of representing and formulating a subject that make it comprehensible to others…an understanding of what makes the learning of specific topics easy or difficult … knowledge of the [teaching] strategies most likely to be fruitful …"*[5] When defined in this way, physics PCK refers to a very broad array of knowledge elements dealing with curriculum, instruction, and assessment that, in principle, extends to all major topics covered in the physics curriculum.

A major challenge in physics teacher preparation is that no currently accepted, standardized instruments exist with which to measure or assess a physics teacher's PCK. Much of the published research focuses instead on more modest goals of documenting aspects of teachers' PCK or of assessing specific elements of it. In this context, researchers have most often focused on investigating teachers' knowledge of students' reasoning processes in physics, with specific reference to knowledge of students' confused or erroneous ideas about specific physics principles.

B. Documentation of teachers' ideas about physics pedagogy

Studies that simply document, rather than assess or evaluate, teachers' pedagogical ideas on a number of physics topics have been published by the Monash University group led by Loughran and his collaborators in Australia.[6] Their method is to choose a specific topic (e.g., "Forces") and then gather together a group of experienced teachers who begin by generating a set of "Big Ideas" for this topic (e.g., "The net force on a stationary object is zero"). The teachers then collaborate to provide responses to such questions as the following:

- What do you intend the *students* to learn about this idea?
- What are difficulties/limitations connected with teaching this idea?
- What knowledge about students' thinking influences your teaching of this idea?
- What are some teaching procedures/strategies (and particular reasons for using these) to engage with this idea?
- What are specific ways of ascertaining students' understanding or confusion around this idea?

Several other authors have assembled compilations of research results that address some of these questions in the context of university-level physics instruction.[7] However, the particular merit and distinction of the Monash work is that it brings together the combined knowledge and insight of a group of experienced teachers whose ideas have been developed and tested specifically in the context of high school physics.

C. Investigating teachers' knowledge of students' ideas

A common theme in the research literature is to investigate and evaluate teachers' (or prospective teachers') knowledge of students' ideas in physics. For example, Berg and Brouwer[8] asked Canadian high school physics teachers to give predictions of students' responses to a set of conceptual questions in physics. These questions included a prediction of the trajectory of a ball connected to a string, after the string breaks, when it had been swung along a circular path. Other questions included a prediction of the path of a wrench dropped on the moon, and the direction of net force on a ball thrown in the air. It was found that the teachers predicted much higher correct-response rates than those actually observed among their students.[9] Similarly, teachers underestimated the prevalence of specific alternative conceptions among the students. For example, teachers predicted that only 33% of students would claim incorrectly that the direction of the total force on a thrown ball is upward and that there is no force at the top of its path. Actually, 56% of the students had made that claim.

In a similar study, Halim and Meerah[10] interviewed postgraduate student teachers in Malaysia. The teachers were asked to give answers to several physics questions and to provide predictions of how students would answer those same questions. They were also asked how they would teach students to understand the teachers' answers. The researchers found that some teachers were not aware of common incorrect ideas related to the physics concepts and, of those who were, many did not address those ideas through their teaching strategies. An analogous study in Holland in the context of heat and temperature was reported by Frederik et al.,[11] and one in astronomy in the U.S. by Lightman and Sadler.[12]

D. Developing and assessing physics teachers' PCK

There are a variety of approaches to the challenging task of assessing physics teachers' PCK. Perhaps the most "traditional" of these is the observational approach in which teachers' classroom behaviors are assessed according to some standard. Examples of this are discussed by MacIsaac and Falconer,[13] and by Karamustafaoğlu.[14]

Another approach to assessment of physics PCK is to evaluate prospective teachers' interpretations of responses by hypothetical students to specific physics problems. This has proven to be—unsurprisingly—an extremely challenging task to carry out with any reliability. A somewhat more straightforward approach is to assess teachers' ability to predict and describe difficulties students might have with specific physics problems, based on findings in the research literature. The paper included in this volume by Thompson, Christensen, and Wittmann[15] represents one of the best documented studies in this area; it extends work previously reported by Wittmann and Thompson in the context of a course sequence on physics teaching taught in a graduate teacher education program.[16] (This course sequence is described further in the next section.) A program at Rutgers University with more far-reaching goals that also focuses on development of students' physics PCK is the subject of a recent report by Etkina, written for and published in this volume.[17] This program will be discussed further in Section V below.

Several research reports on physics teacher education programs outside the United States have an explicit focus on the development of pedagogical content knowledge and so they will be discussed in this section.

A program in Italy has been described by Sperandeo-Mineo and co-workers. In this program, post-graduate student teachers whose primary background was in mathematics were guided through a 30-hour workshop to become more effective teachers of specific topics in physics. The student teachers carried out laboratory investigations and, guided closely by experienced physics teachers, developed and analyzed teaching and learning sequences for use in high school classes. Evidence indicated that the student teachers made substantial gains in their ability to communicate the targeted physics ideas.[18]

A Finnish in-service program that has similarities to the Rutgers program was described by Jauhiainen, Koponen, and co-workers.[19] This program includes a sequence of four courses that address principles of concept formation in physics, "conceptual structures" in specific topics such as electric circuits and relativity, experimentation in the school laboratory, and history of physics. The impact of this program on participants' physics PCK was assessed through a series of interviews.[20] Similar themes in preservice physics teacher education programs can be found in earlier reports by Nachtigall (Germany)[21] and Thomaz and Gilbert (Portugal);[22] both of these programs stress study of physics-specific teaching methods as well as early student-teaching activities that also are physics specific. They involve hands-on laboratory activities, and require substantial reflection on and review of the teaching experiences that are guided by physics education specialists.

A recent discussion of a German in-service program focusing on physics PCK is given by Mikelskis-Seifert and Bell.[23] An unusually careful study of a different physics education program for in-service teachers in Germany, this one focusing on development and evaluation of teachers' beliefs and behaviors, has also recently been published.[24] A report by Zavala, Alarcón, and Benegas describes a short (3-day) course on mechanics in Mexico that, although focused on physics content, was intended to provide direct experience with research-based, guided-inquiry curricula and instructional methods for in-service physics teachers.[25]

III. RESEARCH ON INDIVIDUAL COURSES FOR PHYSICS TEACHERS

Almost all research reports related to individual courses specifically designed for preservice high school physics teachers originate from outside the United States. A small sampling of such reports will be cited here, along with references to analogous work in the United States. Preservice and in-service programs in the U.S. that may include several such courses are discussed in Sections IV and V, and discussions of courses developed for those programs will be found in those sections.

A. Courses outside the U.S.

As discussed in Section I, many nations have instituted regular courses and programs designed specifically to educate physics teachers. Many of these have been documented in research journals and their impacts on teacher participants have been assessed. Some courses focus primarily on methods for teaching basic physics topics at the high school level, particularly concepts that are found to be difficult by students. Examples of these includes courses in Jamaica,[26] Peru,[27] Italy,[28] Germany,[29] Japan,[30] and South Africa,[31] and, in the context of a laboratory course (for both in-service and preservice teachers), in Finland.[32] In other cases, the courses focus primarily on more advanced physics content but are designed for and taught to an audience that is wholly or primarily composed of preservice teachers. As representative examples, we may cite courses on electricity and magnetism in Denmark,[33] on quantum mechanics in Finland[34] and on modern physics (focusing on relativity) in Italy,[35] as well as problem-solving seminars in Spain and Britain.[36]

B. Courses in the U.S.

In this section we will review all published reports of individual courses for U.S. high school physics teachers that we have been able to locate, apart from courses that are integral parts of broader programs. Such programs and the courses within them are discussed in Sections IV and V of this review.

Among the earliest reports of courses for physics teachers in the U.S. were those in the context of summer programs for in-service high school teachers in the late 1950s, such as those at the University of New Mexico,[37] UCLA,[38] and the University of Pennsylvania.[39] (See also Section IV below.) These reports consistently indicate high degrees of enthusiasm among both participants and instructors, although little attempt is made to evaluate direct impacts on participants' knowledge or teaching behaviors.

Much more recently, Finkelstein has described a course on physics pedagogy for physics graduate students at the University of Colorado which, although not targeted specifically at prospective high school teachers, has the potential to be adapted to such a purpose.[40] In fact, a similar two-course sequence at the University of Maine, mentioned in Section II above, is in part just such an adaptation; it has been described by Wittmann and Thompson[41] and by Thompson, Christensen, and Wittmann.[42] These courses on physics teaching are taught in a graduate teacher education program for both preservice and in-service teachers. The courses at the Universities of Maine and Colorado all incorporate learning of physics content using research-based curricula, as well as analysis and discussion of physics curricular materials and research papers related to those materials. The courses are specifically designed to improve teachers' knowledge and understanding both of physics content and of students' ideas about that content. The authors provide evidence that the courses were at least partly successful in these goals. In all cases, the authors present evidence to show that course participants improve their understanding of physics concepts and, potentially, their ability to teach those concepts.

The physics teacher education program at Rutgers University incorporates a sequence of six separate courses designed specifically for physics teachers; this program is discussed in Section V.

Singh, Moin, and Schunn describe a course on physics teaching targeted at undergraduates at the University of Pittsburgh. They found that the course had positive effects on the students' views about teaching and learning, and noted that at least half of them went into K-12 teaching soon after receiving their undergraduate degree.[43] A graduate-level course targeted at both preservice and in-service teachers has been discussed by Baldwin, who focused on effects of the classroom layout. This course was taught in a graduate school of education.[44]

Most research reports on U.S. physics courses for teachers have focused on courses targeted at prospective elementary school teachers. Such reports—and the dozens of reports of similar courses outside the U.S.—are not covered in this review. Nonetheless, two of the original papers written for this volume and one of the reprints are in that specific context. Loverude, Gonzalez, and Nanes discuss an unusual approach to the use of a "real-world" thematic context to provide a story line in which physics learning activities are set.[45] Goldberg, Otero, and Robinson describe carefully guided student group work centered on experiments and computer simulations designed to help students recognize and grapple with their evolving ideas about physical phenomena.[46] Marshall and Dorward report an investigation of the effectiveness of adding guided inquiry activities to a previously existing course, a considerably easier option than creation of an entirely new course as discussed in the other two papers.[47] All of these papers provide substantial evidence that students in the courses made significant improvements in their understanding of physics concepts. The instructional methods they describe and the curricular materials they employed all have potential value for courses targeted at prospective high school teachers.

IV. EVALUATIONS OF IN-SERVICE PHYSICS TEACHER EDUCATION PROGRAMS IN THE U.S.

Many teacher education programs include both preservice and in-service teacher participants. In this section we will focus on those programs that specifically target in-service teachers, while Section V will address programs that include preservice teachers; these latter programs may also include in-service teacher participants.

A. Early history, 1945–1971

Summer programs designed for in-service (practicing) physics teachers began in the U.S. in the 1940s, initially supported by technology-oriented private companies such as General Electric. These programs were very diverse, but generally included various courses and laboratory experiences aimed at enriching participants' physics knowledge and bolstering their enthusiasm for teaching. One of the earliest evaluations of such in-service programs was in 1955 by Olsen and Waite; they examined the six-week summer fellowship program for physics teachers sponsored by the General Electric Corporation, held at Case Institute of Technology (CIT) each summer from 1947 to 1954.[48] These authors received responses to questionnaires from 60% of former participants in these programs and found that 50% of those respondents reported improved attitude or enthusiasm for teaching as a result of the program. An impressive piece of evidence regarding the indirect effects of the program was a dramatic increase in enrollment at CIT of students taught by these teachers (from 0 to 45 per year), in comparison to the years before the teachers had attended the program. It was also noted that these students had scores on a pre-engineering "ability test" that were well above the average of other CIT freshmen.

Support for summer in-service programs (known as "institutes") by the National Science Foundation (NSF) followed just a few years after NSF's founding in 1950, with low levels of initial, tentative support rapidly expanding during the mid-1950s and, under pressure from the U.S. Congress, exploding to unprecedented levels after Sputnik in 1957.[49] During the period 1959-1966 there were an average of 23 summer physics in-service institutes per year; this was approximately 7% of all summer science in-service institutes held during that period.[50] Published reports of such institutes tended to be merely descriptive, with little attempt at rigorous evaluation or assessment of their impact.[51] At the same time, there was a rapid expansion in NSF-supported development of science curricula, initially aimed primarily at high schools. Arguably the best-known and most influential of these was the physics curriculum project begun in 1956 by the Physical Science Study Committee (PSSC).[52] The other major NSF-supported high school physics curriculum project during this period was Project Physics, often known as "Harvard Project Physics." This curriculum, developed during the 1960s, put a greater emphasis on historical and cultural aspects of physics than did PSSC and was intended for a broader audience.[53]

Starting in 1958, the PSSC project incorporated NSF-supported summer institutes for in-service high school physics teachers as a key element in its dissemination plan. During the initial summer of 1958, five teacher institutes trained 300 physics teachers in the use of the new PSSC curriculum.[54] By the 1961-62 academic year, users of the PSSC course numbered approximately 1800 teachers and 72,000 students. According to surveys, most users felt it was pitched at an appropriate level while a minority felt it was too advanced.[55] By the late 1960s, over 100,000 high school students were using the PSSC curriculum, approximately 20-25% of all students studying physics in high school.[56] In 1965, there were 30 summer physics institutes enrolling from 22 to 71 participants each; about 1/3 of these institutes were specifically dedicated to the PSSC curriculum. In addition to the "physics-only" institutes, many of the multiple-field or general science institutes also offered physics as part of their curriculum.[57]

Although there were a few research reports that examined the effect of the PSSC curriculum on the high school students who studied it,[58] most investigators did not attempt to assess directly the effects of the summer institutes on the physics teachers who attended them. Instead, several reports focused on the characteristics of the teacher participants in PSSC or Project Physics summer institutes.[59] Among the few investigators who did assess the impact of the institutes on the teachers and on the students of those teachers were Welch and Walberg.

Welch and Walberg (1972)[60] reported an unusually careful evaluation of the effects of a six-week summer "Briefing Session" designed to prepare teachers to teach the Project Physics curriculum in their high school classes. When compared to students of teachers in a control group who taught only their regular physics course, students of teachers in the experimental group who attended the Briefing Session reported significantly higher degrees of course satisfaction, while achieving equal levels of performance on physics content tests.

Another investigation by Welch and Walberg (1967) involved an explicit examination of the effects of the summer institutes on the participants themselves.[61] They reported that participants at four summer physics institutes during 1966 (curriculum not specified) made significant gains in understanding of physics content, whereas evidence for gains in understanding of "methods and aims of science" was more ambiguous. However, in a comment on this study by the Physics Survey Committee of the National Research Council, it was noted that "the gains in mean scores…were…so slight that it is doubtful that any long-term effects exist. There also is considerable anecdotal evidence to support the view that summer institutes are often presented at the same breakneck speed that contributes to the necessity for them in the first place."[62]

B. Further developments, 1972–1994

Despite the large numbers of in-service institutes for physics teachers held over the years following their initiation in the 1940s, there continued to be only a few scattered reports in the literature that attempted to assess the impact of these institutes on their participants. (The in-service institute at the University of Washington, Seattle, has been closely integrated with a preservice program since the early 1970s and so it is discussed in Section V below.) In this section we will review, at least briefly, all such reports that we have been able to locate.

In 1986, Heller, Hobbie, and Jones discussed a five-week summer workshop held at the University of Minnesota. They reported that participants enjoyed and valued their experience.[63] In a follow-up report on the same institute, Lippert et al.[64] stated that participants' responses to questionnaires indicated a variety of positive effects of the workshop, including increases in the amount of modern physics taught, implementation of new student experiments, adoption of a more "conceptual" approach in their classrooms, and a dramatic shift away from heavy use of lecture instruction. Many also reported increased enrollment in their classes.

Lawrenz and Kipnis reported on another three-week summer institute for high school physics teachers held at the University of Minnesota in 1987. The institute promoted an historical approach to teaching physics, and it emphasized experimentation through student investigations conducted in classrooms or at home.[65] The researchers found that, in comparison to a control group, students of institute participants were more likely to enjoy their physics classes, to help plan the procedures for the experiments they did in class, and to conduct experiments at home that were not assigned. A very brief contemporaneous report by Henson and collaborators focused on a summer institute at the University of Alabama in 1987 that was specifically targeted at teachers with weak preparation in physics.[66]

A report by Nanes and Jewett in 1994[67] evaluated two four-week summer in-service institutes held in southern California. As in many other similar institutes, participants were also involved in follow-up activities during the academic year. The participants were "crossover" teachers who had weak physics backgrounds and whose expertise lay in other subjects. It was found that the participants made substantial gains on physics content tests (from 40% to 73%, pre- to post-instruction). The participants also reported a large and significant increase in their teaching confidence, as well as in the amount of modern physics taught in their courses.

C. Recent developments, 1995-2011

In recent times, some form of assessment of teacher preparation programs has become more common than in earlier years, in part because it has more often been required by funding agencies. However, there is generally no requirement that such assessments be published in peer-reviewed journals and so, from the standpoint of the research literature under review here, the picture has not changed significantly.

i. University of Washington, Seattle

The oldest ongoing in-service physics teacher education program in the U.S. is at the University of Washington in Seattle, led by the Physics Education Group in the Department of Physics since the early 1970s. The program is unusual—perhaps unique—in that it has involved extensive assessment of teacher learning of content for most of the time since its inception. The program also incorporates extensive preparation for preservice students and so it is discussed in Section V A.

ii. Arizona State University, Modeling Instruction in Physics

Beginning around 1990, Arizona State University instituted a new type of in-service workshop for physics teachers designed on what was called the "Modeling Method" of physics instruction.[68] These Modeling workshops have persisted and expanded to the point where they are today among the most influential and widely attended education programs for physics teachers in the United States. Initial reports regarding results of this form of instruction were included in the 1992 paper that introduced the "Force Concept Inventory" (FCI), the most widely used of all physics diagnostic tests.[69] A more complete account of the design and development of this instructional method, including initial assessment data, can be found in a 1995 paper by Hestenes, Wells, and Swackhamer;[70] that paper is reprinted in this volume. The authors describe Modeling Instruction as based on organization of course content around a small number of basic physical models such as "harmonic oscillator" and "particle with constant acceleration." Student groups carry out experiments, perform qualitative analysis using multiple representations (graphs, diagrams, equations, etc.), conduct group problem-solving, and engage in intensive and lengthy inter-group discussion. Extension of the original workshops into a regular Masters degree program has been discussed by Jackson[71] and, most recently, by Hestenes et al.[72]

There are a number of published reports that provide evidence to support the effectiveness of the Modeling workshops in increasing learning gains of the students whose teachers attended the workshops and/or of the teachers themselves. For example, data provided by Hake in 1998[73] show much higher learning gains on the FCI and other diagnostic tests for students in high school classes taught by teachers who used the Modeling methods instead of traditional instruction. Andrews, Oliver, and Vesenka[74] examined a three-week summer institute that used the Modeling method with both pre-service and in-service teachers. They found learning gains for the preservice teachers were well above those reported using similar tests in more traditional learning environments. Similarly, Vesenka's three-year study reported very high gains on a test of kinematics knowledge for in-service teachers who took two-week workshops based on Modeling Instruction.[75] Strong learning gains and improved teacher confidence growing out of a similar workshop in Ohio were noted by Cervenec and Harper.[76] In addition, improved learning gains in college courses taught with the Modeling method were reported by Halloun and Hestenes (1987)[77] and Vesenka et al. (2002),[78] and in high school courses by Malone.[79]

iii. San Diego State University

Another long-standing program devoted to research-based instruction for physics teachers is that at San Diego State University. Huffman and colleagues have reported evaluations of the Constructing Physics Understanding (CPU) project, targeted at high school teachers, which included two-week-long, 100-hour workshops conducted in the summer and during the following school year. These workshops incorporated inquiry-based investigative activities that made substantial use of computer simulations. The authors found significantly higher FCI scores for students taught by workshop participants than for students taught the same concepts by a very comparable group of teachers who had not taken the CPU workshops. The highest scores were recorded by students of teachers who had previous CPU experience and who had helped lead the workshops. Surveys indicated that instructional strategies recommended in the National Science Education Standards were used more often by CPU classes than by traditional classes.[80]

Another curriculum developed by the San Diego State group is called Physics and Everyday Thinking (PET);[81] it is aimed more directly at elementary school teachers.[82] A detailed description of this instructional approach along with an assessment of its effectiveness is presented in a paper by Goldberg, Otero, and Robinson, one of the five original papers published in this volume.[83]

iv. The Physics Teaching Resource Agent (PTRA) program

The PTRA program, sponsored by the American Association of Physics Teachers and funded by the National Science Foundation, has provided workshops and curricular materials for in-service physics and physical science teachers since the 1980s.[84] Although peer-reviewed studies of the effectiveness of these workshops are yet to be published, preliminary data suggest that students of long-term workshop participants make gains in physics content knowledge that are significantly greater than those made by students of non-participants.[85]

v. Other programs

A variety of other in-service programs have been discussed in brief reports that focus primarily on program description. Long, Teates, and Zweifel[86] have described a two-year summer in-service program (6-8 weeks each summer) for physics teachers at the University of Virginia. The 31 participants report high satisfaction with the program as well as deeper coverage of concepts in their classes, and increases in the use of labs, demonstrations, and computers in their classes. Other reports on in-service physics programs include those by Escalada and Moeller at the University of Northern Iowa,[87] Jones at Mississippi State University,[88] and Govett and Farley at the University of Nevada, Las Vegas.[89]

V. RESEARCH ON EDUCATION OF PROSPECTIVE PHYSICS TEACHERS IN THE U.S.

There are few reports that provide significant detail regarding preservice physics teacher preparation programs in the United States. (The recent report by Etkina has been mentioned in Section III above.) Here we provide a sampling of reports in the research literature that address programs of this type.

A. University of Washington, Seattle; Physics Education Group

The oldest on-going physics teacher education program in the U.S. is that in the physics department at the University of Washington, Seattle (UW), led by the Physics Education Group. UW began physics courses for preservice high school teachers in 1972, and their summer in-service institutes—originally designed for elementary school teachers—later expanded to include high school teachers as well. In 1974, McDermott reported on an inquiry-based, lab-centered "combined" course for preservice elementary and secondary teachers at UW; the paper is reprinted in this volume.[90] Curricular materials developed for this course formed the progenitor of what later turned into *Physics by Inquiry*,[91] a curriculum targeted at both prospective and practicing teachers. Based on 40 years of intensive research on student learning, with an effectiveness validated through multiple peer-reviewed studies, *Physics by Inquiry* is currently one of the most widely used curricula in physics courses for pre- and in-service K-12 teachers.

Based on work in the UW physics teacher education program, McDermott published a set of recommendations for high school physics teachers that emphasized a need to understand basic concepts in depth, to be able to relate physics to real-world situations, and to develop skills for inquiry-based, laboratory centered learning.[92] In 1990 McDermott emphasized the particular need for special science courses for teachers; that paper is reprinted in this volume.[93] In 2006, she reviewed and reflected on 30 years of experience in preparing K-12 teachers in physics and physical science.[94] At the same time, McDermott et al. documented both content-knowledge inadequacies among preservice high school teachers, and dramatic learning gains of both preservice teachers and 9th-grade students of experienced in-service teachers following use of *Physics by Inquiry* (PbI) for teaching certain physics topics.[95] The second of those 2006 papers is reprinted in this volume. Messina, DeWater, and Stetzer have provided a description of the teaching practicum that gives preservice teachers first-hand teaching experience with the UW program's instructional methods.[96]

The effectiveness of the *Physics by Inquiry* curriculum in courses for prospective elementary school teachers has been documented by numerous researchers.[97] Of particular interest here are reports that focus on its use for the education of high school teachers. In one of these reports, Oberem and Jasien discussed a three-week summer in-service course for high school teachers. There were no lectures; the course was laboratory-based and inquiry oriented, and used the *Physics by Inquiry* curriculum. Over three years, their students demonstrated high learning gains (relative to traditional physics courses) using various diagnostic tests for topics that included heat and temperature, kinematics, electric circuits, light and optics, electrostatics, and magnetism. Delayed tests administered 6-8 months after instruction found good to excellent retention of learning gains on heat and temperature, and on electric circuits.[98] By contrast, the same authors had reported in 2002 that incoming students in these and similar courses had shown high (30-60%) incorrect pretest response rates on basic questions about heat, temperature, specific heat, and internal energy.[99] A separate study reported an investigation into a grade-11 student's learning of heat and temperature concepts using the *Physics by Inquiry* curriculum, documenting advances in conceptual understanding.[100] Together, these reports suggest that teachers who learn with the *Physics by Inquiry* curriculum may be able to adapt the materials for direct use in high schools; anecdotal reports provide further support for this conjecture.

B. University of Colorado, Boulder; Learning Assistant program

The University of Colorado, Boulder has pioneered a program in which high-performing undergraduate students are employed as instructional assistants in introductory science and mathematics courses that use research-based instructional methods. These students, known as "Learning Assistants" (LAs), are required to participate in weekly meetings to prepare and review course learning activities, and also to enroll in a one-semester course specifically focused on teaching mathematics and science. Program leaders have documented improved learning of students enrolled in classes that make use of Learning Assistants and the program has come to be highly valued by faculty instructors.[101] The Learning Assistant program has been used very deliberately as a basis for preparation and recruitment of prospective mathematics and science teachers and, particularly in physics, significant increases in recruitment of high school teachers have been documented during the past five years. A detailed report on the program along with a discussion of the assessment data are provided by Otero, Pollock, and Finkelstein in an original paper written for and published in this book.[102] Follow-up observations and interviews with former participants in the LA program indicate that teaching practices of first-year teachers who were former LAs are more closely aligned with national science teaching standards than practices of a comparable group of beginning teachers who had been through the same teacher certification program but who had not participated in the LA program.[103] A short report of a program at Florida International University based on the Colorado model has been provided by Wells et al.[104]

C. Rutgers, The State University of New Jersey; Graduate School of Education

The physics teacher education program at Rutgers Univesity is described in a paper by Etkina written for and published in this volume.[105] It leads to a Masters degree plus certification to teach physics in the state of New Jersey. It includes six core physics courses with emphasis on PCK in which students learn content using diverse, research-based curricula, as well as design and teach their own curriculum unit. The course sequence includes extensive instruction related to teaching, and assessing student learning of, specific physics topics; course examinations assess the prospective teachers on these specific skills. A variety of evidence is presented to show that the prospective teachers make significant gains in their understanding of physics concepts and of science processes such as experiment design, and that they become effective teachers at the high school level.

D. Reports on other programs

There are a number of other preservice programs for which brief reports have been published, providing descriptions of the courses, course sequences, and strategic plans. Although these programs are, to one extent or another, based on or informed by physics education research, to date the assessments of their impact on participants are very limited and primarily anecdotal, based on self-reports or a few case studies. Programs are listed below in chronological order of most recent published report.

1. Haverford College

Roelofs has described the concentration in education designed for future physics teachers at Haverford College, which includes two courses that provide practical instruction in teaching both classroom and laboratory physics.[106]

2. University of Massachusetts, Amherst

Among the most extensive research-based curriculum projects targeted directly at high school students themselves was the NSF-funded *Minds-On Physics* at the University of Massachusetts, Amherst. This project focused on the production of a multi-volume set of activity-based curricular materials that emphasize conceptual reasoning and use of multiple representations.[107] The materials also formed the basis of a course for undergraduate university students who had an interest in teaching secondary physical science. Mestre[108] has described this course which, in addition to undergraduates, also enrolls graduate students and in-service teachers who are or plan to become secondary-school physical science teachers. The course makes extensive use of graphical and diagrammatic representations and qualitative reasoning, and participants develop activities and assessment techniques for use in teaching secondary physics. Class time is spent in a combination of activities, including class-wide discussions, collaborative group work, and modeling the type of coaching and support that should be provided to high school students.

3. Illinois State University

In 2001 Carl Wenning described the physics teacher education program at Illinois State University.[109] Although the program has evolved since that time, it still retains the distinction of including six courses offered by the physics department (a total of 12 credit hours) that focus specifically on physics pedagogy and teaching high school physics.

4. California State University, Chico

Kagan and Gaffney[110] have described a bachelor's degree program in the physics department at Cal State Chico that incorporates revised requirements for prospective teachers. There are fewer upper-level physics courses included in the program than in the regular Bachelor's degree program; instead, students choose from courses in other sciences in addition to participating in a teaching internship. The authors report a substantial number of graduates of the new degree program; at the same time, the number of graduates in the traditional degree program has been maintained. Consequently, the new program has resulted in a substantial number of additional physics graduates over and above the number who would have graduated solely through the traditional degree program. (However, not all of the graduates in the new program have ultimately entered the teaching profession.)[111]

5. *University of Arizona*

Novodvorsky et al.[112] have described the preservice physics teacher education program at the University of Arizona that, very unusually, is contained entirely within the College of Science. Case studies suggest that the program has had positive impacts on participants' content knowledge and ability to recognize and articulate teaching goals, with the potential of improving their effectiveness in the classroom.

6. *Buffalo State College (State University of New York)*

MacIsaac and his collaborators have described an alternative certification, post-baccalaureate Masters degree program in New York State.[113] The program includes summer and evening courses in addition to intensive mentored teaching. Program leaders have found a high demand for the program, requiring them to be quite selective in their admission criteria.

VI. CONCLUSION

The education of physics teachers has been a specific focus of researchers for over 50 years and hundreds of reports on this topic have been published during that time; the great majority of such reports are from outside the United States. A variety of practical and logistical challenges have made it difficult to assess reliably the effectiveness of diverse program elements and courses. Moreover, local variations in student populations and cultural contexts make it challenging to implement effectively even well-tested and validated programs outside their nation or institution of origin.

Nonetheless, certain themes have appeared in the literature with great regularity. Evidence has accumulated regarding the broad effectiveness of certain program features and types of instructional methods. The major lesson to be learned from the accumulated international experience in physics teacher education is that a specific variety of program characteristics, when well integrated, together offer the best prospects for improving the effectiveness of prospective and practicing physics teachers. This improved effectiveness, in turn, should increase teachers' ability to help their students learn physics. These program characteristics include the following:

1. a prolonged and intensive focus on active-learning, guided-inquiry instruction;
2. use of research-based, physics-specific pedagogy, coupled with thorough study and practice of that pedagogy by prospective teachers;
3. extensive early teaching experiences guided by physics education specialists.

With specific regard to developments in the United States, it is possible to discern several promising trends over the past fifty years.[114] Perhaps the single most significant factor during this period has been the development of physics education as a focus of scholarly research in a significant number of U.S. physics departments. This ongoing research has revealed previously underestimated shortcomings in traditional educational practices, and at the same time has provided powerful new tools and techniques for in-depth assessment of student learning in physics. Moreover, physics education research has led to new instructional methods whose increased effectiveness has been repeatedly validated by numerous investigators nationally and worldwide.[115]

As is documented in the references cited in this review, research-based instructional methods and research-validated instructional materials have played an increasingly large role in U.S. physics teacher education courses and programs. At the same time, outcomes measures that grow out of research-based assessment tools—such as, for example, documented learning gains by the students of the new teachers and by the teachers themselves—have provided a degree of reliability for evidence of program effectiveness and guidance for program improvement that has previously been unobtainable. Largely due to these developments, current trends in physics teacher education have much more the character of cumulative, evidence-based scientific work than did the well-meaning efforts of teacher educators a half-century ago.

Most of the world outside the U.S. has accepted the idea that effective education of physics teachers must be based on sound research and led by specialists in physics education. In other nations, these activities have been conducted both in physics departments and in schools of education. For a variety of reasons, it seems unlikely that substantial improvements in the education of U.S. physics teachers can take place without primary responsibility being accepted by physics departments at colleges and universities. In sharp contrast to the situation in some other countries, there is no tradition in U.S. colleges of education that would allow them to take on significant responsibility for preparation of physics teachers in the absence of a clear and unequivocal leadership role on the part of departments of physics. However, if that leadership continues to emerge and to build on the foundation of modern research in physics education, there is great promise for continued future advances in the education of teachers of physics.

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[a]Electronic mail: david.meltzer@asu.edu

[1]Until 1993 the teaching assignment of most high school physics teachers in the U.S. was primarily in courses other than physics, since few schools had enough physics students to justify hiring a full-time physics teacher. This had been the case since physics first become a regular part of the U.S. high school curriculum in the late 1800s. It wasn't until 2009 that a majority of U.S. physics teachers taught all or most of their classes in physics. See, for example, C. Riborg Mann, *The Teaching of Physics for Purposes of General Education* (Macmillan, New York, 1912), Chap. I; and Susan White and Casey Langer Tesfaye, *Who Teaches High School Physics? Results from the 2008–09 Nationwide Survey of High School Physics Teachers* (American Institute of Physics, College Park, MD, 2010), p. 3 (Figure 2).

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Summaries: Original Papers and Reprints

Pages 17–30 consist of summaries of all papers printed in this book.

Summary of "Design principles for effective physics instruction: A case from physics and everyday thinking," Fred Goldberg, Valerie Otero, and Stephen Robinson, pp. 33–45.

This article describes a curriculum (*Physics and Everyday Thinking,* PET) and its implementation in a course for elementary school teachers. PET incorporates findings from research in cognitive science and science education which indicate that, in order to have significant impact on student learning, teachers must create learning environments in which students are actively engaged in the construction of science concepts. This article illustrates how such instruction can be modeled effectively for teachers so as to deepen their understanding of basic physics concepts as well as enhance their attitudes about science.

Physics and Everyday Thinking is a semester-long, guided inquiry-based curriculum that focuses on the themes of interactions, energy, forces, and fields. It is intended for broad use in general education physics courses and more specifically in courses for prospective and practicing elementary teachers. There are two major goals. The first is a content goal: to help teachers develop a set of physics ideas that can be applied to explain a wide range of phenomena, in particular, those that are typically included in elementary school science curricula. Each of the chapters in PET is designed to address one or more of the big ideas in physics contained in the National Science Education Standards and the AAAS Benchmarks for Science Literacy. Each big idea (*e.g.,* the Law of Conservation of Energy or Newton's Second Law) is broken down into a series of smaller sub-ideas, which serve as targets for one or more individual activities in that chapter. The second major goal of PET focuses on learning about learning: to help teachers become more aware of how their own physics ideas change and develop, how children think about science ideas, and how knowledge is developed within a scientific community. About three quarters of the activities in PET are aimed at achieving the content goal. The remainder specifically target learning about learning.

The structure of the PET curriculum, the structure of each activity, and the pedagogical approach to teaching and learning were informed by five major design principles derived from results from research in cognitive science and science education. These principles are built on the idea that teachers must create learning environments in which students articulate, defend, and modify their ideas as a means for actively constructing the main ideas that are the goals of instruction. The paper describes the design principles and illustrates how they are integrated into the structure of the curriculum. Case studies of teachers working through the activities illustrate how the principles play out in the classroom. (Note: In the paper and in the following discussion, the "students" are preservice elementary school teachers in a university course based on PET.)

I. DESIGN PRINCIPLES

The first design principle is that ***learning builds on prior knowledge***. Prior knowledge may come in the form of experiences and intuitions as well as ideas (both correct and incorrect) that were previously learned in formal education settings. Incorrect prior knowledge is often strongly held and resistant to change, but it also has valuable aspects that can serve as resources for further learning.

Each activity in PET consists of four sections: *Purpose*, *Initial Ideas*, *Collecting and Interpreting Evidence,* and *Summarizing Questions*. The *Purpose* section places the material to be introduced in the context of what students have learned before, while the *Initial Ideas* section is designed to elicit students' prior knowledge about the central issue of the activity. Both within the small groups and in the whole-class discussion that follows, students usually suggest ideas and raise issues that are later explored in the *Collecting and Interpreting Evidence* section. The sequence of questions in the latter section prompts students to compare their experimental observations with their predictions. As often happens, the experimental evidence supports some of their initial ideas but not others, prompting students to reconsider their initial ideas. Finally, the questions in the *Summarizing Questions* section, which address aspects of the key question for the activity, help students recognize what they have learned in the activity and how their final ideas might have built on, and changed from, their initial ideas.

The second design principle is that ***learning is a complex process requiring scaffolding***.

During the learning process students move from the ideas they have prior to instruction toward ideas that are consistent with generally accepted principles and concepts with more explanatory power. This view of learning thus assumes that students' knowledge develops gradually and that this process takes time. Such a learning process can be facilitated by providing a high degree of guidance and support (referred to as "scaffolding") for students as they take their first tentative steps in modifying their initial ideas. However, as they move toward mastering a certain concept or skill, the degree of related scaffolding provided can be gradually diminished.

In the PET curriculum guidance is provided within the structure of each activity. The *Initial Ideas* section helps students make connections between what they are going to learn and what they already know. The *Collecting and Interpreting Evidence* section consists of a carefully designed sequence of questions that ask students to make predictions, carry out experimental observations, and draw conclusions. Guidance is especially provided to help students make sense of unexpected observations. Finally, in the *Summarizing Questions* section students are guided to synthesize what they had learned during the activity.

The third design principle is that ***learning is facilitated through interaction with tools***.

Within the scientific community, various tools such as laboratory apparatus, simulations, graphical representations, and specialized language are used in the development and communication of scientific ideas. In the PET classroom, similar tools are used to facilitate the articulation and development of scientific ideas. For example, students often work with computer simulations following laboratory experimentation. The simulations serve as visualization tools, using representations such as graphs, speed and force arrows, energy bar representations and circuit diagrams to help students test their models of the physical phenomena.

The fourth design principle is that ***learning is facilitated through interactions with others***. The scientific enterprise relies on argumentative practices in the interpretation of empirical data and in the social construction of scientific knowledge. The pedagogical structure of each activity in PET was designed to provide multiple opportunities for students to talk, think, develop their ideas, and to engage in argumentation practices both in small groups and in whole class discussions. As students are put in positions where they are expected to articulate and defend their ideas in the face of evidence, they are able to move toward more robust explanatory models and deeper understandings of phenomena.

The fifth design principle is that ***learning is facilitated through establishment of certain specific behavioral practices and expectations***. Classroom behavioral practices and expectations play a large role in science learning, both in *what* students learn and in *how* students learn in the classroom setting. As students learn physics they learn not only what is typically referred to as the canonical knowledge of the discipline (such as Newton's Second Law or the Law of Conservation of Energy), but also how knowledge is developed within the discipline. For example, a student must learn what counts as evidence; that scientific ideas must be revised in the face of evidence; and that particular symbols, language, and representations are commonly used when supporting claims about scientific ideas. Also, in the classroom itself, teachers and students must agree on their expected roles. These classroom expectations for how students are to develop science knowledge are known in the research literature as *norms*.

The PET classroom is a learning environment where the students are expected to take on responsibility for developing and validating ideas. Through both curriculum prompts and interactions with the instructor and their classmates, students come to value the norms that ideas should make sense, that they should personally contribute their ideas to both small-group and whole-class discussions, and that both the curriculum and other students will be helpful to them as they develop their understanding. With respect to the development of scientific ideas, students also expect that their initial ideas will be tested through experimentation and that the ideas they will eventually keep will be those that are supported by experimental evidence and agreed upon by class consensus.

II. ASSESSMENT OF IMPACT

To illustrate the above design principles in practice, the paper provides a case study of a small group of students working through the first activity of the chapter on forces and motion. Excerpts of the students' discourse provide evidence that they draw on their prior knowledge when answering the initial ideas question and when they interpret evidence from experiments and simulations. The transcripts also demonstrate that they engage in substantive discussions with each other and maintain certain classroom norms. By the end of the activity, the students in the group have made some progress, but they are far from having a good conceptual understanding of Newton's Second Law.

The Evaluation section of the paper focuses on the impact of the curriculum both on the case study group and on a large group of students taking PET at different institutions around the country. A locally developed physics conceptual instrument was used to assess the impact on students' conceptual understanding. The evidence suggests that by the end of the chapter on force and motion, all members of the case study group had developed a better understanding of Newton's Second Law than that suggested at the end of the first activity. The conceptual instrument was also administered by an external evaluator to 1068 students at 45 different field-test sites between Fall 2003 and Spring 2005, during the field-testing phase of PET. For all sites the change in scores from pre- to post-instruction was both substantial (>30%) and statistically significant.

The Colorado Learning Attitudes About Science Survey (CLASS) was used to assess the impact on students' attitudes and beliefs about science and teaching. In scoring the survey the students' responses are compared to expert responses (from university physics professors with extensive experience teaching the introductory course) to determine the average percentage of responses that are "expert-like." Of particular interest is how these average percentages change from the beginning to the end of a course, the so-called "shift." A positive shift suggests the course helped students develop more expert-like views about physics and physics learning. A negative shift suggests students became more novice-like (less expert-like) in their views over the course of the semester. The CLASS was given to 395 PET and PSET students from 10 colleges and universities with 12 different instructors. (PSET is a course similar to PET, but focusing on physical science.) Results show an average +9% shift (+4% to +18%) in PET and PSET courses compared to average shifts ranging from −6.1% to +1.8% in other physical science courses designed especially for elementary teachers.

In summary, the paper describes how a set of research-based design principles has been used as a basis for the development of the *Physics and Everyday Thinking* curriculum. These principles guided the pedagogical structure of the curriculum on both broad and detailed levels, resulting in a guided-inquiry format that has been shown to produce enhanced conceptual understanding and also to improve attitudes and beliefs about science and science learning.

Summary of "Inquiry-based course in physics and chemistry for preservice K-8 teachers," Michael E. Loverude, Barbara L. Gonzalez, and Roger Nanes, pp. 46–83.

This paper describes an inquiry-based course for preservice K-8 teachers (Physics/Chemistry 102) developed at California State University, Fullerton (CSUF). CSUF is a regional comprehensive university in southern California, primarily serving students from Orange, Los Angeles, and neighboring counties. With 35,590 students as of Fall 2010, CSUF has the largest enrollment of the 23 campuses in the California State University (CSU) system.

Physics/Chemistry 102 [Phys/Chem 102], "Physical Science for Future Elementary Teachers," is taught jointly by the Department of Physics and the Department of Chemistry and Biochemistry. The course is one of three that were developed as part of an NSF-funded initiative to enhance the science content understanding of prospective teachers; the other courses cover geology and biology. This structure was motivated by the fact that general education requirements at CSUF as well as state content standards for teachers and K-12 students are divided into three categories: physical science, earth/astronomical science, and life science. In Phys/Chem 102, one instructor from each department is typically assigned to the course, although one or both may be a part-time lecturer.

Phys/Chem 102 is taught in a weekly six-hour laboratory format: either three hours twice a week, or two hours three times a week. There is typically no lecture; rather, students work in small groups on carefully structured learning activities. Because of the lab format, enrollment is limited to 26 students per section. The course emphasizes learning science in context, a focus that was influenced by the Physics in Context thread of the IUPP project[1] as well as the American Chemical Society's Chemistry in Context curriculum.[2] The intention is that students will see science as an interconnected discipline with real-world implications, rather than a collection of facts and equations. The text used for the course is *Inquiry Into Physical Science: A Contextual Approach,* by Roger Nanes. The text is built around three contexts: Global Warming, centered on the physics and chemistry of climate change, including heat and temperature as well as the interaction of light and matter; Kitchen Science, focusing on everyday aspects of chemistry and some additional topics from thermal physics, such as phase transitions and specific heat; and the Automobile, emphasizing kinematics, dynamics, and electricity and magnetism. Each topic is rich with difficult content, and could easily occupy a full semester or more, but the units are tightly focused on introductory science that meets the California content standards.

The last point is a crucial one; teaching in a contextual approach can involve very challenging content and may not demonstrably improve student understanding. This course focuses on activities and experiments that cover basic concepts suitable for the target audience but rely on the context to stitch together these activities into a storyline. The individual activities are strongly influenced by published physics and chemical education research and research-based curricula, and in several cases our own research led to new activities and modification of existing ones. Thus, the course functions on multiple levels: day to day, students work on activities not too different from those in comparable research-based courses for prospective teachers, but these activities are placed in the context of real-world applications to provide a more coherent learning experience.

In addition to the non-traditional course structure, the course assessments are designed to reflect course goals and emphasize conceptual understanding and reflective thinking. In addition to conceptually-oriented homework and exams, students write one or two reflective essays tracing how their own understanding of target topics has changed over the course of instruction. In-class performance tasks for each unit provide hands-on authentic assessment.

Since the course was first taught in Spring 1999, it has grown in enrollment to a peak of eight sections per academic year. The number of sections has been reduced to four per year in response to state budget difficulties, and it should be noted that the course is expensive compared to more traditional offerings.

The article documents research on the course and the student population. In particular it presents results from a study that compares the outcomes of the course to those obtained from the more traditional general education science offerings that teachers would take in the absence of Phys/Chem 102. The research findings include:

- Students entering Phys/Chem 102 often have difficulty with written conceptual questions focusing on the physical science content that is included in K-12 content standards. Topics for which data are presented include density, sinking and floating, energy, and the particulate model of matter.
- Students entering Phys/Chem 102 seem to have a weaker level of science preparation than their peers in traditional general education physical science courses. Before instruction, students in the traditional courses were more likely to answer written problems correctly than students in Phys/Chem 102.
- Instruction in Phys/Chem 102 significantly improves student performance on written questions on the target topics. However, work on sinking and floating in particular illustrates that attention to the details of the activities is essential; early versions of the curriculum made little difference in student responses, but revisions based on research on student understanding led to better results.

These findings illustrate the importance of Phys/Chem 102 for this student population. The prospective teachers entering the course have relatively weak science preparation, even compared to other non-science majors at the same university. In the absence of Phys/Chem 102, many would be among the weaker students in a large survey lecture course, and in such a course they would have little opportunity to reflect upon their learning or discuss the content with other students. The evidence suggests that for these students, taking Phys/Chem 102 makes a significant impact on their learning.

[1]R. diStefano, "Preliminary IUPP results: Student reactions to in-class demonstrations and to the presentation of coherent themes," Am. J. Phys. **64** (1), 58–68 (1996).

[2]L. Pryde Eubanks, C. H. Middlecamp, C. E. Heitzel, and S. W. Keller, *Chemistry in Context*, Sixth Edition (American Chemical Society, 2009).

Summary of "A physics department's role in preparing physics teachers: The Colorado learning assistant model," Valerie Otero, Steven Pollock, and Noah Finkelstein, pp. 84–90.

U.S. science education faces serious challenges: undergraduates are inadequately prepared in science and mathematics, and there is a critical shortage of K-12 teachers in these key areas. The Colorado Learning Assistant (LA) model helps address these intertwined problems: it provides an easy-to-adapt program that both enhances university-level science instruction and improves teacher preparation. The LA program builds on and contributes to efforts based on discipline-based education research (DBER) that are departmentally based. This paper documents some of the evidence that the Colorado Learning Assistant model positively impacts undergraduate student performance while at the same time significantly increasing the number and quality of science and mathematics K-12 teachers. It also engages research faculty in improving undergraduate courses as well as in taking some responsibility for recruiting and preparing their majors for all careers, *including* K-12 math and science teaching.

This paper reports on the Colorado Learning Assistant program as it is implemented in the physics and astronomy departments at the University of Colorado, Boulder (CU Boulder). Learning Assistants (LAs) are talented students, typically math, science, and engineering majors, who are hired to help transform large-enrollment undergraduate courses so that these courses are more closely aligned with instructional methods supported by educational research, such as interactive techniques that build on student prior knowledge. The LA program is composed of three key elements: 1) use of LAs in transformed instructional settings, in which students engage with each other in small-groups supported by LAs, 2) weekly meetings around disciplinary content that support LAs, TAs, and instructors, and 3) a multi-disciplinary science education course that provides practical and theoretical grounding in methods for instructional transformation. Currently, each year the physics and astronomy departments at CU Boulder hire 50 LAs to help run approximately 6 transformed courses. This paper describes in detail one of the transformed instructional models in the physics department: LAs are used to implement the research-based *Tutorials in Introductory Physics*[1] that replace the traditional recitation sections of the introductory sequence.

Since the program's beginning in 2003 through Spring 2010, over 300 LA positions have been filled in the physics and astronomy departments, and 16 physics and astronomy majors were recruited to teaching careers through the LA program. This more than doubled the annual number of physics and astronomy majors going into teaching at CU Boulder in comparison to the period before the LA program began. The LA program impacts roughly 2,000 introductory physics students per year and is still growing. Over 25 physics faculty have been involved in transforming a course or in sustaining previous transformations. Transformed physics courses that are supported by LAs show learning outcomes that are far superior to those in traditional courses as measured by conceptual content surveys. For example, student learning gains on the Force and Motion Conceptual Evaluation are two to three times higher than those of students enrolled in traditional courses. The LAs themselves greatly outperform their peers on these same assessments, posting scores similar to our high-level graduate students.

At CU Boulder the Learning Assistant program, which began in a single department with four learning assistants, has grown to become a university-wide effort. Because teacher recruitment and preparation are tied to improved education for all students through the transformation of undergraduate courses, many members of the university community at CU have a vested interest in the success of the LA program. The program brings together interested faculty members, department heads, deans, and senior administrators, each of whom has a stake in, and benefits from, increasing the number of high-quality teachers, improving undergraduate education, and increasing the number of math and science majors. The LA program has demonstrated success throughout campus and has been emulated by dozens of universities throughout the nation. In 2010, 85% of the LAs hired in 9 different departments were supported by CU Boulder's administration and private donations. It is anticipated that by 2012 the program will be fully integrated into the standard operations of the university and not dependent upon grant funding.

This paper suggests how the commitment of physics and astronomy departments to the enhanced education of all students and to the recruitment and preparation of future teachers can collectively enhance the status of education, both for the students considering teaching careers and for the faculty teaching these students. It implies that scientists can take action to address the critical shortfall of science teachers by improving undergraduate programs and by engaging more substantively in evidence-based solutions in undergraduate physics education and in teacher preparation.

[1]Lillian C. McDermott, Peter S. Shaffer, and the Physics Education Group, *Tutorials in Introductory Physics*, 1st ed. (Prentice-Hall, Upper Saddle River, NJ, 2002).

Summary of "Preparing future teachers to anticipate student difficulties in physics in a graduate-level course in physics, pedagogy, and education research," John R. Thompson, Warren M. Christensen, and Michael C. Wittmann, pp. 91–102.

There now exists a decades-long record of physics education research (PER) on student learning and on the evaluation of reform-based curricular materials. The major results of PER have been used to create a course at the University of Maine that moves beyond the current apprenticeship or internship models for preparing teachers, to one that also prepares teachers and researchers to use the results of PER. This graduate-level course, "Integrated Approaches in Physics Education," is designed to help the participants—primarily future secondary teachers and future academic faculty—learn about PER from three different perspectives: research into student learning, development of instructional materials based on this research, and documentation of the effectiveness of these materials.

Results from PER suggest that one must prepare future physics teachers to have an awareness of how their students might think about various topics, as well as an awareness of the kinds of curricular materials available to help guide students to the proper scientific community consensus thinking about the relevant physics. These are components of what is known as "pedagogical content knowledge" (PCK). In the broader science education research literature, research on science teachers' PCK has focused on the nature and the development of PCK in general, rather than investigating teachers' PCK about specific topics in a discipline. The course described in this article is designed to promote the development of content-specific PCK, in part, by improving future teachers' knowledge of student ideas (KSI) in physics.

This article describes an investigation of future teachers' thinking about student ideas in physics, and it discusses the design of a teacher-preparation curriculum that has been explicitly informed by physics education research. The authors believe that this work will contribute to improving future teachers' understanding of students' ideas, an understanding that has proved to be important for effective learning and teaching of physics. The work described here addresses only the most basic elements of instruction on KSI. Learners are first asked to answer, for themselves, carefully developed questions that probe conceptual understanding. They are then asked to supply an answer they think would be consistent with the most common incorrect student response and to explain how a student might be thinking when giving this incorrect line of reasoning.

The authors present results on student learning of physics concepts and of PER literature in the context of electric circuits (batteries and bulbs in parallel and series circuits). Data come from exam questions and ungraded quizzes answered over multiple years of instruction. Prospective teachers' knowledge of physics and their pedagogical content knowledge are examined in terms of their understanding of common student difficulties with the physics, as well as their understanding of which existing curricula are most likely to help students learn the appropriate physics. Results for prospective teachers both with and without a physics background are compared.

A preliminary analysis suggests that the course provides future teachers with tools to anticipate student thinking, to incorporate student ideas about the content into their teaching and assessment, and to analyze student responses with various types of assessments. All the students in the courses have been able to learn the physics content if they did not already begin the course knowing it. Although content understanding has typically been greater among the physics students, the results suggest that the non-physics students may be better able to identify which instructional materials might best help students.

While the sample size at this time is still small, the results nevertheless demonstrate the utility of the methodology. The findings are consistent with aspects of pedagogical content knowledge espoused by many different researchers in science and mathematics education. These aspects are not explicitly taught or assessed in most science and mathematics education research or physics teacher preparation programs. The course design and corresponding research begin to address the need for the PER community to engage in helping future teachers develop both content knowledge, and the knowledge of student ideas that is an essential part of pedagogical content knowledge.

Summary of "Pedagogical content knowledge and preparation of high school physics teachers," Eugenia Etkina, pp. 103–128.

This paper describes some key pedagogical practices of the Rutgers University Physics/Physical Science Teacher Preparation program. The program focuses on three aspects of teacher preparation: knowledge of physics, knowledge of pedagogy, and knowledge of how to teach physics (pedagogical content knowledge – PCK). Three elements of the program work together to produce well-qualified physics teachers who remain in the profession: course work, clinical practice, and a post-graduation learning community. The program has been in place since 2001 and has been steadily graduating an average of 6 teachers per year. The retention rate of high school teachers who have been through the program is about 90%. The philosophy, structure, and elements of the program can be implemented either in a physics department or in a school of education. The paper provides details about the program course work and teaching experiences and suggests ways to adapt them to other local conditions.

The main premise of the program is that for high quality physics instruction a teacher should be skilled in physics concept knowledge and also be familiar with the processes through which physicists build and apply knowledge. In addition, she/he should know how people learn. Finally, an especially critical aspect of teacher knowledge is the knowledge of how to help students master concept knowledge and the processes through which it is constructed, in a pedagogically appropriate environment; this is known as "pedagogical content knowledge" (PCK). PCK is what distinguishes a content expert from an effective teacher of the same subject matter. Figure 1 below shows the complex nature of teacher knowledge.

The physics teacher preparation program at Rutgers, The State University of New Jersey, is tailored to the specific certification requirements of the state. In NJ, all high-school teachers are required to have a major in the subject they are teaching or a 30-credit coherent sequence in that subject (with 12 credits at the 300-400 level). They must also pass the appropriate licensure exam(s). Because of these requirements, the program at Rutgers is a graduate-level program. The Rutgers Graduate School of Education (GSE) has had a master's program in teacher preparation for the last 15 years; however, before 2001, there was no special preparation program for physics/physical science teachers and only 0 to 2 physical science teachers were certified per year. In 2001, the science program was reformed and split into two parts: life science and physics/physical science. Both are offered as a 5-year program or a post-baccalaureate program.

The program goal is to prepare teachers of physics or physical science who are knowledgeable in the content and processes of physics, can engage students in active learning of physics that resembles scientific inquiry, and can assess student learning to improve learning. The new program uses multiple approaches to prepare pre-service teachers to teach physics/physical science. These can be split into three categories: 1) strengthening physics content knowledge; 2) preparing to teach physics/physical science; 3) practicing new ways of teaching in diverse environments (clinical practice). In addition, the program builds a learning community of teacher candidates as they take courses in cohorts and continuously interact with each other during the two years of the program. A particularly important program element is that the program does not end when pre-service teachers graduate and become high school physics teachers. There is an infrastructure in place to help graduates continue to interact with program faculty and with each other (maintaining and strengthening the community of all program graduates) and participate in a continuous professional development program.

Students in the program take general education courses with other pre-service teachers in the GSE, and then follow a separate track to take physics PCK-related courses and clinical practice. In addition, students take a 300/400-level physics elective. In all courses, in addition to weekly homework, students do a group project that involves designing a unit of instruction and teaching part of it to their peers ("microteaching"). Three of the courses are briefly described below.

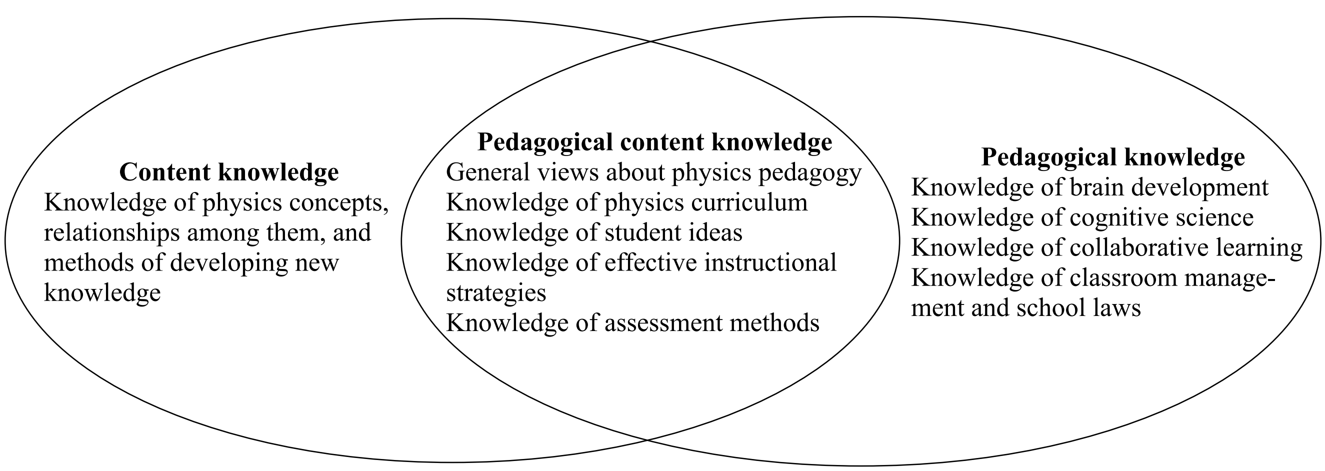

Fig.1. The Structure of Physics Teacher Knowledge.

The course “Development of Ideas in Physical Science” is offered in the first semester of the program. Its goal is to help students learn how physicists developed the ideas and laws that are a part of the high school physics curriculum. The “ideas” that students investigate correspond to the major building blocks of physics and chemistry, such as motion, force, energy, molecular structure of matter, electric charge and current, magnetic field, light, and atomic and nuclear structure. In this course, students use elements of science practice (conducting observations, seeking patterns, devising explanations and testing them by predicting the results of new experiments) as means through which to examine the historical process. They examine the sequence in which ideas were historically developed and determine which ideas were prerequisites for others, as well as read and discuss physics education research papers on student learning of the same concepts.

“Teaching Physical Science” is a second-semester course in which pre-service teachers learn in greater depth how to build student understanding of crucial concepts (Newton’s laws, electric charge and electric field, magnetic field and electromagnetic induction, etc.), how to engage students in experiment design and complex problem solving, how to motivate students, and how to develop and implement curriculum unit plans and lesson plans, including formative and summative assessments. The focus on listening to high school students, and interpreting what they say and do, becomes even stronger. To achieve this goal, pre-service teachers practice listening to and interpreting the responses of their peers in class to specific physics questions, read physics education and science education research papers, and conduct problem-solving interviews with high school or middle school students.

“Multiple Representations in Physical Science” is offered in the last semester of the program after pre-service teachers have done student teaching. The physics content of the course includes waves and vibrations, thermodynamics, electricity and magnetism, geometrical and physical optics, and atomic physics. The goal is to help pre-service teachers systematically integrate different representations of physics knowledge into their problem-solving practice. An emphasis is on the connection between the use of multiple representations in physics and knowledge of how the brain works. In addition to reading research papers relevant to the weekly topics and using the book “Five Easy Lessons” by R. Knight,[1] the students read the book “The Art of Changing the Brain” by J. Zull.[2]

In addition to coursework the program engages the students in clinical practice through multiple venues. Students plan and implement their own “high school” lessons under close supervision, with immediate feedback from the program coordinator. During the second semester, they spend 10 half-days in high schools observing physics lessons and interacting with students. In addition, for the first two semesters and after student teaching, pre-service teachers work as instructors (in labs or problem-solving sessions) in reformed physics courses, similar to what physics graduate students would do. Their teaching in the course is a simplified and sheltered version of high school teaching as they do not plan lessons and assessments. The pre-service teachers’ major responsibility is to implement instruction in a reformed atmosphere and reflect on what happened in class.

In the fall of the second year pre-service teachers do their student teaching internship. They are placed with cooperating teachers who are graduates of the program. (These placements are only possible because of the continuous interaction of the program staff with the graduates.) This careful placement allows the interns to practice what they learned and avoid the conflict between how they are “supposed to teach” and “how real teachers teach.”

After students finish the program and start teaching, they join a community that consists of a web-based discussion board established by the students in the program, along with face-to-face meetings twice a month. Since fall 2004 there have been on average 70 messages per month on the discussion board (the number is growing steadily every year), most of them related to the teaching of specific physics topics, student difficulties and ideas, difficult physics questions, new technology, and interactions with students and parents. Posted questions stimulate rapid responses and lively discussion.

The Rutgers Program is an Ed. M. (master’s degree) program housed entirely in the Graduate School of Education. Two major reasons for such hosting are the NJ certification requirements and the history of teacher preparation at Rutgers. However, the fact that the GSE houses the program does not mean that it is the only participant in the process; rather, it is the collaboration between the Department of Physics and Astronomy and the Graduate School of Education that makes the program successful. Crucial aspects of this collaboration are: advising of undergraduates, opportunities to teach in PER-reformed courses, extra time spent by physics staff and faculty providing training for the pre-service teachers, and support for course reforms in the physics department. Without this array of connections, true integration of physics and pedagogy would not be possible in the teacher preparation program.

[1]R. Knight, *Five Easy Lessons* (Addison Wesley Longman, San Francisco, CA, 2003).

[2]J. Zull, *The Art of Changing the Brain: Enriching the Practice of Teaching by Exploring the Biology of Learning* (Stylus Publishing, Sterling, Virginia, 2003).

Summary of:

(1) Lillian C. McDermott, "Combined physics course for future elementary and secondary school teachers," pp. 129–137;

(2) Lillian C. McDermott, "A perspective on teacher preparation in physics and other sciences: The need for special science courses for teachers," pp. 138–146;

(3) Lillian C. McDermott, Paula R. L. Heron, Peter S. Shaffer, and MacKenzie R. Stetzer, "Improving the preparation of K-12 teachers through physics education research," pp. 147–151.

This Summary presents an overview of three articles that were published in the *American Journal of Physics* over a span of more than 30 years. The first section is devoted to the first article, which dates from 1974. It describes the development of a combined physics course for prospective K-12 teachers at the University of Washington (UW). The second section outlines the evolution of this course and provides the context for the discussion of the other two articles in the third section. Published in 1990 and 2006, respectively,[1] these identify some important characteristics that courses for teachers should have and illustrate the kind of research in physics education that has proved to be a useful guide for the preparation and professional development of precollege teachers.

I. DEVELOPMENT OF A COMBINED COURSE FOR K-12 TEACHERS (1971-1974)

Concerned by the 1957 success of Sputnik, physicists and other scientists became engaged in the development of precollege "hands-on" science curricula that were inquiry-oriented. NSF supported these efforts. It was anticipated that short workshops in which elementary school teachers could work through a few activities would be sufficient preparation because they could continue to learn with their students.[2] This expectation proved unrealistic. At the high school level, Summer Institutes would prepare teachers to teach *Physical Science Study Committee* [PSSC] *Physics* and *The Project Physics Course*. It was assumed that they were well prepared in the content and just needed to learn how to teach by inquiry. Relatively few met this expectation.

In the late 1960s, the UW Physics Department instituted a new course to prepare prospective elementary school teachers to teach physical science by inquiry.[3] A related NSF summer inservice program was begun in 1971. Both provided a learning environment in which the teachers could construct scientific concepts from direct experience with the physical world and develop the reasoning skills necessary for applying the concepts to real objects and events.

There was also a need for a similar course in which prospective high school teachers could learn (or relearn) physics in a manner consistent with the inquiry-oriented approach in *PSSC Physics* and *Project Physics*. We realized that the same learning environment could also include students planning to teach in middle or junior high school. It was obvious, however, that even with the addition of these students, the number of prospective secondary school teachers would be too small to make a compelling case for a new course. Therefore, we invited students who had done well in the course for prospective elementary school teachers to enroll. We also decided to include liberal arts students who had taken a year of physics. University credit (but not the course number) was the same for everyone in this "combined" course.

There is a strong tendency to teach as one has been taught (not only *what* but *how*). Development of a sound conceptual understanding and capability in scientific reasoning provide a firmer foundation for effective teaching than the superficial learning that often occurs during rapid coverage of many topics. In the combined course, students gained direct experience with physical phenomena, rather than by passively listening to lectures and observing demonstrations. The course provided an environment in which future teachers could develop the capacity to implement inquiry-oriented curricula by working through a substantial amount of content in a way that reflects this spirit. The perception that the one who learns most from explanations by the teacher is the teacher, *not* the student, set the tone for the type of *guided inquiry* that characterized instruction. The daily opportunity for informal observations helped us identify what teachers needed to know and be able to do to teach science as a process of inquiry. We had many in-depth discussions with the students. We soon realized that most had learned physics by memorizing definitions and formulas, rather than by going through the reasoning involved in the construction and application of concepts. What they seemed to need most was not to listen to lectures on special relativity or black holes but to deepen their understanding of basic concepts and to develop the ability to apply them to real objects and events.

The curriculum developed for this course gradually evolved into *Physics by Inquiry*.[4] The choice of topics was influenced by their inclusion in the new precollege curricula and by what could be encompassed within a few broad unifying themes. The emphasis in the combined course was on depth rather than breadth. We wanted students to recognize what it means to understand a scientific concept. The students themselves were expected to go through the process of constructing and applying conceptual models for the topics typically taught in introductory physics and physical science (*e.g.,* mechanics, electricity and magnetism, optics, waves, and observational astronomy). For some topics, the prospective teachers were expected to write a logically constructed report on how their understanding had evolved. Sometimes they were asked to describe how they could use their own experience as a guide to lead students through inquiry to predict and explain some simple physical phenomena. Whatever the topic under investigation, the question of *how* we know *what* we know was raised. Teachers need to examine the nature of the subject matter, to understand not only what we know but also on what evidence and through which lines of reasoning we have come to this knowledge.

Although our decision to create a combined course for several populations was initially motivated to increase enrollment, other advantages became apparent. All of the prospective teachers benefited from the unusual class composition. The elementary school teachers developed skill in proportional reasoning and in ability to apply simple geometry, trigonometry, and even vector algebra. Teachers at all levels demonstrated substantial growth in logical reasoning and in the use and interpretation of graphical representations. After a year of learning by inquiry, the elementary school teachers had acquired sufficient self-confidence to help wean their secondary school classmates from dependence on memorized formulas and textbooks. The elementary school teachers quickly became aware of their own greater skill in inquiry-oriented learning and were not intimidated about asking for help. They were willing to accept, however, only a certain type of assistance. Some would say "Don't just tell me the answer, I want help in finding out for myself." Such statements helped the high school teachers recognize the value of independent learning and encouraged them to reflect on their own intellectual development.

II. EVOLUTION OF UW PHYSICS COURSES FOR K-12 TEACHERS (1974-2006)

In the 1990s, the student population in the combined course gradually changed. It began to include physics graduate students with a strong interest in teaching. The preservice course for elementary school teachers was discontinued. Thus there were no graduates of that course to take the combined course. We continued to offer the NSF Inservice Summer Institutes for teachers from elementary through high school, as well as an academic-year Continuation Course open to all former participants in any of our courses for teachers.

The present version of *Physics by Inquiry (PbI)* is the result of a long iterative process. Not intended to be read like a text, *PbI* consists of laboratory-based modules that contain carefully structured experiments, exercises, and questions that require active intellectual involvement. The equipment is simple and can be reproduced in K-12 classrooms. The students collaborate in small groups as they work through the *PbI* modules. Experiments and exercises provide the basis on which they construct physical concepts and develop scientific reasoning and representational skills. The role of the instructor is not to present information and answer questions but to engage students in dialogues that help them find their own answers. Expressly designed for use with teachers, *PbI* has also worked well with other populations.

PbI provides the opportunity to learn (or re-learn) physics in a way consistent with how teachers are expected to teach. It is characterized by four general principles:

- Concepts, reasoning ability, and representational skills are developed together within a coherent body of subject matter.
- Physics is taught as a process of inquiry, not as an inert body of information.
- The ability to make connections between the formalism of physics and real world phenomena is expressly developed.
- Certain common conceptual and reasoning difficulties that students encounter in physics are expressly addressed.

Implementation in *PbI* of the fourth principle required systematic research to determine not only what students could or could not do but also whether the instructional strategies we developed were effective. Daily interactions with individual students in the combined course suggested that systematic questioning would be fruitful for probing student thinking in depth. During the early days of the combined course, we also began trying to identify the conceptual and reasoning difficulties that physics presents to underprepared students who aspire to careers in science, mathematics, and medicine. In 1973, the year before the paper on the combined physics course was published, our group began exploring student understanding in physics by conducting individual demonstration interviews.[5] The students involved were enrolled in the courses for K-12 teachers, special courses with similar content that we offered for under-prepared students, and the standard large introductory physics courses. In 1980–1981 the *American Journal of Physics* published two papers that reported on some of this early research.[6]

During the 1990s we began to administer pretests and post-tests to large numbers of students from the introductory to the graduate level. We identified many similar intellectual hurdles with basic physics in all of these populations and often found that similar instructional strategies worked well. Teachers who might not have a particular difficulty themselves would certainly have students who did. Therefore, a well-prepared teacher of physics or physical science should have acquired, in addition to a strong command of the subject matter, both knowledge of the challenges that it presents to students and familiarity with instructional strategies most likely to be effective. As the combined course evolved and as the development of *PbI* progressed, the prospective teachers in our classes gained this experience.

III. NEED FOR SPECIAL PHYSICS COURSES FOR K-12 TEACHERS GUIDED BY PHYSICS EDUCATION RESEARCH

The other two papers on teacher preparation reprinted here were published in 1990 and 2006, respectively, long after the paper on the combined course. Together they describe the need for in-depth preparation of teachers in physics and comment on how we determine through research whether the instructional strategies that we develop are effective.

The 1990 paper begins by summarizing the history of K-12 science education in the U.S. and describes the ongoing lack of appropriate preparation for teachers at all levels of instruction. A strong case is made for physics departments to offer special courses for both preservice and inservice teachers. The 2006 paper supports these recommendations by illustrating the mismatch between standard topics in the K-12 curriculum and the physics knowledge of many teachers. The following examples are in the context of balancing, kinematics (acceleration), electric circuits, dynamics, and geometrical optics.

Elementary school curricula often include a unit on balancing. About 50 elementary school teachers (many of whom had taught this topic) were shown a diagram of a baseball bat balanced on a finger placed closer to the wide end of the bat. They were told that the bat was of uniform mass density and asked to compare the total mass to the left and right of the balance point. Only about 15% of the K-5 teachers responded correctly. Nearly everyone who gave an incorrect answer claimed there must be equal mass on both sides. They did not seem to be aware that it is not only the amount of mass but also its distribution that determines the turning effect.

A question to probe understanding of acceleration was administered to about 180 preservice and inservice teachers (primarily grades 9–12). The question was based on a strobe diagram of a ball rolling up and down an inclined ramp. Only about 50% of the teachers drew correct sketches that showed acceleration vectors of constant magnitude that were always directed down the ramp. The most common incorrect answers were that the acceleration would be zero at the turnaround point or directed vertically downward, rather than always along the ramp.

The topic of electric circuits is included in many precollege curricula. We have frequently asked for the ranking of the brightness of identical bulbs in three circuits with identical, ideal batteries. The circuits contain, respectively, one bulb, two bulbs in series, and two bulbs in parallel. The correct ranking is that the single bulb and the two in parallel are equally bright and brighter than the two in series. Of the many teachers who have been asked this question, only about 15% have given a correct ranking. Research has revealed two widespread mistaken beliefs: (1) the battery is a constant current source and (2) current is "used up" in a circuit.

Our development of an instructional sequence in the *Dynamics* module in *Physics by Inquiry* was motivated by the inability of many students to apply Newton's Laws properly. In one example, students were shown a diagram of a system consisting of three blocks in horizontal contact with one another. A hand pushes horizontally on one of the end blocks, thus accelerating the system. The question asked was how, if at all, the acceleration changes if the middle block is replaced by one of greater mass while the hand exerts the same horizontal force. To answer that the acceleration has decreased, students must recognize that the inertial mass has increased while the net force exerted on the blocks has remained the same. When this question was administered after standard instruction in introductory physics, fewer than 20% of the students answered correctly. The question has also been given to introductory physics students (N > 100) after they have worked through the tutorial on Newton's Second and Third Laws in *Tutorials in Introductory Physics*, our supplementary curriculum in which the treatment of Newton's Laws is less thorough than in *Physics by Inquiry*.[7] About 55% (N ~ 720) gave correct responses. While this improvement (*i.e.*, 20% to 55%) is significant, high school teachers must understand the material at a deeper level than students in an introductory university course. About 90% of the teachers (N = 45) who worked through the *Dynamics* module in *PbI* gave a correct response.

The research paper also contains an example from geometrical optics that demonstrates the positive effect that even inexperienced teachers can have when they understand the material in depth. Their study of this topic begins with a pretest on the image produced by a triangular hole in a mask placed between a long-filament bulb and a screen. Like introductory physics students, only about 20% of our teachers have responded correctly. Most have had no mental model in which light rays travel in straight lines in all directions from every point on an object. After working through the *Light and Color* module in *PbI*, the teachers develop a ray model that enables them to account for the patterns formed by light sources and apertures of various shapes. After teaching this topic in a ninth-grade classroom, the preservice teachers have given a post-test. About 45% of their students have given correct answers. If the teachers had not developed a ray model, their students would likely have done no better than they had done on the pretest.

When research in physics education has a strong disciplinary focus, it can significantly contribute to the preparation and professional development of precollege teachers. The research summarized in this article should help convince university faculty about the type of preparation in physics that teachers need. The article also contains data from other populations, which are a resource that instructors can draw upon in teaching students at the introductory level and beyond.

[1]The 2006 article accompanied an editorial that described in detail some general issues relevant to physics teacher preparation that are described in this summary. See, Lillian C. McDermott, "Editorial: Preparing K-12 teachers in physics: Insights from history, experience, and research," Am. J. Phys. **74**, 758-762 (2006).

[2]At the elementary school level, the curricula included *Elementary Science Study (ESS)*, *Science Curriculum Improvement Study (SCIS)*, and *Science – A Process Approach (SAPA)*.

[3]A. Arons wrote *The Various Language* (Oxford University Press, NY, 1977) while teaching this course.

[4]L.C. McDermott and the Physics Education Group at the University of Washington, *Physics by Inquiry* (John Wiley & Sons, NY, 1996). Development of the published curriculum began in the combined course.

[5]These were initially inspired by the clinical interviews of J. Piaget, a Swiss psychologist.

[6]D.E. Trowbridge and L.C. McDermott, "Investigation of student understanding of the concept of velocity in one dimension," Am. J. Phys. **48** (12) 1020-1028 (1980); D.E. Trowbridge and L.C. McDermott, "Investigation of student understanding of the concept of acceleration in one dimension," *ibid.* **49** (3) 242-253 (1981). These articles were the first in AJP resulting from research toward a physics Ph.D. in a U.S. physics department.

[7]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 Sadddle River, NJ, 2002); Instructor's Guide, 2003. A *Preliminary Edition* was published in 1998.

Summary of "Inquiry experiences as a lecture supplement for preservice elementary teachers and general education students," Jill A. Marshall and James T. Dorward, pp. 152–161.

This article describes an investigation to test the usefulness of including inquiry-based laboratory activities as a supplement to traditional lecture and demonstration curriculum, in an introductory physics course for pre-service elementary teachers and general education students. The research comprised two studies: a preliminary study for two consecutive academic terms, and a comparison study during one subsequent term.

In the first term of the preliminary study, six lecture periods were replaced with sessions in which small groups of general education students engaged in inquiry-based activities. In some cases, these were shortened versions of the *Physics by Inquiry* activities developed for elementary education majors by McDermott et al.[1] Pre-service teachers did not attend on these days, but were still required to complete traditional prescriptive activities during lab sessions. (The lecture portion of this course was the same for all students, taught by the same instructor. Pre-service teachers had an additional requirement of completing six two-hour labs.) In the following term of the preliminary study, the prescriptive labs for the pre-service teachers were replaced with inquiry-based activities and the general education students engaged in no inquiry activities, but instead completed extra homework problems.

An analysis was performed on outcome measures for all students from both terms (N = 171) to determine whether three outcomes (course grade, final exam grade, and total score on exam problems covering the topics of the inquiry activities) had any dependence on major (pre-service teachers vs. general education), on whether the students experienced inquiry activities or not, or on a combination of major and inquiry activities. The analysis controlled for both gender and grade point average. Results showed that there was a significant difference between students who experienced inquiry and those who did not, on exam problems covering topics from the inquiry activities.

Additional statistical tests indicated that pre-service teachers who experienced the inquiry activities had significantly higher exam scores than those who did not experience those activities ($p < 0.001$). In contrast, there was no statistically significant difference between general education students who experienced inquiry exercises and those who did not. This outcome led us to suspect that gender was contributing to the difference between inquiry and non-inquiry experiences, as more than 90% of the future elementary teachers were female.

A second statistical analysis examined exam scores of female students broken down by major, inquiry or non-inquiry instruction, and a combination of the two. The results supported the conjecture that women had higher achievement on some measures when they experienced inquiry activities. Statistical tests confirmed that women experiencing inquiry activities outperformed those who did not on exam questions dealing with topics covered by the inquiries. A similar test for the corresponding groups of male students showed no significant difference. Likewise, female students showed no significant difference between elementary education majors and others who experienced inquiry exercises.

In the second (comparison) study, all students in the target course were engaged in the inquiry activities, the preservice teachers during the six two-hour lab periods and the general education students during six lecture periods (which the elementary education majors did not attend). Their scores on a final exam problem, taken from Reference 2(a),[2] were compared with scores on the same problem given on a final exam in a calculus-based physics course and on an ungraded quiz in an algebra-based course, both at the same institution. Students in the combined inquiry course significantly outperformed those in the algebra- and calculus-based courses. Their scores, however, did not reach the level that has been seen as a result of instruction that is completely inquiry-based (Reference 2[b]).

Pre- and post-instruction focus group interviews were conducted with a volunteer sample of students who experienced the inquiry-based activities. Coding of responses confirmed that students found the inquiry exercises valuable in solidifying their understanding of concepts, and indicated that engaging in the activities appeared to change some students' perceptions of science and science teaching.

Strengths of the studies lay in the quasi-experimental design and use of statistical techniques that allowed comparisons of small subgroups within the population and disaggregation by gender and major. Limitations included the sample size (N = 171 in the preliminary study and 325 in the comparison study) and the fact that implementation was in only three sections of the same course at the same institution and covered only a limited number of topics.

In summary, engaging in limited inquiry activities as a supplement to lecture improved learning outcomes and perceptions, for female students and pre-service elementary teachers in particular. The effect was not as large as for students who experienced completely inquiry-based instruction at other institutions, leading us to posit a continuum of increasing effectiveness for increasing amounts of inquiry engagement.

[1]Lillian C. McDermott, *Physics by Inquiry* (Wiley, New York, 1996), Vol.1, pp. 3–42; Vol. 2, pp. 383–418 and 639–669.

[2](a) Lillian C. McDermott and Peter S. Shaffer, "Research as a guide for curriculum development: An example from introductory electricity. Part I: Investigation of student understanding," Am. J. Phys. **60** (11), 1003–1013 (1992); (b*) ibid*., "Part II: Design of instructional strategies," 1003–1013.

Summary of "A modeling method for high school physics instruction," Malcolm Wells, David Hestenes, and Gregg Swackhamer, pp. 162–175.

OVERVIEW:

This paper describes the creation, development, initial testing, and preliminary dissemination of a physics instructional approach that has come to be called Modeling Instruction. The instructional design is centered on *models*, defined as conceptual representations of physical systems and processes; these representations may be both mathematical and non-mathematical. There is a particularly strong emphasis on the use of qualitative reasoning aided by a diverse array of representational tools such as motion graphs, motion maps, force diagrams, etc. Such representational tools are considered essential for competent modeling and problem solving.

The modeling approach organizes the course content around a small number of basic models, such as the "harmonic oscillator" and the "particle subject to a constant force." These models describe basic patterns that appear ubiquitously in physical phenomena. Students become familiar with the structure and versatility of the models by employing them in a variety of situations. This includes applications to explain or predict physical phenomena as well as to design and interpret experiments. Explicit emphasis on basic models focuses student attention on the structure of scientific knowledge as the basis for scientific understanding. Reduction of the essential course content to a small number of models greatly reduces the apparent complexity of the subject. In modeling instruction, physics problems are solved by creating a model or, more often, by adapting a known and explicitly stated model to the specifications of the problem.

Students begin each laboratory activity by specifying the physical system being investigated, and then identify quantitatively measurable parameters that might be expected to exhibit some cause/effect relationship, some under direct control by the experimenters, others corresponding to the effect. The central task is to develop a functional relationship between the specified variables. A brief class discussion of the essential elements of the experimental design (which parameters will be held constant and which will be varied) is pursued, following which the class divides into teams of two or three to devise and perform experiments of their own. Computer tools are frequently employed for data acquisition and analysis. Students are guided in their activities and discussion through Socratic questioning and remarks by the instructor. For a post-lab presentation to the class, the instructor selects a group which is likely to raise significant issues for class discussion—often a group that has taken an inappropriate approach. At that time, the group will outline their model and supporting argument for public comment and discussion by the other students.

Modeling instruction is strongly guided by research on students' ideas and misconceptions in physics. These research findings are used for course planning, both to improve the coherence of the overall course structure and to ensure that class activities provide repeated opportunities for students to confront all serious misconceptions associated with each major topic. Specific misconceptions are targeted and addressed in connection with each activity in a way that flows naturally from the manner in which the activities themselves are structured. In both problem-solving and laboratory activities, students are required to articulate their plans and assumptions, explain their procedures, and justify their conclusions. The modeling method requires students to present and defend an explicit model as justification for their conclusions in every case; verbal, mathematical, and graphical representations are all employed in this analysis. As students are led to articulate their reasoning in the course of solving a problem or analyzing an experiment, their naïve beliefs about the physical world surface naturally. Rather than dismiss these beliefs as incorrect, instructors encourage students to elaborate them and evaluate their relevance to the issue at hand in collaborative discourse with other students. In pursuit of this goal, substantial amounts of class time are allotted to oral presentations by students, including "postmortems" in which students analyze and consolidate what they have learned from the laboratory activities. In these presentations student groups outline their models and their supporting arguments for joint examination and public discussion.

This paper outlines how initial testing of the effectiveness of the modeling instruction methods was done in high-school classes by author Wells and in college classes by a collaborator of the authors. Wells's students increased their scores on research-based mechanics diagnostic tests by about 35% in comparison to their pre-instruction scores. This is far higher than the 13-21% observed in comparable high-school classes taught with traditional methods by other instructors, and higher even than Wells's own students in classes he had previously taught using other methods. Similarly, students in the college classes taught with the modeling methods showed pre- to post-instruction improvements of about 25%, well above the 11% observed in comparable classes taught with traditional methods.

To develop a practical means for training teachers in the modeling method, a series of NSF-supported summer workshops for in-service teachers was designed and conducted. The first five-week summer workshop was held in 1990, followed by similar workshops in 1991 and 1992 which incorporated increasing amounts of teacher-developed written curriculum materials and greater focus on the pedagogical methods. After the first year, scores on the "Force Concept Inventory" diagnostic test by the students of the participating teachers were greater than they had been before the workshop, but only by 4%. After the improvements incorporated in the second year, these gains had risen substantially to 22%.

During more than two decades following the initial activities reported in this paper, several thousand high-school physics teachers throughout the U.S. have participated in Modeling Instruction workshops. Data reflecting learning gains by these teachers' students have been very consistent with the initial observations reported in this paper. Further details and documentation are available on the Modeling Instruction website at http://modeling.asu.edu.

HISTORICAL NOTE, BY DAVID HESTENES:

This paper serves as a published account of Malcolm Wells' 1987 doctoral thesis. Since I regard that work as the most significant experiments in physics education history, I want to take this opportunity to explain why. I was so impressed with the results that I contacted Raymond Hannapel at the NSF, who arranged a pilot grant for a workshop to see if we could train other teachers to do as well as Malcolm. This got Malcolm engaged in designing and conducting workshops for teachers that evolved into the *Modeling Instruction Program,* to the immense benefit of teachers throughout the country. It also got me engaged in running the Program and continuing education R&D. I repeatedly urged Malcolm to write up his thesis for publication, but he was too dedicated to students and teachers to find the time. When he was diagnosed with ALS (Lou Gehrig's disease) I decided to do it for him. Sadly, he was too far-gone even to read the paper when it was finished.

Here is what impressed me about Malcolm's thesis:

First, he had devoted more than two decades to incorporating into his teaching the best available ideas and methods from PSSC to the learning cycle of Karplus, so he was already experienced in "teaching by inquiry." When he saw how badly college students performed on the precursor to the FCI [I. Halloun and D. Hestenes, *Am. J. Phys.* **53**, 1043–1055 (1985)] he said "My students can do better than that!" He got the shock of his life when they didn't. The high school data reported in that paper is for his class. Finally, he knew what to do for his thesis! He had an outstanding set of student activities and sharp data on his teaching, so he was set up for an experiment using his previous class as a control group.

Second, with his treatment group he used exactly the same set of activities and allocated the same time to each. He changed only the classroom dynamics using discourse with two major new features: (1) Socratic dialog that elicited student misconceptions so they could be publicly examined and corrected; (2) Incorporating notions of models and modeling into the learning cycle to clarify what to do in each stage.

Third, as a second control he engaged a fellow teacher named Wayne Williams who taught the same course and was well matched by age and experience. Wayne agreed to cover the same subject matter in the same amount of time as Malcolm did, immediately after which students in both classes took the same exam. Wayne used a conventional didactic approach with emphasis on problem solving. Malcolm used an inquiry approach enhanced with emphasis on constructing and using models without mentioning problem solving.

Fourth, Malcolm made substantial improvements on instruments for detecting misconceptions and evaluating problem solving that were eventually incorporated into two widely used evaluation instruments, the FCI and the Mechanics Baseline Test.

Finally, results of evaluation were clean and decisive. Besides huge FCI gains compared to both control groups, Malcolm's class bested Wayne's on problem solving by close to 20%.

When Wayne saw the data he exclaimed: "How did you do that?" After taking a "Modeling Workshop" later on, Wayne was so energized that he put off retirement to continue teaching for many more years.

Summary of "Research-design model for professional development of teachers: Designing lessons with physics education research," Bat-Sheva Eylon and Esther Bagno, pp. 176–189.

This article describes a model for the professional development of practicing high school teachers of physics. The model has components that draw explicitly on results from physics education and science education research to help teachers deepen their understanding of how to teach more effectively and how to assess student learning. A case study is used to illustrate how aspects of the program help to achieve five primary goals: (a) raising the awareness of teachers about deficits in their own understanding of the content and the teaching of physics, (b) enhancing teacher knowledge of both physics and the teaching of physics, (c) informing teachers about how the results of physics education research (PER) can guide the design of lessons, (d) forming a community of practice among participating teachers, and (e) deepening the familiarity of teachers with the central results of PER.

Research on the learning and teaching of physics and on teacher professional development both indicate that bringing about profound changes in teachers' views and practices requires a long-term, multi-faceted, and comprehensive program. The professional development model discussed in this paper took place in Israel and spanned 1.5 years (about 330 hours). It consists of 10 consecutive steps, which are grouped into three distinct stages. The stages involve the teachers in (1) defining teaching and/or learning goals based on analysis of students' prior knowledge, (2) designing lessons that they implement and test in their classrooms, and (3) conducting a small-scale research study and preparing a paper that summarizes the process of curriculum design and assessment of student learning. At the end of each stage, the teachers organize and participate in a mini-conference that helps them synthesize and generalize their work.

The stages in the program are carefully structured so that together they help achieve the five primary goals. The first stage attempts to help teachers recognize the need to introduce innovation into their teaching of a particular topic. The teachers define the goals for a particular lesson, review the literature on the teaching and learning of that topic, try to identify the problems that they (as learners) and their students encounter and then revise their instructional goals accordingly. During the second stage, they become familiar with new instructional strategies and then plan and design lessons through a process of successive refinements of the goals and the means for achieving them. The process involves expert consultation, critique by peers, and observations of the instructional strategies used by their colleagues. Finally, in the third stage, the teachers conduct a detailed examination of their students' learning and report on the results to other participants and colleagues. They also prepare a paper for submission to a professional journal.

The article describes the design and results of a study that assessed the contribution of this program to the professional development of the participating teachers. Qualitative and quantitative data were collected through documentation of the meetings of the participants (observations, transcriptions of audiotapes, and written materials produced by the teachers), student work brought by teachers to the workshops, informal conversations with the teachers, journals kept by the course leaders, and questionnaires administered to the participants immediately after the program and six years later. The focus of this article is a case study involving six of the teachers who participated in the program. These teachers were offered a choice of topics on which to work, ranging from Newton's laws to waves and electromagnetic induction. This particular group worked on a unit entitled "From electrostatics to currents."

The evaluation of the program traces the teachers' activities through the three main stages of the program. Specific questions and comments made by the teachers, as well as the materials prepared by the teachers, are used to illustrate their progress and how the structure of the program facilitated the achievement of the program goals. For example, during the first stage, as the teachers considered what content to teach and how to assess student thinking, their conversations illustrate the initial gaps in their understanding and how they came to recognize for themselves what they did and did not understand about the underlying physics. The article also traces the progress the teachers made resulting from discussions with one another and with workshop leaders, as well as through review of the literature and through discussions with scientists and science educators. Teachers had to grapple with basic questions related to designing test questions for probing student thinking, and even struggled with the basic question of what is meant by "understanding."

The assessments of the second stage, designing lessons, and of the third stage, performing and publishing the results of a research study, illustrate the development of pedagogical content knowledge of the teachers. Comments by the teachers, as they progressed through these stages, demonstrate this growth as they reflected on how to teach the content, learned about instructional strategies with which they had not been familiar, and gained appreciation for the difficulties inherent in the process of designing curriculum. At the end, the teachers assessed student learning in their classrooms and reflected on how their materials might be changed in the future to address the problems they had identified on their post-tests. The results were written up and accepted for publication in *Tehuda*, the journal of Israeli physics teachers.

Teachers' responses to questionnaires given immediately afterward and six years later suggest that the program had lasting beneficial impacts on the participants' attitudes toward teaching and for their classroom practice. In particular, most of the teachers singled out the development of the lesson/lessons as an activity that was most meaningful, useful, or important to them.

The paper concludes with reflections on this model for professional development of precollege teachers and the long-term, intensive nature of the teachers' activities. The authors stress that the lesson development activity described in the article serves as a context for the professional development of teachers and not an activity that is to be carried out routinely by teachers. It is expected that through this activity they will become better consumers and customizers of curricular materials and PER relevant to their work. A central insight that emerges is the power of the kind of cognitive conflict that arises when teachers examine student work critically and reflect on the gap between what they have taught and what their students have learned.

Articles: Original Papers and Reprints

Pages 33–189 contain original papers written for this book, along with reprints of related papers previously published in AJP and PRST-PER.

Design principles for effective physics instruction: A case from physics and everyday thinking

Fred Goldberg[a)]
Department of Physics, San Diego State University, San Diego, California 92120

Valerie Otero[b)]
School of Education, University of Colorado, Boulder, Colorado 80309

Stephen Robinson[c)]
Department of Physics, Tennessee Technological University, Cookeville, Tennessee 38501

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Although several successful inquiry-based physics and physical science curricula have been developed, little has been published that describes the development of these curricula in terms of their basic design principles. We describe the research-based design principles used in the development of one such curriculum and how these principles are reflected in its pedagogical structure. A case study drawn from an early pilot implementation illustrates how the design principles play out in a practical classroom setting. Extensive evaluation has shown that this curriculum enhances students' conceptual understanding and improves students' attitudes about science.

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I. INTRODUCTION

There is a national need for physics courses that are designed for nonscience majors, particularly prospective and practicing elementary and middle school teachers.[1,2] Among the issues is the need for undergraduate science courses that not only address fundamental content goals but also explicitly address the nature of scientific knowledge, science as a human endeavor, and the unifying concepts and processes of science. Researchers and curriculum developers have responded by developing inquiry-based physical science curricula especially for the postsecondary, nonscience major population. Such curricula include *Physics By Inquiry*,[3] *Powerful Ideas in Physical Science*,[4] *Workshop Physical Science*,[5] *Operation Primary Physical Science*,[6] *Physics and Everyday Thinking*,[7] and *Physical Science and Everyday Thinking*.[8] Each of these curricula is based on findings from research in physics education, and each has demonstrated large conceptual gains.[6,9,10] Among these courses, only *Physics and Everyday Thinking* and *Physical Science and Everyday Thinking* have demonstrated replicable positive shifts in students' attitudes and beliefs for several different implementations with different instructors in different types of institutions.[11] Although the curricula we have cited are valued by the physics and physics education research community, little has been published that makes clear the design principles on which the curricula were established.

In this paper, we describe the design principles on which *Physics and Everyday Thinking* (PET) is based, how this curriculum was designed around these principles, and how they play out in an actual classroom setting.

In Sec. II, we present the design principles on which the curriculum is based and discuss the overall structure of the PET curriculum in Sec. III. We present a case study in Sec. IV to illustrate how the curriculum and design principles play out in practice. In Sec. V, we provide information about the impact of the curriculum on students' conceptual understanding of physics and their attitudes and beliefs about science and science learning. We end with a brief summary.

II. DESIGN PRINCIPLES

The PET curriculum was developed on the basis of five design principles derived from research in cognitive science and science education. These principles are based on the idea that teachers must create learning environments in which students articulate, defend, and modify their ideas as a means for actively constructing the main concepts that are the goals of instruction. The design principles are listed in Table I and are described in the following.

A. Learning builds on prior knowledge

Cognitive psychologists, cognitive scientists, and educational researchers agree that students' prior knowledge plays a major role in how and what they learn.[12,13] Prior knowledge may be in the form of experiences and intuitions as well as ideas that were learned in formal education settings (both correct and incorrect).[14] Theoretical perspectives from different academic traditions vary on their perceptions of the characteristics, organization, properties, size, and scope of this prior knowledge. However, they all agree that prior knowledge influences learning.[15–17] This prior knowledge is often strongly held and resistant to change,[18] but it also has valuable aspects that can serve as resources for further learning.[19]

In the *PET* curriculum, the *Initial Ideas* section is the first of three main sections within each activity. It is designed to elicit students' prior knowledge about the central issue of the activity. Both in the small-group and in the whole-class discussion that follows, students usually suggest ideas and raise issues that are later explored in the *Collecting and Interpreting Evidence* section. The sequence of questions in the latter section prompts students to compare their experimental observations with their predictions. As often happens, the experimental evidence supports some of their initial ideas but does not support others. The questions in the *Summarizing Questions* section, which address aspects of the key question for the activity, help students recognize what they have learned in the activity and how their final ideas might have built on their initial ideas.

Table I. Design principles of the PET curriculum.

No.	Design principle
1	Learning builds on prior knowledge
2	Learning is a complex process requiring scaffolding
3	Learning is facilitated through interaction with tools
4	Learning is facilitated through interactions with others
5	Learning is facilitated through establishment of certain specific behavioral practices and expectations

B. Learning is a complex process requiring scaffolding

Instruction that builds on students' prior knowledge views learning as a process by which students iteratively modify their understanding.[14] In this way, students move from the ideas they had prior to instruction toward ideas that are consistent with generally accepted principles and concepts with more explanatory power. This view of learning admits that students' knowledge develops gradually and that this process takes time. Throughout the learning process, it should not be surprising that a student's understanding does not become aligned with the target idea immediately and that states of "partial knowledge" can exist. Such a learning process can be facilitated by providing a high degree of guidance and support ("scaffolding") for students as they take their first tentative steps in modifying their initial ideas. As they move toward mastering a certain concept or skill, the degree of related scaffolding provided can be gradually decreased.

The structure of PET incorporates the gradual decrease of scaffolding for student learning at the curriculum, chapter, and activity levels. In terms of curriculum-wide themes,[20] examples introduced in the later chapters are more complex than, but build on, the examples discussed in the earlier chapters. At the chapter level, each complex National Science Education Standard[1] and/or AAAS Project 2061 benchmark[2] idea was broken down into smaller subobjectives that make up the target ideas of individual activities, as illustrated in Sec. III B. In addition, the target ideas addressed in the later activities in each chapter build on the ideas introduced earlier. In the final activity of each chapter, students apply the target ideas to explain real-world phenomena.

C. Learning is facilitated through interaction with tools

One of the most difficult parts of designing instruction that scaffolds the development of students' knowledge is determining how to help students move from where they are in their understanding (prior knowledge) to where the teacher wants them to be (target ideas/learning goals). Within the scientific community, various tools such as laboratory apparatus, simulations, graphical representations, and specialized language are used in the development and communication of scientific ideas. In a classroom, similar tools can be used to facilitate the articulation and development of scientific ideas. For example, computer simulations can serve as visualization tools, and laboratory experiments can provide evidence that can help students test, revise, and elaborate their current ideas. Learning environments that are designed to utilize such tools can promote deep, conceptual understanding.[21]

Major pedagogical tools within the PET curriculum include laboratory experiments, computer simulations, and various types of representations. The simulations include representational tools such as graphs, speed arrows, energy bar charts, and circuit diagrams, requiring students to make sense of these representations and make connections between them and the simulated (as well as the observed) phenomena. For example, in the activity described in Sec. III C, the students make connections between the simulator-generated speed-time graph [see Fig. 1(a)] and their own graph generated by a motion detector and between their predicted force-time graph and the simulator's graph [see Figs. 1(b) and 2]. Students also learn to represent the energy and force descriptions of phenomena by drawing energy diagrams and force diagrams. Questions within the curriculum help students make explicit connections between these two representations of the same interaction, which is a process that helps learning.[21]

D. Learning is facilitated through interactions with others

Interactive engagement refers to settings in which students interact with tools as well as with other learners.[22] Hake[23] demonstrated that courses that use methods of interactive engagement show much higher conceptual learning gains than those that rely exclusively on passive lecture methods. Social interactions in physics learning environments open new opportunities for students to talk, think, and develop their ideas.[24,25] Because the scientific enterprise relies on argumentative practices in the interpretation of empirical data and in the social construction of scientific knowledge, the case has been made for explicitly helping students to learn to engage in argumentation practices in the classroom.[26] As students are put in the position of articulating and defending their ideas in the face of evidence, they are able to move toward more robust explanatory models and deeper understandings of phenomena.

Each PET activity is divided into periods of carefully structured and sequenced small-group experimentation and discussion and includes organized and facilitated whole-class sharing of ideas and answers to questions. In the small-group discussions, students are given many opportunities to articulate and defend their ideas. Even as early as the *Initial Ideas* section of an activity, students can engage in discourse regarding their intuitions about the physical world. During the whole-class discussions in *the Summarizing Questions* section, students can compare the ideas they developed within their group with the ideas developed in other groups. This interaction can reinforce their confidence in their ideas and, in cases where they are still struggling with possible ideas, can provide the opportunity to hear ideas or ways of thinking that are helpful to them.

E. Learning is facilitated through the establishment of certain specific behavioral practices and expectations

Classroom behavioral practices and expectations play a large role in science learning, both in what students learn and in how students learn in the classroom setting.[27,28] As students learn physics, they learn not only what is typically referred to as the canonical knowledge of the discipline (such as Newton's second law or the law of conservation of energy) but also how knowledge is developed within the discipline. For example, a student must learn what counts as evidence, that scientific ideas must be revised in the face of evidence, and that particular symbols, language, and representations are commonly used in arguments by experts in the field. Also, in the classroom, teachers and students must agree on their expected roles. These classroom expectations for how students are to develop science knowledge are known in the research literature as *norms*.[27] One such expectation might be that students sit quietly and take notes. An alternative norm might be established such that students are expected (by the teacher and by other students) to talk, to state their current understandings and support their ideas with explanations or evidence, and to challenge the ideas of others.

Regardless of the learning context and the extent to which the instructor attends to classroom norms, obligations and expectations are generated and maintained by the students and the teacher, and these norms greatly impact the type of learning that can take place. Therefore, this last design principle calls for explicit attention to promoting the types of norms that support the view of the learning process that is the basis for the first four design principles.

The PET classroom is a learning environment where the students are expected to take on responsibility for developing and validating ideas. Through both curriculum prompts and interactions with the instructor and their classmates, students come to value the norms that ideas should make sense, that they should personally contribute their ideas to both small-group and whole-class discussions, and that both the curriculum and other students will be helpful to them as they develop their understanding. With respect to the development of scientific ideas, students also expect that their initial ideas will be tested through experimentation and that the ideas they will eventually keep will be those that are supported by experimental evidence and agreed upon by class consensus.

III. DESIGN OF THE PHYSICS AND EVERYDAY THINKING CURRICULUM

We first describe the structure of the PET curriculum and then describe the structure of a typical chapter and of a typical activity. PET was developed over a 6-year period, and we revised the curriculum nine times before it was published.[7] Each draft included changes based on feedback from our pilot and field-testers.

A. Structure and goals of the PET curriculum

PET is a semester-long, guided-inquiry-based curriculum that focuses on interactions, energy, forces, and fields. The learning objectives address many of the benchmarks and standards for physical science enumerated in Refs. 1 and 2. There are two major course goals for PET. The content goal is to help students develop a set of ideas that can explain a wide range of physical phenomena and that are typically included in elementary school science curriculum. The learning goal is to help students become more aware of how their own ideas change and develop and to develop an understanding of how knowledge is developed within a scientific community.

The PET curriculum is divided into six chapters (see Table II), each of which consists of a sequence of five to eight activities and associated homework assignments designed to address one or more of the benchmarks or standards. Because most benchmarks or standards represent comprehensive ideas, each was broken down into a series of subobjectives, which serve as target ideas forming the focus of one or more individual activities. Each subobjective builds on its predecessors toward the development of the broader benchmark idea that serves as the main objective of a sequence of activities.

Table II. Summary of the PET curriculum.

Chapter	Title
1	Interactions and Energy
2	Interactions and Forces
3	Interactions and Systems
4	Model of Magnetism
5	Electric Circuit Interactions
6	Light Interactions

About three quarters of the activities and homework assignments focus on helping students learn the physics target ideas (and help achieve the content goal). The remaining activities and homework assignments focus on *Learning about Learning*, where students are explicitly asked to reflect on their own learning, the learning of younger students, and the learning of scientists. These are embedded throughout the curriculum and are important not only because they help students investigate the nature of science and the nature of learning science but also because they draw the instructor's attention to the design principles that guide the curriculum. These specific activities, as well as students' active engagement in all the content activities, help achieve the learning about learning goal.

As can be seen in Table II, interaction is a unifying theme in PET. Most interactions can be described either in terms of energy or in terms of forces. In an earlier curriculum development project directed by one of us,[29] the energy description of interactions was introduced before the force description because the students' intuitions about energy seemed more aligned with the physicist's ideas than were the students' intuitions about force. Because this approach seemed to work well, the PET project staff decided early on to also start with the energy description. In Chap. 1, students learn to describe interactions in terms of energy transfers and transformations, culminating in the development of the law of conservation of energy. Chapter 2 addresses students' ideas about forces and aims to develop a semiquantitative understanding of Newton's second law. Students then use both energy and force approaches in Chap. 3 (focusing on magnetic, electrostatic, and gravitational interactions) and thereafter use either approach as appropriate throughout the remainder of the curriculum.

B. Structure of a chapter

The conceptual focus of Chap. 2 is on Newton's second law, at a level consistent with the AAAS Project 2061 benchmark:[2] An unbalanced force acting on an object changes its speed or direction of motion or both.[30]

To design a sequence of activities that would help students develop a deep understanding of this benchmark, we first reviewed the research literature on students' understanding of force and motion to determine the common ways that students make sense of their everyday experiences with pushes and pulls. For example, students often think that giving a push to an object transfers force to it that is then carried by the object until it eventually wears out.[31] They also tend

Table III. Target ideas and Chap. 2 activities for Newton's second law benchmark.

Target idea	Activity number
Interactions between objects can be described in terms of the pushes and pulls that objects exert on each other, which scientists call forces. Forces only exist while an interaction is taking place and is not transferred between the interacting objects.	1, 2, 2HW, 3, 4, 5, 8
When a combination of forces is applied to an object, the individual forces can be combined to determine a single "net" force that would have the same effect on the object's motion.	3HW, 7, 8
When a single force (or an unbalanced combination of forces) acts on an object at rest, the object will begin to move in the direction that the (net) force is applied.	1, 2, 3HW, 8
When a single force (or a net force due to an unbalanced combination of forces) acts on a moving object in the same direction as its motion, the object's speed will increase.	1, 2, 3HW, 7, 8
When a single force (or a net force due to an unbalanced combination of forces) acts on a moving object in the opposite direction to its motion, the object's speed will decrease.	3, 3HW, 5, 5HW, 8
When a single force (or a net force due to an unbalanced combination of forces) acts on an object, the rate at which its speed changes depends directly on the strength of the applied force and inversely on the object's mass.	6
If no forces (or a balanced combination of forces) act on an object, its speed and direction will remain constant.	3, 6HW, 7, 8

Note: HW: Target idea is addressed in a homework assignment that follows the indicated activity.

to think that if they observe an object moving, there must be a force in the direction of motion causing it to move and that constant motion requires a constant force.[32] We then teased out these ideas into several smaller subobjectives, which then served as target ideas that became the focus of one or more individual activities. Table III lists the target subobjectives (target ideas) for Chap. 2 and the activities and homework assignments associated with them.

C. Structure of an activity

Each activity in PET consists of four sections: *Purpose*, *Initial Ideas*, *Collecting and Interpreting Evidence*, and *Summarizing Questions*. We will describe each section in the context of the first activity in Chap. 2. The two main purposes of Chap. 2, Act. 1, are to help students begin to work out the differences between energy and force (two ideas often confounded by students) and to begin thinking about the relation between force and change in speed, which is the essence of Newton's second law. (Although it would be more accurate to focus on the relation between force and change in velocity, we have chosen to focus on speed rather than velocity because the wording of the Newton's second law benchmark focuses only on changes in speed.[33])

The *Purpose* section of Chap. 2, Act. 1 first reminds students that they described interactions in terms of energy in Chap. 1 and tells them that they will now describe the same interactions in terms of forces. The key question of the activity, "When does a force stop pushing on an object?" is posed after the term "force" is defined as a push or a pull.

In the *Initial Ideas* section of Chap. 2, Act. 1, students' prior knowledge is elicited as they imagine a soccer player giving a ball a quick and powerful kick, projecting the ball straight outward along the ground. They are asked to draw pictures of the ball during the time the player is kicking it and after the ball leaves his foot. On each picture students are asked to draw arrows representing forces they think might be acting on the ball at those times, to label what those forces represent, and then to explain their reasoning. Students first answer this question in small groups and then share ideas in a whole-class discussion, ending up with a variety of plausible ideas about possible forces on the soccer ball both during and after the kick.

Students spend the majority of their time working in small groups on the third section, *Collecting and Interpreting Evidence*. In this section, as the name implies, they conduct experiments and interpret the results. For Chap. 2, Act. 1, this section begins by asking students: Is the motion of a cart after it has been pushed the same as during the push? In this experiment students give a low-friction cart short, impulsive pushes with their fingers (both to start it moving and also while it is in motion) and observe the motion and the speed-time graph[33] generated using a motion sensor and appropriate software. The students are then asked to consider a conversation between three hypothetical students, Samantha, Victor, and Amara, each of whom expresses a different idea about what happens during the times when the hand is not in contact with the cart. Students indicate with whom they agree and explain their reasons.

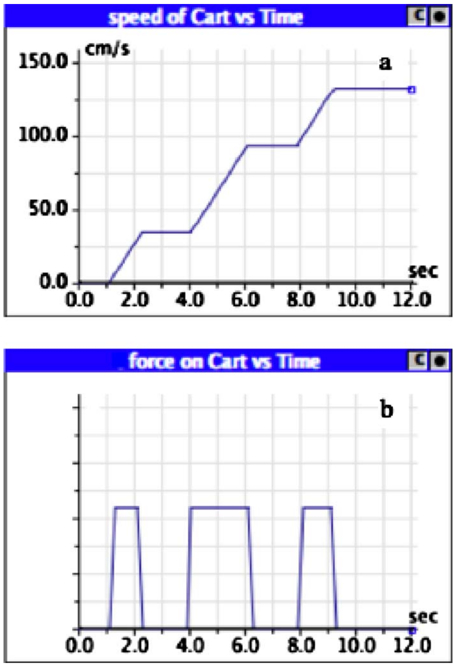


Fig. 1. (a) Computer simulated speed-time graph and (b) force-time graph. Students were first asked to predict the force-time graph from the given speed-time graph. They then compared their prediction with the computer-generated force-time graph.

Samantha: "The force of the hand is transferred to the cart and keeps acting on it. That's why the cart keeps moving."
Victor: "The force of the hand stops when contact is lost, but some other force must take over to keep the cart moving."
Amara: "After contact is lost there are no longer any forces acting on the cart. That's why the motion is different from when it is being pushed."

Next, students are shown a computer-generated speed-time graph [see Fig. 1(a)] and are asked to indicate the times on the speed-time graph when the hand was pushing on the cart. Then they are asked to sketch the general shape of a corresponding force-time graph that represents how the force applied by the hand was behaving over the same time. Following their predictions, students run an applet that simulates a cart moving along a track and press the spacebar on the keyboard each time they want to exert a "push" on the cart. The simulator generates the corresponding speed-time and force-time graphs (see Fig. 1). (These graphs represent only the force exerted on the cart by the push and do not include friction or any other forces.) They are then asked a sequence of questions aimed at helping them make sense of the force-time graph and its connection to the speed-time graph.

The final section of the activity, *Summarizing Questions*, is intended to provide opportunities for students to synthesize their evidence to address the key question and to compare their initial ideas with their end-of-activity ideas. Students answer the questions first in their small groups and then share answers in a whole-class discussion. For Chap. 2, Act. 1, the first summarizing question focuses on what happens to the motion of a cart during the time that a hand is pushing it. The second summarizing question asks whether the force of the hand is transferred to the cart during the interaction and continues to act on it (a common initial idea). The last two questions focus on what happens to the cart after the hand loses contact with it and ask students what they think is transferred during the interaction.

Much of what we have described seems straightforward. However, because of the role of students' prior knowledge in learning and the complexity of the learning process, students' conversations tend to be quite interesting. We use the case study in Sec. IV to illustrate how students actually construct knowledge with the PET curriculum.

IV. CASE STUDY: STUDENT LEARNING AND THE DESIGN PRINCIPLES

In this section, we describe a case study involving actual students working through the three main sections of Chap. 2, Act. 1.[34] By focusing on a small group of three students (the focus group), as well as on the entire class, we illustrate how the five design principles played out in practice.

A. Context of study

This study was done in a large state university in the southwestern part of the United States. As part of their undergraduate degree, prospective elementary teachers are required to take an inquiry-based physical science course, which in this case was PET. The class met for two 140-min sessions per week. Thirty students were enrolled, mostly females in their senior year, about half of whom had taken a high school physics course. The three students selected to be in the focus group were chosen mainly because of their willingness to verbalize their ideas and to be videotaped. In terms of their final course grades, none of the three focus group students were in the top sixth of the class, but all of them were in the top half of the class (out of 32 students).

We videotaped the selected group throughout the second chapter of the curriculum and collected their workbooks, homework assignments, and exams. Here we focus only on their interactions during the first activity in the chapter. The three students, Deli, Karin, and Ashlie (all pseudonyms), spent about 150 min on the activity, over two class periods.

The following transcript excerpts are intended to show how the students in the focus group were struggling in their attempts to make sense of the phenomena and to emphasize how the curriculum and class structure together provide opportunities for students to make their evolving ideas explicit and subject to critique by fellow students. Although the reader may wonder whether these students ever reached a reasonable understanding of Newton's second law, we provide evidence in Sec. V that they did.

B. Initial ideas

On the first day of Chap. 2, Act. 1, the group began their discussion of the *Initial Ideas* questions. Delia and Karin expressed many useful prior ideas and intuitions. For example, both students agreed that in a soccer ball kick, the foot exerts a force on the ball during the kick and friction is the force that slows the ball down. They also tried to make direct connections with what they had learned about interactions and energy from Chap. 1. The following excerpt illustrates how the students used prior knowledge in the discussion. At first they tried to apply energy ideas from the previous chapter to the soccer ball question, replacing chemical (potential) energy with chemical force and motion energy with motion force. (Ashlie was absent during the first discussion in the following, and another student in the class, Barb, replaced her.)

We use ellipses to indicate where we have left out a segment of the transcript for brevity. Descriptive comments are shown in brackets [ ], and a slash represents moments when two students are talking at the same time. The numbers in the first column are included for easy reference to specific statements made by the students.

1	Karin	The foot exerted a force on the /ball.… Now, what kind of force do you think?…
2	Barb	Yeah, it would be the same [like with energy], but we're just calling it a force now….
3	Karin	Do you think it means like a chemical force or a motion force? Is that what it's meaning?
4	Delia	I think it's motion force, which is causing the ball to move, to go somewhere….
5	Karin	Remember before [in Chap. 1], like if our hand pushed the cart it was a stored… [potential], uh, energy.… Cause what I was thinking, if we were going back to what we learned before, you know with the energy, I was thinking like, okay, the foot was exerting a chemical force on the ball, which in turn, you know, increases the motion in, er, force of the ball.

The group eventually abandoned energy terminology, and in the ensuing whole-class discussion, they spoke only in terms of force. Three main ideas emerged from the subsequent whole-class discussion: The foot exerts a force on the ball during the kick; this force continues to act on the ball after the kick, keeping the ball moving forward; and other forces such as gravity and friction act on the ball as it moves forward. No judgments were made by the teacher or students regarding the correctness of these ideas. Instead, the variety of ideas provided motivation for the class to carry out experiments in the next section of the activity.

C. Collecting and interpreting evidence

This section begins with an experiment designed to help students answer the question: Is the motion of the cart after it has been pushed the same as during the push? At the beginning of the experiment, students give a low-friction cart a series of impulsive pushes and observe its motion along the track and the speed-time graph generated on the computer display using the motion detector. The graph made by the three students was similar to the idealized one in Fig. 1(a), and they were able to interpret the graph by making explicit connections between the features of the graph (the upward-sloped parts and the nearly horizontal parts) and what they had done to the cart. All three students wrote in their workbooks that when the hand was in contact with the cart, the cart sped up quickly, and when the hand was not in contact with the cart, the cart moved at a constant speed. At this point, the first day ended.

For the second day of the activity, the students began considering the hypothetical discussion among Samantha, Victor, and Amara about what happened after the hand lost contact with the cart (see Sec. III C). Delia and Karin tried to clarify what Victor and Amara were saying, in particular, whether motion after the push implied that there was a force acting on the cart. Ashlie initially supported Samantha because she thought that energy was transferred. However, Karin pointed out that they were talking about force, not energy. At the end of the following transcript, Karin reminds the group that they don't have to reach a consensus at this time and that they will soon perform an experiment to help them figure it out.

6	Karin	I think Victor's right. Who do you think?
7	Ashlie	I was going to say that Samantha was right.
8	Delia	…Amara's saying that she's not saying there's no motion. She's just saying it's different.
9	Karin	No, no, so you're saying that just because there's motion, that doesn't mean there's any force.…
10	Delia	[To A] Why do you think Samantha's right?
11	Ashlie	Um, because I'm thinking of, as far as energy transfers, the energy that's being transferred is still with the cart.
12	Karin	It's force. We're not doing energy. Its force transfers. We're not talking about energy.
13	Ashlie	Okay, force transfers. Well, I'm saying the transfer is still with the cart, so, yeah, that's why I thought she was right, but I could be totally wrong.
14	Delia	I mean, what you're saying makes sense to me too.
15	Karin	I don't think we have to answer it as a consensus of the group, do we? … It doesn't have to be right. We're going to be doing an experiment to figure it out anyway. I'd say, just go with your initial thought, and whatever your initial thought is, we'll figure it out.

This discussion illustrates how all five of the design principles in Table I come into play. Ashlie's initial interpretation of Samantha's idea about force transfer was in terms of energy (line 11) that she had learned about in Chap. 1 (design principle 1). Karin's reminder that they were talking about force, not energy (line 12), helped Ashlie distinguish between the two (line 13). Karin's comment at the end of line 15 suggests the students recognized that learning will take some time (design principle 2) and that it was okay to not fully understand something in the midst of the learning process because they would eventually perform experiments (design principle 3) to help them figure it out for themselves (design principle 5). Finally, the transcript shows students engaging in collaborative discussion and respecting (line 14) and clarifying one another's ideas (line 9, design principle 4).

At the end of their discussion, the students wrote their ideas in their notebook. Karin agreed with Victor because she believed there was another force that kept the cart moving besides the initial push of the hand. Although Delia initially was inclined to agree with Amara, she ended in agreement with Victor for reasons similar to Karin's. Ashlie justified agreeing with Amara by claiming that the cart remained at a constant speed after the push because there was no longer any force changing its motion, an idea aligned with the physicist's view.[35]

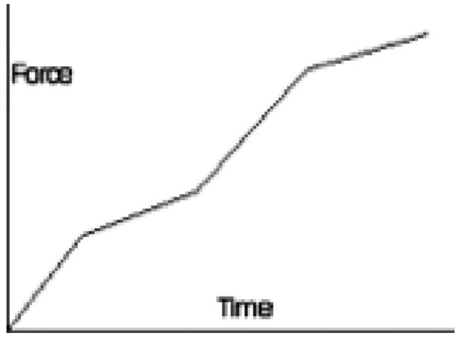


Fig. 2. Karin's predicted force-time graph corresponding to the speed-time graph shown in Fig. 1(a).

Immediately before producing the simulated force-time graph, students considered the simulator speed-time graph that represented the motion of the cart with three successive pushes [see Fig. 1(a)]. After a brief discussion in which the students correctly identified the intervals on the speed-time graph corresponding to the hand pushing on the cart, they spent over 6 min considering what they thought the corresponding force-time graph would look like. For brevity, we comment just on Karin's ideas. She struggled with trying to understand how to represent friction and/or gravity on the force-time graph—forces that she believed were acting on the cart after each push and that would be consistent with Victor's idea. The force-time graph she sketched in her workbook is shown in Fig. 2. She apparently assumed that the slope of the graph, rather than its ordinate value, corresponds to the amount of force acting on the cart, and thus she represented more force acting on the cart during the push and less force acting on it between pushes by drawing steeper slopes during the pushes and less-steep slopes between the pushes. She expressed uncertainty but thought that eventually she would be able to figure it out.

The group then ran the simulator to generate the speed-time and force-time graphs for the three successive quick pushes. They spent about 30 min trying to make explicit connections between their pressing and releasing the keyboard spacebar (which generated "pushes" on the simulated cart), the resulting speed-time graph and the resulting force-time graph (see Fig. 1). At the end, they all wrote in their workbooks that the force was not acting on the cart during the time that the speed was constant. Delia wrote: "No, the simulator force-time graph did not agree with my prediction. Once the cart is being pushed there is force acting on it and once it is released there is no force anymore, and I agreed with Victor [who] believed that there was another force that acted on the cart which kept it moving." Karin wrote: "The simulator did not agree with my prediction. It showed that there was no force on the cart after it was pushed. I had agreed with Victor in saying there was another force on the cart at that time. New ideas: There may be another force acting on the cart but it is not significant when discussing the pushes. I have switched to Amara's ideas." Ashlie wrote: "Yes. In the beginning I was going to agree with Samantha but then I was reminded by my teammate that we are now talking about forces not energy; after that I agreed with Amara."

The discussion further illustrates how the five design principles come into play. Karin's belief that there was another force present after the ball left the kicker's foot influenced both her predicted force-time graph (Fig. 2) and her interpretation of the simulator force-time graph shown in Fig. 1(b) (design principle 1). The significant time the group spent on predicting and then making sense of the computer-generated force-time graph for the three pushes suggests the complexity of the situation and how the activity guides them through the process (design principle 2) by focusing their attention on the simultaneous comparison between the kinesthetic experience of pressing the spacebar and the speed-time and force-time graphs that are generated (design principle 3). Much of the discussion within the group was to clarify how they were interpreting the graphs and connecting those interpretations to the previous discussion between the three hypothetical students (design principle 4). Finally, the effort put forth by the group in trying to understand the graphs suggests that they understood their role was to make personal sense of the phenomena and to take the reasoning of their peers seriously even when it was different from their own reasoning, sensing that the curriculum would eventually help them if they could not resolve the issues themselves (design principle 5).

D. Summarizing questions

The final section of an activity is *Summarizing Questions*. In our case study, it included the following questions: "Do you think the force of the hand was transferred from the hand to the cart during the interaction and then continued to act on it after contact was lost? What evidence supports your idea?" We expected these questions to generate much discussion within the group and the class because they explicitly address the difficult issues involving the relations between force and motion and between force and energy that are at the heart of the activity. The focus group did struggle with their answer to these questions, and the same issues also emerged during the subsequent whole-class discussion.

A student (S1) from another group began this discussion by describing how she and her group were confused. She initially thought that the force was transferred and stayed with the cart, although the simulator graph suggested otherwise. She then thought there was not any transfer of the push from the hand to the cart and that perhaps the transfer had something to do with energy not force, but she was very uncertain. She later sought help from the class.

16 S1 But as I got to thinking about it, I got more confused…. I thought it had something to do with some type of energy or something and not a force, and we didn't really know and we were hoping that someone might have some other way to explain it to us.

Rather than respond directly to her confusion, the teacher asked the class for further comment, and Karin and then Delia shared their own confusions. Karin still believed there was another force acting on the cart after it was let go, but was troubled because she found no supporting evidence from the activity. Delia didn't understand how there could be motion without a force pushing on the object, and was confused because the simulator-generated force-time graph didn't show any force even though the cart was still moving.

17 Karin I don't understand. 'Cause, like I am not completely convinced through this experiment that there's not another force on the cart after…the hand has let go of the cart. I understand on the graph like she was saying, after you let go, there's, on the graph, there's nothing in that point in time when the cart is moving at a constant speed, you know you're not touching it anymore, that shows no net force. Um, but I'm not completely convinced there's not something else acting on it. So, I don't know how to, I don't know how to back that up with evidence, except that this hasn't convinced me of that, so I don't know. That's why I'm confused.

18 Delia I'm confused also.… When they're saying that the force of the hand was transferred from the hand to the cart during the interaction and then continued to act on it, I think it does. But then I have to write "no" because the graph is telling me otherwise. But I think there's still because if it was no more force, then why the cart keeps moving?…I don't know if there's a relationship between speed and force. I don't know. I'm confused.

Again the teacher asks the class if anyone can offer a suggestion for how to resolve this confusion. Student S2 then offers a distinction between force and energy, drawing on what she had learned in Chap. 1 about energy transfer. She suggests that the force actually pushes the cart, but that the cart's energy stays with it.

19 S2 Maybe since like we were doing energy before, when you give force to an object, I mean I don't know, maybe force creates energy and the energy continues but the force stops. So it would be like the force is actually pushing it but the energy stays with it.

The teacher does not validate this comment but merely queries the students about their thinking. It is apparent that not all are convinced, and so the teacher points out that it is okay for this issue to remain unresolved at this early point in the chapter.

The discussion of this summarizing question, coupled with those earlier in the activity, provides another illustration of how the five design principles play out in the PET classroom. Delia's labeling of "motion force" (line 4) in the *Initial Ideas* discussion, her support of Victor's idea in the *Collecting and Interpreting Evidence* section, and her admission of her confusion in line 18 suggest that her prior belief that motion requires force strongly influenced her thinking and learning during the entire activity (design principle 1). The fact that Karin (line 17) and Delia (line 18), as well as other students in the class (represented in line 16), continued to be confused about the distinction between force and energy and the relation between force and motion suggests that these issues are complex and require multiple opportunities to revisit them in various contexts before we expect students to make sense of them in a way consistent with the physicist's ideas (design principle 2). Moreover, even though Karin and Delia both understood the substance of the computer simulated force-time graph [Fig. 2(b)], their comments in lines 17 and 18 suggest they still had difficulty accepting its implication that there was no (forward) force on the cart after the initial push (design principle 3).

The *Summarizing Questions* section provided the opportunity for several students to articulate their ideas and confusions so that other students could address them or at least hear them (design principle 4). The whole-class discussion also provided evidence that norms related to responsibility for learning and for the development of scientific ideas had been established (design principle 5), at least in part. S1 in line 16 asked the class to help her resolve her confusion about whether force is transferred. Both Karin and Delia added their own confusions (lines 17 and 18). Finally, student S2 (line 19) responded with a plausible resolution. These student comments suggest that they expected ideas to make sense and they expected other students to help them resolve their confusions rather than depending only on the instructor. The teacher, in turn, promoted this class responsibility norm by deflecting questions to the class rather than answering them himself. Furthermore, Karin's concern about the lack of evidence to support her idea (line 17) suggests she expected that for ideas to be accepted, they needed to be supported by evidence.

These classroom norms did not happen serendipitously. Instead, they were partially established by the structure of the curriculum and partially established and maintained by the teacher and the students. If the teacher had intervened as soon as students showed signs of confusion, the students might not have felt the need to grapple with the issues or make sense of the phenomenon. Instead, they might have waited for the teacher to tell them the answer, resulting in less personal investment in their interactions with the tools and with one another.

After completing Chap. 2, Act. 1, the students went through the next activity, focusing on what happens when an object is subject to a continuous and constant force. Then they went through the rest of the activities and homework assignments in Chap. 2, where they considered forces applied in a direction opposite to the motion, friction, the effects of force strength and mass, and combinations of forces (see Table III). Despite the students' difficulties that emerged during Chap. 2, Act. 1, on the relation between force and motion, in the next section we provide evidence that the focus group students did eventually develop a good understanding of this relation. We also discuss the extent to which the PET curriculum achieved both its content and learning about learning goals (see Sec. III A).

V. COURSE EVALUATION

The case study we have described suggests there was considerable uncertainty within the focus group about the relation between force and motion following the first activity in Chap. 2. How did the students' understanding of this relation evolve during the chapter and the entire course? To help address this question, we look at the focus group students' performance on a relevant homework they did shortly after finishing the first few activities in Chap. 2, on the test following Chapters 1–3, and on a conceptual assessment administered at the beginning and at the end of the course.

Following Chap. 2, Act. 4, students were given a home-

Suppose a spacecraft is at rest in deep space, far from any stars or planets – so that no form of friction or gravity will act on it. The main engine, at the rear of the spacecraft, is fired for a period of 2 seconds (to start the spacecraft moving) and is then shut off.

What do you think the motion of the spacecraft will be like after the engine is shut off? Explain your reasoning.

Fig. 3. Homework question following Chap. 2, Act. 4.

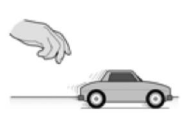
work assignment that focused on what the motion of a object would be like if it were subject to a short duration force and then the force was removed (see Fig. 3).

The responses of the three students in the case study suggested a reasonable understanding of what would happen in this situation. Karin wrote: "The spacecraft will continue to move forever without ever slowing down or stopping. Because if there is no gravity and no other forces acting on the ball, it has no reason to slow down. It can travel forever without any interactions from anything." Ashlie wrote: "The spacecraft would continue moving because there would be no forces acting on it to cause any change in its motion." Delia wrote: "The spacecraft will continue moving in the direction it was heading. If it has no interaction, or there are no forces acting on it, I believe it will continue to move at a constant speed."

The class test following Chap. 3 included questions from the first three chapters of the curriculum and was administered two weeks following the completion of Chap. 2. The question most relevant to the issues raised in the case study described a conversation between four hypothetical students about why a toy car (without a motor) slows down and comes to a stop after being given a quick push on a floor. The statements of one of the four hypothetical students reflected the scientific reason, and statements of the three others represented incorrect ideas that students commonly articulate. The students were asked to state which of the four hypothetical students they agreed with and to write a justification for their choice (see Fig. 4).[36]

The three case study students all chose the correct choice (Victor) and provided adequate justifications for their choices. Karin wrote: "I agree with Victor because when an object is moving, in this case, a car, there is an opposing force constantly acting on the object. Friction is present and is a constant, single unbalanced force acting in the opposite direction of the motion. This constant force causes the car to gradually decrease its speed and come to a stop. If there were no friction to oppose the car's motion, then the car would continue to travel at a reasonably constant speed." Ashlie wrote: "I agree with Victor because the force of friction is

A child playing with a toy car gives it a quick shove on a smooth level floor. (The car does not have any type of motor inside it.) After his push, the car very gradually slows down and stops.



Four students are discussing why the car very gradually slows down and stops, after the shove. Which student do you agree with (if any)? Please explain your reasoning.

Kristen: ***The car slows down because the force pushing it forward is getting weaker and weaker.***

Daryl: ***It slows because, after the shove, there is no more force to keep it moving.***

Samantha: ***It slows down because the forces acting on it are balanced, and balanced forces make a moving object come to rest.***

Victor: ***The car slows down because there is a force acting on it in the opposite direction to its motion.***

Fig. 4. One of the questions on the exam following Chaps. 1, 2, and 3.

1. A soccer goalie is practicing by punting a ball straight up into the air and then catching it again when it falls back down. Consider a moment just after the ball has been kicked, but is still moving upward (as shown in the picture). Which of the following forces do you think are acting on the soccer ball at this moment? (Choose <u>all</u> those that you think are present.) Briefly explain the reasoning behind your choice(s).

a) A force of gravity pulling downward.
b) A force from the kick pushing upward.
c) A force of gravity pushing upward.
d) A force pushing upward due to the motion of the ball.
e) Some other force (describe what you think it is below)

2. A hockey player uses his stick to maintain a <u>constant strength push</u> on the puck as he moves it across the smooth ice. Assuming that the effects of friction are negligible, which of the following choices best describes the motion of the puck while this constant strength push is acting on it? Briefly explain the reasoning behind your choice.

a) The speed of the puck will continuously decrease.
b) The puck will move at a constant speed.
c) The speed of the puck will continuously increase.
d) Something else – you describe it.

Fig. 5. The first two questions on the PET pretest and post-test.

acting on the car in the opposite direction of its motion. The force of friction would be a single unbalanced force which causes the car to slow down." Delia wrote: "I agree with Victor because the car slows down due to the force of friction that acts in the opposite direction of the car's motion which causes the car to slow down and stop."

A final piece of data that provided information on the focus group's understanding of the relation between force and motion was a conceptual test developed by the course authors and administered to the class at the beginning and end of the Spring 2003 semester. The pretest and post-test included five questions, the first two focusing on force and motion, the third dealing with multiple forces, the fourth on light and seeing, and the fifth on energy conservation. Each question presented a scenario and a question, several possible answer choices, and space for students to explain their reasoning. The first two questions are shown in Fig. 5.

During the Spring 2003 semester, the first author and another member of the project staff, a doctoral student, scored the pretests and post-tests of the students in the class. Responses to each question were scored on the basis of 0, 1, 2, or 3 points, according to a rubric designed by the project team. To receive a score of 3, a response needed to indicate the correct answer and include a full and appropriate justification. A correct answer, with an incomplete (but not incorrect) justification, received 2 points. A response including the correct answer, with either very little justification or with one that was partially incorrect, received 1 point. (A response that included both the correct answer and one or more incorrect answers, with justification for questions for which more than one answer was allowed, would have received 1 point.) To receive 0 points, the student could have chosen a wrong answer with justification or provided any answer (correct or incorrect) with no justification.

To give a sense of how the ideas of the three focus group students changed from the beginning to the end of the semester, we provide both their pretest and post-test responses to each of the two questions in Fig. 5 along with their scores. All three students had preinstruction ideas that were consistent with the belief that a force (from the foot) continues to act on the ball even after the ball leaves the foot (from question 1) and that an object experiencing a constant force moves with constant speed (from question 2). On the post-test, both Karin's and Ashlie's answers to the two questions were consistent with an understanding of Newton's second law. The results for Delia were mixed. For the first question, her answer on the post-test suggested she still believed the force from the kick remains with the ball after it leaves the foot. On the second question, her response is consistent with the idea that an object acted on by a constant strength force will continuously increase in speed.

For question 1 on the pretest, Karin circled answers (a) and (b) and wrote: "My reasoning for my choices is there is a force when a ball is kicked upward and gravity is always present so there is also a force pulling the boy downward." On the post-test she circled (a) only and wrote: Gravity is the only force acting on the ball pushing (pulling) it downward because gravity is a constant force. Also the force of the kick ends when the foot leaves contact with the ball. The only force is gravity." She received 1 out of 3 points on the pretest, and 3 out of 3 points on the post-test.

For question 2, on the pretest Karin chose answer (b) and wrote: "If the strength push is constant so is the speed to the puck." On the post-test she chose answer (c) and wrote: "The speed of the puck will continuously increase if there is a constant strength push on it because the push get [sic] the puck to move and then it is like the speed keeps adding on top of itself creating more speed even though the push is the same." She received 0 out of 3 points on the pretest and 3 out of 3 points on the post-test.

For question 1, on the pretest Ashlie circled answers (a) and (b) and wrote: "Gravity is a constant force. The force of the kick is acting against gravity." On the post-test she circled (a) and (e) and wrote: "The force of gravity is constantly acting on the ball. That is why the speed of the ball decreases and eventually moves in the opposite direction (down). Otherwise the ball would continue to rise. Under choice (e) she wrote: Force of friction of the air against the ball (but not very significant)." She received 1 out of 3 points on the pretest, and 3 out of 3 points on the post-test.

For question 2, on the pretest Ashlie chose answer (b) and wrote: "The puck will continue to move for a short time of [sic] the stick stops pushing it." On the post-test she chose answer (c) and wrote: "If an object receives a constant push (force) then its speed will continually increase as long as friction is negligible. Eventually the puck will move faster than the stick and the player will have to adjust it in order to maintain contact with the puck." She received 0 out of 3 points on the pretest and 3 out of 3 points on the post-test.

For question 1, on the pretest Delia circled answer (b) and wrote: "The force from the kick pushing upward is the force acting on the soccer ball because as the girl puts the force on the ball then it will go up and it depends how much force she puts on the ball that will determine how far upward the ball will go." On the post-test she again circled (b) and wrote: "As the ball moves upward just after it was kicked, the only force that are acting on the soccer at this moment is the force from the kick pushing upward because the ball continues to move upward. Therefore there is no other force at this time acting on it." She received 0 out of 3 points on the pretest and 0 out of 3 points on the post-test.

For question 2, on the pretest Delia chose answer (b) and wrote: "I believe that the puck will move at a constant speed because if the hockey player maintains a constant strength push than is logic that the puck will also move at a constant speed unless the hockey player chooses to change the strength." On the post-test she chose answer (c) and wrote: "As a constant strength push keeps being applied to the puck, then it will continuously increase. The puck will continuously increase when a constant force is applied as long as no other force is applied in the opposite direction." She received 0 out of 3 points on the pretest and 3 out of 3 points on the post-test.

The results from the homework assignment, the unit test, and the pre-post test suggested that the activities in Cycle 2 provided the opportunity for both Karin and Ashlie to develop an understanding of the correct relation between the force and motion. Although Delia displayed a good understanding of the relation between force and motion on the homework and unit test, she reverted to her initial non-Newtonian thinking on at least one of the postassessment force and motion questions. Even though the case study in Sec. IV C emphasized that all three of the students were struggling to make sense of the relation between force and motion during Chap. 2, Act. 1, in later assessments two of the students consistently applied Newton's second law appropriately and the third student did so on most of the assessments.

How representative were these three students with respect to the whole class? To help answer this question, we compared their average pre-to-post score changes on the two questions described in Fig. 5 to the average changes for the other 28 students in the class. For question 1, the average pretest to post-test score changes for the three focus group students were 0.7–2.0, compared to the other students for which the average pretest to post-test score changes were 0.8–1.4. For question 2, the average pretest to post-test score changes for the three focus group students were 0.0–3.0 compared to 0.8–2.3 for the other students. The pre-post data suggest that for the two questions, the average pre-to-post changes for the three focus group students were higher than the average pre-to-post changes of the remaining students. These results are consistent with their final course grades, which were also somewhat above average (see Sec. IV A).

Our data suggest how some of the force and motion ideas of the three students in the focus group evolved during the semester. In Sec. III A, we mentioned that the content goal for PET was to help students develop a set of ideas that can be applied to explain a wide range of physical phenomena. In the following, we provide some data about the impact of PET on students' conceptual understanding.

The students in the Spring 2003 class used an early draft of the PET curriculum. Based on feedback from pilot and field test implementations, the PET curriculum was revised several times over the following years prior to the publication of the first edition in 2007. To gather student impact information over this development period, an external evaluator administered two versions of a pre/post physics conceptual test to 45 different field-test sites between Fall 2003 and Spring 2005. The first version of the conceptual test, administered in Fall 2003 and Spring 2004, included the same five questions mentioned in Sec. IV, including the two force and motion questions shown in Fig. 5. Each question required students to choose an answer from several choices and justify their choice. One member of the external evaluation team graded all the questions on both the pre- and post-tests using the scoring rubric developed by the project staff and discussed with the external evaluator. Eleven different instructors were involved in administering the tests in 16 classrooms, and a total of 349 students completed both pre- and post-tests. Most of those instructors had previously taught courses with a pedagogical approach similar to PET, which is why they were selected to field-test the initial drafts of the curriculum. The mean pretest score across all sites was 21.2%, and the mean post-test score was 65.2%. The average normalized gain[37] for all sites was 0.56 with a standard deviation of 0.12. Values for the average normalized gain across sites ranged from 0.37 to 0.72. To determine the significance of changes from pretest to post-test, a paired *t*-test was done on total scores. For all sites, the change in scores from pre to post was significant at $\alpha \leq 0.01$.[10]

The second version of the pre-post test included the same five questions as the first version plus two additional questions involving electric circuits (because later field-test versions of the PET curriculum included additional activities on this topic). This version was administered during Fall 2004 and Spring 2005. Twenty-one different instructors were involved in administering the tests in 27 classrooms, and a total of 719 students completed both pre- and post-tests. Two of these instructors had also administered the first version of the pre-post test. Most of the rest had not previously taught a course with a similar pedagogical approach. These field testers also administered the pre-post assessment during their first semester of teaching PET. The mean pretest score for all sites was 24.1%, and the mean post-test score was 54.2%. The average normalized gain for all sites was 0.40, with a standard deviation of 0.13. Values for the average normalized gain across sites ranged from 0.14 to 0.62. As with the results from the first version, a paired t-test showed that for all sites the change in scores from pre to post was significant at $\alpha \leq 0.01$.[10]

In summary, the overall student responses to test questions were significantly higher (based on the scoring rubric criteria) from pre to post for both versions of the test and suggest that the PET curriculum helped students at diverse sites enhance their conceptual understanding of important target ideas in the curriculum, including Newton's second law, light, energy and electric circuits, thus achieving our content goal. As the field-test data suggests, classrooms taught by instructors who had previous experience teaching with a pedagogy similar to PET showed much higher average normalized learning gains (0.56 compared to 0.40) than classrooms with teachers who did not have that previous experience. Hence, we expect that the average normalized learning gains in the classrooms of the instructors in the 2004–2005 study would improve as the instructors gained more experience teaching the PET course. However, we could not test this conjecture because our evaluation study did not follow these teachers beyond their first implementation. Furthermore, there was considerable variation across sites in the average normalized gains in both the 2003–2004 and 2004–2005 studies, especially in the latter. Hence, although our evaluation data show that students made learning gains that were statistically significant, future instructors who might consider using PET in their classrooms need to be cautious in drawing conclusions from the data about what specific student learning gains they might expect to achieve.

We now discuss the extent to which the PET curriculum helped students become more aware of how their own physics ideas changed and developed and to develop an understanding of how knowledge is developed within a scientific community. Because the PET classroom pedagogy and curriculum were designed to promote more student responsibility for developing physics ideas and because there were many activities embedded in the curriculum to engage students in thinking about the nature of science and their own learning, one might expect that the PET course would have a positive impact on students' attitudes and beliefs about physics and physics learning. To gather information on this possible impact, the Colorado Learning Attitudes About Science Survey (CLASS) (Ref. 38) was administered in Spring 2007 in a separate study.[33] This survey consists of 42 statements about physics and physics learning. Students respond to each on a five-point Likert scale (from strongly disagree to strongly agree). The survey designers interviewed university physics professors with extensive experience teaching the introductory course about the questions and thus determined the "expert" responses. The students' responses are compared to the expert responses to determine the average percentage of responses that are "expertlike." Of particular interest is how these average percentages change from the beginning to the end of a course. A positive shift suggests that the course helped students develop more expertlike views about physics and physics learning. A negative shift suggests students became more novicelike (less expertlike) in their views over the course of the semester.

The CLASS was given to 395 PET and PSET (*Physical Science and Everyday Thinking*, a related curriculum) students from ten colleges and universities with 12 different instructors, in classes of 13–100 students.[11] Results show an average of 9% shift (+4%–+18%) in PET and PSET courses compared to average shifts of −6.1–+1.8 in other physical science courses (of 14–22 students) designed especially for elementary teachers.[6] Results for larger sections of introductory physics typically show shifts in traditional courses of −8.2–+1.5 in calculus-based physics (40–300 students in each course section) and −9.8–+1.4 in algebra-based physics for nonscience majors and premed students.[39] The nationwide PET/PSET study concluded that CLASS presurveys suggested that the students thought about physics problem solving as a process of arriving at a predetermined answer through memory recall and formulaic manipulation. Their answers on the CLASS postsurveys suggest that after experiencing PET/PSET, students were more inclined to think about physics problem solving as the process of making sense of physical phenomena. The curriculum focus on eliciting initial ideas, collecting and interpreting evidence, and using that evidence to support conclusions in the summarizing questions section was different from what they have experienced in other lecture-based college-level or high school physics courses. Otero and Gray[11] concluded that the rich experience of engaging in the scientific experiments and discussions allowed them to obtain a more personal connection to the physics content of the course.

VI. CONCLUSIONS

We have described how a set of research-based design principles was used as the basis for the development of the *Physics and Everyday Thinking* curriculum. These principles dictated the pedagogical structure of the curriculum, resulting in a guided-inquiry format that has been shown to produce enhanced conceptual understanding and to improve attitudes and beliefs about science and science learning. We also used the same design principles to develop *Physical Science and Everyday Thinking* (PSET).[8]

The curriculum development and associated research we have described are intended to assist other faculty in considering alternative methodologies not only for courses for nonphysics majors but also for all physics courses that frequently fail to include opportunities for students to connect their own sense-making about the central principles covered in the course with the physical phenomena from which these principles were derived. We presented some data to support claims about the efficacy of curricula, and we continue to study the impacts of the PET and PSET curricula in both small- and large-enrollment settings.[40]

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[a]Electronic mail: fgoldberg@sciences.sdsu.edu
[b]Electronic mail: Valerie.Otero@colorado.edu
[c]Electronic mail: sjrobinson@tntech.edu

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[35] There is no evidence in the full transcript as to why Ashlie ultimately agreed with Amara, although it is possible that she remembered this idea from a previous physics course. She did not bring up this idea in her discussions with the other two members of the group.
[36] The question showed images of the four students whose ideas are described. We omitted the images to save space.
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Inquiry-based course in physics and chemistry for preservice K-8 teachers

Michael E. Loverude,[1] Barbara L. Gonzalez,[2] and Roger Nanes[1]

[1]*Department of Physics, California State University Fullerton, Fullerton, California 92834, USA*
[2]*Department of Chemistry and Biochemistry, California State University Fullerton, Fullerton, California 92834, USA*
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We describe an inquiry-based course in physics and chemistry for preservice K-8 teachers developed at California State University Fullerton. The course is one of three developed primarily to enhance the science content understanding of prospective teachers. The course incorporates a number of innovative instructional strategies and is somewhat unusual for its interdisciplinary focus. We describe the course structure in detail, providing examples of course materials and assessment strategies. Finally, we provide research data illustrating both the need for the course and the effectiveness of the course in developing student understanding of selected topics. Student responses to various questions reflect a lack of understanding of many relatively simple physical science concepts, and a level of performance that is usually lower than that in comparable courses serving a general education audience. Additional data suggest that course activities improve student understanding of selected topics, often dramatically.

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I. INTRODUCTION

In the midst of ongoing national debates about education, there has been increased attention to the role of science departments in the preparation of preservice teachers. In the recent past, preparation of teachers, particularly those in lower grades, focused on general teaching strategies or "methods" without specific attention to the subject matter context in which they would be implemented. Science departments rarely paid any special attention to preservice teachers, viewing their preparation as the duty of education programs, and these students were rarely tracked or even noticed in courses serving broader student populations. However, as concerns arose about the general state of science education in K-12, many in the science disciplines have pointed out the importance of content knowledge for teachers, and the fact that science departments are best qualified to influence this content knowledge. In California, as elsewhere, teaching science content is the responsibility of science departments, not of the college of education. And yet, until recently, most science content departments paid little attention to the special needs of preservice teachers. The role of science departments in the preparation of teachers has grown to be an important focus of professional societies and faculty in the physical sciences [1].

It should be noted that there is little conclusive evidence of the impact of teacher content knowledge on student achievement in science. The published research is at best ambiguous, as noted by Wilson *et al.* [2], and what research there is typically does not directly measure teacher content knowledge, rather using markers like courses and degrees completed [2]. For example, Goldhaber and Brewer performed an econometric analysis on the NELS:88 data set that linked students to specific classes and teachers, finding that teachers with baccalaureate degrees in science were associated with higher student science test scores [3]. In a later study, though, Goldhaber and Brewer reported no impact of science degrees on student achievement. Other studies provide similarly contradictory signals [4]. In one widely cited study, Monk found a positive and statistically significant relationship between the number of science and math courses taken by teachers and gains in student performance, though with diminishing marginal returns or threshold effects [5]. Confounding this result, Monk also reported for sophomore students enrolled in a high school physical science course a *negative* relationship between the count of undergraduate physical science courses taken by a teacher and student performance on the National Assessment of Educational Progress in science.

Several authors have also suggested that preparing teachers requires more than just content knowledge, but also attention to pedagogical issues that are discipline-specific. Shulman supports the importance of subject matter knowledge in the preparation of elementary teachers, but further argues that subject matter knowledge must be integrated with discipline-specific "pedagogical content knowledge [6]." In the context of mathematics, Ball and others have developed this idea further, with one study showing connections between teacher scores on a measure of "mathematical knowledge for teaching" and student gain scores [7].

In light of the importance of subject matter knowledge, it is troubling to note how little experience many K-8 teachers have with certain disciplines, particularly math and the physical sciences [8]. We have performed surveys of students in courses for preservice teachers at our university in which they were asked to report all high school science courses ($N = 124$). While the data do not constitute a formal study of student content knowledge, they do give some sense of student science preparation. About 20% of the students reported a strong background including three or more years of science with at least one honors or advanced placement (AP) course. Only a third of the students reported taking any high school physics course. In addition, 40% reported only two years of high school science, the bare minimum to satisfy requirements. A review of courses taken by multiple-subject credential candidates at our university between Spring 2005 and Spring 2009 shows similar trends, revealing that at best 20% had completed a college physics or chemistry course [9]. Even if preservice teachers do take science content courses, the research on what most students learn in those courses is not encouraging [10]. In this paper we describe one local response to these issues.

II. LOCAL ENVIRONMENT AND CONSTRAINTS

Any curricular change is of necessity situated in a local context, and the context will impose constraints and challenges. In some cases, the issues will be of a general nature so that solutions can be widely generalizable. Other constraints are likely to be idiosyncratic and a function of local circumstances that are not likely to be repeated in other institutions. California has a number of specific requirements for preservice teachers that may be unusual.

A. California State University Fullerton (CSUF) environment

California State University Fullerton (CSUF) is a regional comprehensive university in southern California. CSUF primarily serves students from Orange, Los Angeles, and San Bernardino counties. With 36 262 students as of Fall 2009, CSUF has the largest enrollment of the 23 campuses in the California State University (CSU) system, and the second-largest enrollment of all California universities. Until recently, the CSU system by state law did not offer doctoral degrees; a joint doctoral program offered by San Diego State University in partnership with University of California San Diego is a notable exception. In 2005, a state law was passed that allows the CSU system to offer Ed.D. degrees, and CSUF is one of several campuses that offers the Ed.D. in educational leadership. CSUF, like most of the CSU campuses, offers bachelor's and master's degrees in a wide variety of fields including all of the sciences and mathematics.

B. State requirements for teacher preparation

In California, students seeking to teach grades K-8 pursue what is known as a *multiple-subject credential*. Undergraduate students do not major in education. Rather, they complete a bachelor's degree in a content discipline, typically Liberal Studies or Child and Adolescent Studies, and then enter a postbaccalaureate credential program. In order to qualify for the credential program, prospective teachers are required to master a series of content standards as articulated in a series of state documents [11]. Mastery of these standards is demonstrated by completion of a series of courses and/or standardized multiple-choice examination(s) [12]. Typically students complete lower-division courses in several disciplines, with each university offering different courses that meet these requirements. Most of these courses exist so that students may fulfill general education (GE) requirements and are not particularly targeted toward preservice teachers. The courses tend to be traditionally taught in large lecture settings, with little opportunity for interaction or discussion.

At CSUF, general education requirements for all students include one course in biology, one in a physical or Earth science, and one lab in any science. Students preparing for a multiple-subject credential have to satisfy additional requirements and typically take three lower-division courses, one each in biology, physical science, and Earth and space science, plus one upper-division course in either life or physical science. Students admitted to the fifth-year multiple-subject credential program often come from other four-year schools with different requirements and may not have completed all of the science courses. These three science content areas do not perfectly match the departmental structure in most universities, but they are tailored to California's K-12 science standards, particularly those for grades 6, 7, and 8, which cover Earth science, life science, and physical science, respectively. In particular, physical science standards include both physics and chemistry content, a matter that has particular implications for this work.

C. Undergraduate reform initiative

The willingness of science content faculty at CSUF to focus on nontraditional instructional strategies did not develop overnight. A gradual evolution of interest began in the early 1990s, with an increasing awareness of the results of discipline-based education research and the reformed pedagogy resulting from this research. Several members of the faculty of the College of Natural Sciences and Mathematics (NSM) at CSUF developed an interest in reforming the teaching of lower-division science courses. The Physics Department participated in several NSF-funded projects in this vein: CSUF shared oversight with Cal Poly Pomona for the Southern California Alliance of Mentors for Physics Instruction [13], was a test site for the Physics in Context curriculum developed as part of the Introductory University Physics Project (IUPP) [14], and was a participating site for the NSF-funded Constructing Physics Understanding Project (CPU) directed by Dr. Fred Goldberg at San Diego State University [15].

As the interest in the teaching and learning of science developed, several faculty in the College of NSM sought a means of institutionalizing reform. The College was awarded a grant from the National Science Foundation for the Undergraduate Reform Initiative (URI). The URI sought to reform the teaching and learning of science for GE and preservice teacher education courses as well as courses taken by science majors. Working groups were created to focus on these different student populations. At the same time, the entire university underwent a multi-year reevaluation of its GE program, leading to student learning goals in science, math, and technology that were phrased in terms of objectives more closely linked to assessment (as opposed to broader and more vague statements of purpose). This effort created an opportunity to revise existing courses and develop new ones that were aligned with the newly developed learning goals. The initial efforts of the URI working group to reform foundation courses led to the nationally recognized reform of the entire curriculum in the Department of Biological Science [16].

D. Project ConCEPT

Coincident with the URI, Roger Nanes developed an NSF-funded project titled Contextual Coursework for Elementary Pre-Service Teachers (ConCEPT). ConCEPT was a collaborative effort with five local community colleges to develop inquiry-oriented lab-based courses in the sciences for future elementary teachers that would be better matched than traditional lecture courses to the special needs of this unique population. The primary pedagogical goals of ConCEPT were (1) to focus on the nature of scientific inquiry, i.e., how to pose questions, gather evidence and draw conclusions based on evidence, (2) to model collaborative instructional methods adaptable to the elementary classroom, and (3) to break from traditional theoretical and abstract science courses and focus on teaching science in the context of real-world, interdisciplinary problems.

The three ConCEPT courses were intended to serve as a required nine-unit cross-disciplinary package that would fulfill science content requirements for entry to a multiple-subject teaching credential and provide a strong disciplinary background in biology, Earth science, physics, and chemistry. Two of the courses, ‘‘Biology for Future Elementary Teachers’’ and ‘‘Earth/Astronomical Science for Future Elementary Teachers’’ were developed as single-discipline courses, but Physics/Chemistry 102, ‘‘Physical Science for Future Elementary Teachers’’ (hereafter referred to as Phys/Chem 102), is taught jointly by two departments, Physics and the Department of Chemistry and Biochemistry. This structure was motivated by the fact that GE science requirements at CSUF are, as noted above, divided between the categories physical science, Earth and astronomical science and life science, and that content standards for teachers and K-12 students follow a similar split. In Phys/Chem 102, one instructor from each department is typically assigned to the course, though one or both may be a part-time lecturer. In a few instances at CSUF, graduate students with career goals as teachers have been assigned to teach the course, but have been paired with a faculty member with experience in the course.

Each of the three ConCEPT courses is taught in a weekly six-hour lab format. There is typically no lecture; rather, students work in small groups on carefully structured learning activities. Because of the lab format, enrollment is limited to 26 students per section, compared to the 75–125 student lectures common to the more traditional general education courses in these departments. Some content for these courses was adapted from national curricula and some was developed locally, often in collaboration with two-year college faculty from the partner institutions [17]. While the biology and geology courses have their own compelling story lines, the focus for the remainder of this paper will be on the physical science course, Phys/Chem 102 [18].

ConCEPT emphasized learning science in context, a focus that was influenced by the Physics in Context thread of IUPP as well as the American Chemical Society’s Chemistry in Context curriculum [19]. Each of the courses was developed to include two or more story lines that would motivate the introduction of relevant science content. The intention is that students will see science as an interconnected discipline with real-world implications rather than a collection of facts and equations. For Phys/Chem 102 three contexts were chosen: global warming, focusing on the physics and chemistry of climate change, including heat and temperature as well as the interaction of light and matter; kitchen science, focusing on everyday aspects of chemistry and some additional topics from thermal physics, such as phase transitions and specific heat; and the automobile, focusing on kinematics, dynamics, and electricity and magnetism. Each topic is rich with difficult content, and could easily occupy a full semester or more, but the units focus on introductory science that meets the California content standards. The duration of the units vary according to the topics that the course instructors select.

In order to maintain a balance between some of the more difficult concepts demanded by the story line and teaching scientific fundamentals, the curriculum proceeds with simple first attempts at answering basic questions. As concepts are introduced and developed, the story line is refined by adding more sophisticated concepts. For example, the story line for the global warming context begins with a diagrammatic approach to energy storage, transfer, and transformation using multiple representations [20]. It then proceeds to simple water mixing experiments, the analysis of which leads students to the fundamental differences between heat and temperature [21]. Students then conduct an important experiment that serves as a benchmark for later activities. They heat a black can containing water with a 100-W light bulb and record the temperature of the water from room temperature to thermal equilibrium, constructing a temperature-time graph. They also conduct a related experiment to produce a temperature-time graph for cooling of nearly boiling water in the same can. Students analyze the two graphs in order to generate the idea that the can must be radiating energy even in the heating experiment and formulate the concept of a dynamic equilibrium as a balance between the rates of energy input and radiated energy output.

After this benchmark experiment, students imagine how the experiment would differ if, for example, an insulator were wrapped around the heated can. The story line now spirals back and uses the black can experiment as a model in order to examine the thermal equilibrium of a ‘‘naked’’ Earth with no atmosphere—the light bulb is analogous to the Sun and the water can is analogous to the radiating Earth.

The story line then introduces the electromagnetic spectrum and attempts to refine the model attained thus far by considering the effects of spectral absorption by the atmosphere. Students first consider color formation by plastic filters as a simple model for spectral absorption. The atmosphere can then be compared to the insulator around the can considered in an earlier activity. Atmospheric absorption by greenhouse gases is related to prior activities involving absorption by colored plastic filters, leading to discussion of the greenhouse effect and its effect on global energy balance.

In principle, the contextual approach has the advantage of presenting concepts as needed, and we feel that the approach closely emulates the scientific process, with continual refinement of explanatory models. Consequently, students can more readily perceive the evolutionary and empirical nature of scientific endeavor. On the other hand, the context does sometimes require the introduction of content that is quite difficult for students. Previous research on the IUPP courses suggested that many students lost track of the story line or were dissatisfied at the level of resolution provided [22].

III. PHYSICS/CHEMISTRY 102

In this section, we will describe the course in some detail, including the course structure, pedagogical approach, course materials, and assessment strategies.

A. Course structure and pedagogy

Phys/Chem 102 is different from standard lecture courses, but is similar in structure to other lab-based inquiry-oriented courses. Students meet for six hours in either three two-hour or two three-hour meetings per week. (In the discussion that follows, one ‘‘hour’’ is really 50 minutes of class time.) The class is designated by the university as an activity format, so students receive three units, or one for every two class hours. This format is intermediate between lecture (1 credit per class hour) and lab (1 credit per 3 class hours). As noted above, GE requirements for all students include one course in biology, one in a physical or Earth science, and one lab in any science; Phys/Chem 102 can be an attractive option for students as the one course fulfills both the physical science and laboratory requirements.

All class activities take place in a dedicated lab classroom. There are six fixed tables in the room; each seats four or five students and has its own sink, gas, and electrical connections. The course does not formally incorporate any lecture instruction, and the intention is that most classroom time will involve students working together in small groups; the tables naturally group students into pairs but are angled to allow pairs to discuss as a whole table group. At the same time, the shape and orientation of the tables, and the fact that student seats are on wheels, allow students to face the front of the room, allowing short lectures or whole-class discussions. Enrollment in each class is capped at 26, divided equally between students enrolled in a section designated as Chemistry 102 and one designated as Physics 102, both scheduled for the same time and room. There is no practical difference between the two, as either satisfies the physical science GE requirement. In its inaugural semester, Spring 1999, only one class was offered, and enrollment increased steadily to a steady state of four classes per semester until Fall 2008, when two were cut due to severe statewide budget cutbacks.

While Phys/Chem 102 is not a methods course, the course does seek to model the way science can be taught in the elementary school where lecture is not a desirable option, i.e., with small-group hands-on activities and discussion, with very little whole-class lecture or discussion. The pedagogical philosophy of the course was influenced by curricula like *Physics by Inquiry*, and *Powerful Ideas in Physical Science* [23] as well as state and national standards for science education [24]. Activities include experimental measurements and other hands-on activities, as well as small-group discussions of pencil-and-paper activities. In a variety of activities, student groups prepare whiteboards to present their analysis of a situation or experiment to the entire class. Course activities emphasize conceptual understanding and science process skills, i.e., having students learn how to ask questions, make predictions, gather evidence, and make inferences. The emphasis in the materials is on conceptual understanding and science process skills rather than on definitions of terms or theory and computations.

The course does not claim to be a methods course, but many aspects of the course instruction reflect a view toward the needs of future teachers and the development of pedagogical content knowledge. The instructors explicitly inform students that the inquiry-oriented classroom is designed as a model of the way in which K-8 teachers might teach science. The equipment used for most course activities is simple and readily available, and some former students have indicated that they have used similar activities in their own K-8 classrooms [25]. The hands-on nature of the course is intended to give students experience in using and troubleshooting simple equipment, as well as being mindful of safety procedures, particularly important in the chemistry portions of the course. As will become clear in subsequent sections, several course assessments are designed to cause students to reflect on their own learning. For example, the students are assigned a MERIT essay in which they examine the change in their thinking on particular course topics (the term MERIT is an acronym and will be described more fully in Sec. III C, below). The essay and accompanying peer review process are intended to stimulate thinking about the process of learning.

B. Instructional materials

At the time that this project was started, there was no existing inquiry-oriented course that encompassed both physics and chemistry topics. (Since that time, other materials have been developed that also satisfy this need [26].) As a result, a new course and text were developed locally. The text used for the course is *Inquiry Into Physical Science: A Contextual Approach*, by Nanes [27]. The text follows a lab manual format and questions guide students through making predictions, observations, and explanations. Narrative text is not designed to be all-inclusive as it might be in a traditional textbook but, rather, is intended to provide the background material necessary to be able to understand and interpret in-class activities. It is intended that the majority of student learning will take place in the activities, not by reading the text. In fact, many new ideas are encountered in the activities that are not explicitly discussed in the text itself. Activities are integrated into, and work in tandem with, the narrative text. In order to give a detailed view of how the activities are structured, a sample activity from the Underpinnings chapter entitled ‘‘Understanding Density’’ is reproduced in the Appendix. This is a two-part activity designed to help students to understand mass, volume, and density, and part II of the activity is examined in detail in Sec. V C as one of the research questions discussed later in this paper. A CD is available with ancillary instructor materials that include complete question-by-question discussion of all student activities as well as complete equipment lists, an exam question database, sample syllabi, schedules and other course-related materials.

As discussed above, a contextual approach is used to develop the course content. A separate volume of the book is devoted to each of the three content units (global warming, kitchen science, and the automobile), and a context or theme is established through a real-world problem or issue to provide a story line. The story line is established by a leading question that defines the broad scope of the content. The science concepts that are covered are those necessary to contemplate an answer to the leading question, but are also chosen to reflect the physical science content standards for preservice teachers in California. The three volumes of the book would be well suited for a full year course in physical science but few universities have that luxury, and the separate volumes can be used independently in the more typical one-semester course. At CSUF, the course typically covers selected activities from two of the three volumes each semester. One of those two has always been the Kitchen Science volume (where much of the chemistry resides), with Vol. 1 or Vol. 3 chosen depending on the instructors' preferences. If Vol. 1 is not included, students begin the semester with the introductory Underpinnings and Energy chapters from that volume, which are included as appendices to Vols. 2 and 3. A one-semester physics-only course could use Vols. 1 or 3 or a combination of activities from both volumes.

A brief discussion follows of the course content included in each of the volumes. A detailed table of contents for each volume is included in the Appendix. The content of the ‘‘Global Warming’’ unit (Vol. 1) focuses on the thermal equilibrium of the Earth and is built around the leading question: ‘‘Is global warming really occurring?’’ The first chapter of this volume, entitled Underpinnings, provides fundamental ideas that are important throughout much of the content in all three units such as density, graphical analysis skills, ratios, and proportional reasoning. As noted above, the unit examines energy, heat and temperature, and thermal equilibrium. The last chapter uses experiments with colored plastic filters to learn about light and color, and extends these ideas to spectral absorption as a basis for understanding the greenhouse effect. The chapter ends with three paper-and-pencil capstone activities that highlight some of the key issues in the global warming debate. These activities present numerous graphs of global historical temperature and CO_2 data that aim to give students experience with interpreting graphical representation of data.

Volume 2, titled ‘‘Kitchen Science,’’ includes much of the chemistry in the curriculum, with the leading question, ‘‘Will science be a guest at your next dinner?’’ After activities about the nature of matter, students consider atomic structure and the periodic table. Also, this volume revisits heat transfer, initially examined in Vol. 1, and students study how conduction, convection, and radiation provide different ways to cook foods. Chemical bonding and the shape of molecules are included in this volume as well. In the last chapter of the unit, students perform activities to discover properties of water including latent heats of fusion and vaporization and specific heat. This chapter also covers the chemistry of carbohydrates, fats and proteins.

Volume 3 is titled "The Automobile" and the leading question is, "Will the gas-driven automobile ever become a thing of the past?" Chapters 1 and 2 focus on one-dimensional kinematics and dynamics, respectively, and end with impulse, momentum, and momentum conservation. The leading question comes into greatest focus in Chap. 3, Making Our Car Move, which examines various mechanisms for propulsion systems, from the internal combustion engine to electromagnetism to fuel cells. The chapter begins with activities to introduce students to combustion chemistry, heat of combustion, and the energy content of fuels. Students then study dc circuits, beginning with lighting a bulb, and then develop a model of electric current in a single bulb circuit before moving on to simple series and parallel circuits. Multiple battery circuits and the internal chemistry of batteries using electrochemical galvanic cells are the subject of some activities that follow. Finally, concluding experiments in which students study the compass needle galvanometer, dc motor, solenoid electromagnet, and electric generator inform about electromagnetism. In the final section of the unit, students perform paper-and-pencil activities covering air pollution, electric and hybrid vehicles, and fuel cells.

It is worth considering the ways in which the course curriculum contrasts with other research-based curricula for this population. In some ways, our course is more traditional, with more explanatory text accompanying the materials than is the case for comparable materials, and a coverage of larger number of topics, with the necessary corresponding decrease in depth. *Physics by Inquiry* [23], for example, is a very thorough and self-contained curriculum in which students build a deep understanding of target concepts almost entirely through their own experimentation and reasoning. Despite a deep admiration for this approach, we chose an alternative that is much less pure inquiry, in part due to state content requirements for courses for prospective teachers, which cover a much broader scope of material than *Physics by Inquiry* courses are typically able to do. Another comparable curriculum is *Physical Science and Everyday Thinking (PSET)* [26], which was developed after this course was already in place. In addition to the topic coverage, *PSET* differs from our course in its close adherence to a learning cycle and its explicit attention to themes of the nature of science and learning about learning.

C. Course assessments

Because the Phys/Chem 102 course has a different set of goals than more traditional courses, we have constructed course assessments in such a way as to measure and reinforce those goals. Student grades are based on course examinations, "Making Connections" homework assignments, MERIT essays, in-class performance tasks, and miscellaneous measures of class participation such as attendance and spot checks of activity sheets. Each of these assessments and the ways in which they complement course goals are discussed below. Specific examples of assessment instruments from each category are given in the Appendix.

*Examinations.—*To discourage any motivation to memorize content, all course examinations are given in an open book format—students are allowed to have their books, completed activities, and any additional notes that they may have taken during instructor presentations, whiteboard presentations, etc. Exams generally have two parts: explanatory multiple-choice and free-response questions. Multiple-choice questions always require that students provide an explanation for their choice, with a significant portion of the question score dependent on the quality of the explanation. Free-response questions require more detailed analysis and generally build upon the experiences that students had while doing in-class activities. These are often multipart questions that integrate target concepts that students are expected to have learned from the activities. An example of each question type is given in the Appendix.

*Homework: Making Connections.—*Homework assignments are called "Making Connections" and, as the name implies, are intended to make connections with previous activities and to provide additional exercises that reinforce and extend understanding of the current material. All of these exercises are provided in the text and examples are given in the Appendix.

*MERIT essay.—*The term "MERIT" essay is an acronym derived from the five goals of the assignment and is defined below in the following description taken directly from the course syllabus.

(1) **Metacognition.** A student who is metacognitive pays attention to the way they learn things. A MERIT essay should provide a brief commentary that traces and documents your learning of a new concept that you have learned in the laboratory. The essay is designed to force you to think about your own learning of a concept and *how* you learned it rather than demonstrating what you learned (which is the purpose of the other assessments in the course).

(2) **Evidence.** An important component of the MERIT essay will be to use scientific evidence from your own in-class work to document your learning.

(3) **Reflection.** The MERIT essay is intended to force you to go back over and reflect on what you have done to reach an enhanced understanding of your chosen topic.

(4) **Inference.** Making inferences from experimental data is essential to the learning process in science. The

MERIT essay should describe how you reached conclusions from your experimental data.

(5) **Transmission.** It is one thing to think that you understand something, it is yet another to transmit that understanding to someone else in writing. The MERIT essay will encourage written expression of your learning.

Although the definitions of "metacognition" and "reflection" may seem to overlap, our intention was to make connection between the five parts of the MERIT acronym and the five main categories for the assessment rubric. (See the Appendix.) In this scheme, what we label as metacognition is intended to focus on the student thinking itself, and what we label as reflection is intended to focus on what activities and exercises the students did ("what you have done") that might influence that thinking. Since that initial articulation of the assignment, we have added the peer review process, which typically provides students with an opportunity to reflect in a different way, by considering the learning pathway described by a peer.

The MERIT essay is a maximum of two typewritten pages, in which a student describes their learning pathway for a self-selected topic chosen from several instructor-defined topics. The development of this assignment was strongly influenced by the "Learning Commentary" assignment used by Fred Goldberg at San Diego State University. Students are asked to identify which activities helped to change their understanding and to specifically identify the questions and tasks in those activities and describe how the sequence of those activities and questions were key to their learning. This aspect of the essay is specifically intended to have students think about the relationship between their observations, written responses, and class discussions, and the ways in which these influence the development and modification of their models of the physical world. Students are required to attach to the essay copies of their work from the relevant activities, pretests and posttests, Making Connections assignments, and exams that document and trace the evolving changes in their thinking about the newly learned concept.

This assignment proves to be very difficult for students—they are more accustomed to trying to prove to the instructor what they have learned on an exam or in a descriptive term paper rather than performing a self-evaluation of how they have learned it. To help understand the focus of the essay, students are given at the outset a copy of an actual MERIT essay that had been turned in by a prior student, annotated with suggestions as to what the student might have done to make the essay more consistent with the goals of the assignment. A copy of an annotated essay is included in the Appendix, and, it is noted that this essay relates to the density activity that is reproduced in the Appendix.

The MERIT essay assignment includes three phases over an approximately three-week period—a first draft, a peer review, and a final draft. Students are given a week to write a first draft of their essay. This draft is then given anonymously to a classmate to review. At the time that they are given an essay to evaluate, students are given a list of criteria and a rubric (see the Appendix) that the instructor will use to assess the final draft of the essay when it is turned in. Using these criteria, the student takes one week to review their classmate's essay, to make comments and suggestions, and to assign what they would give as a grade for the assignment. This is a useful exercise for students who will be future teachers. This peer review is then returned to the original author and the instructor retains a copy of the peer review. Students then have an additional week to evaluate the comments made by the peer reviewer and choose the extent to which they wish to revise their essay. The revised essay is then submitted in final form to be graded by the instructor, using the same criteria and rubric used by the students in the peer review process.

In doing their peer review, students are instructed to make a careful and honest appraisal of their classmate's essay, but are told that the grade they assign their peer will not figure into the essay author's grade. The effort and care taken by the student in doing the peer review, as gauged by the instructor review of the retained copy of the peer-reviewed essay, does, however, affect the reviewer's MERIT grade. A student who merely identifies typographical and spelling errors will not score as high on the review component of the grade as a student who makes a serious effort to identify departures from the goals of the essay and makes serious efforts at suggesting improvements. Retaining the peer-reviewed essay also enables the instructor to note how serious an effort the essay author makes to evaluate and incorporate the suggestions made by the peer reviewer.

Performance tasks.—Performance tasks are an attempt at authentic assessment rather than paper-and-pencil tasks. As an example, the following task is given to students after they have completed studies of electric current and electric circuits. At this point in the course, students should understand that the intensity with which a bulb lights is a measure of the amount of electric current through the bulb. They have studied series and parallel circuits and are expected to understand that bulbs in series reduce and bulbs in parallel increase the total current drawn from the battery. Students are also familiar with a series battery and bulb combination configured as a "circuit tester" with test leads and its use to test for open, closed, and short circuits. This activity expects students to extend their thinking and use the brightness of the bulb in the circuit tester as a way to compare the current in several "mystery" circuits and to use this information to identify the circuits. The detailed instructions given to students to perform the task is given in the Appendix.

Another performance task requires students to determine the temperature of a sample of very hot water using a thermometer that has a scale with a maximum temperature of 50 °C. Students are required to first write down their plan and then execute the plan to determine the water temperature based on their prior experience in analyzing mixtures of hot and cold water. Since heat loss is a major source of error, students are not graded on the accuracy of their results. Rather, they are assessed based on the feasibility, simplicity, and uniqueness of their devised procedure, clarity of their written description, care in recording data, and their calculations and data analysis used to obtain their results. After completion of the task, in an instructor-led discussion, students are told the actual temperature of the hot water. The large difference between their measured temperature and the actual temperature allows for a discussion of the error introduced by heat loss and how it could have been minimized.

Class participation.—A small portion of a student's grade is based on attendance and on spot checks of the activity worksheets that students complete as they work through experiments in class. Although these activity sheets are not graded, they are periodically collected and reviewed for completeness. Students are thus encouraged not to leave questions unanswered as they work through the activities. Each individual activity in a batch of completed worksheets is given a small point allocation that is weighted with the attendance into the student's grade.

Grading.—All of the primary assessment instruments discussed above require the evaluation of written responses from students. Needless to say, this type of assessment is much more time-consuming than merely testing students with rapid response ''short answer'' types of questions. As noted above, each section of the course has a cap of 26 students, a number that makes assessment manageable for the grading tasks such as exams, performance tasks, and MERIT essay that occur relatively infrequently during the semester. Exams are constructed to have, typically, approximately three to five multiple-choice questions (each requiring a short written explanation of the chosen answer) and three or four multipart questions, with each part requiring a short free response. Experience has been that careful grading of 26 exam papers of this type might take about 10–12 hours. This is comparable to the time that would likely be required to grade four or five computational problems on a traditional physics exam where careful review is necessary to give students ''partial credit'' for their solutions. Performance tasks can be graded relatively quickly (1–2 hours for the entire class) because of a narrow focus on a single outcome from the students' in-class measurements. Because of the subjective nature of the MERIT essay, careful grading of a class set of essays can be very time-consuming, taking perhaps 15–20 hours. The strict requirement of a maximum length of two pages helps to keep the reading time manageable, but the most difficult aspect of grading the MERIT essays is maintaining consistency and adhering to the grading rubric provided to the students. This is addressed further below. The heaviest grading burden arising from the different assessments used in the course arises from the ''Making Connections'' homework assignments that students are required to turn in every 1–2 weeks. As for any physics course, if an instructor wants to include homework as part of the total course assessment, self-grading these regular assignments could require a prohibitive effort unless grading assistance is available. As discussed below (Sec. IV A), we have been fortunate so far to receive financial support for ''peer assistants'' in each section to grade homework assignments with the help of detailed answer keys and explanations provided in the instructor materials for the text. In many cases we have sample rubrics indicating how much credit should be assigned for common incorrect or incomplete answers. Our use of grading assistance has been only to grade homework—exams, performance tasks, and MERIT essays have always been graded by the instructor.

In addition to the labor-intensive aspect of the assessment instruments used in a course like Phys/Chem 102, one must be concerned with students' view of consistency and fairness in grading. As with all assessment procedures, transparency is crucial to develop trust in the grading process. Returning graded work in a timely way, indicating clearly the reason for assigned scores, and encouraging students to clarify questions about graded work in class or in office hours all help to develop trust. For the MERIT essay, which is more subjective than other assessment instruments, a sense of fairness is greatly facilitated by the way the assignment is administered. The fact that the students have the grading rubric in advance so that they are very clear about the grading criteria, the fact that they receive a sample essay that is annotated to help understand the nature of the assignment, and the fact that they receive feedback from a peer and are given the opportunity to make changes if they choose to all enhance student perception of fair assessment. In assessing the MERIT essay another strategy that enables the instructor to feel that the grades are reasonable while at the same time contributing to student perception of fairness is to read through all the essays while annotating with comments that are aligned with the rubric before putting point scores on any paper. Then, on a second pass, one can divide the papers into groups that fulfilled the goals of the assignment from best to worst and grades can then be recorded. Of course, the second pass takes much less time than the first because written comments are already on the paper, but this approach obviously adds to the time burden of assessing the MERIT essays. However, with all of the above considerations, we have not had student complaints about fair grading.

IV. QUALITATIVE AND PROGRAMMATIC MEASURES TO ASSESS THE COURSE

In a subsequent section we will describe research questions that we have posed in the context of Phys/Chem 102.

First, however, we will describe qualitative and programmatic measures of the success of the course and describe ongoing challenges.

A. Measures of success

The course is locally perceived to be a strong success and has achieved a number of important benchmarks: dissemination of course materials, increased enrollments, and acceptance by faculty in the College of Education. The course materials have been tested or adopted by several other institutions and are currently in use at three: Cal Poly Pomona, Santa Ana College, and Santiago Canyon College [28].

An important measure of success in the CSU system is enrollment, as revenues follow students. Student demand for the course has been strong, and the course has grown from only one 26-student section in Spring 1999 to four sections serving approximately 100 students per semester, until budget constraints as described below. Phys/Chem 102 has become institutionalized as one of the courses that satisfy the lower-division requirements for a Natural Science minor.

Our colleagues in the College of Education have received the course enthusiastically, seeing the course pedagogy as the preferred way to teach science content to future teachers. It is one of the required courses for students in the Streamlined Teacher Education Program (STEP), an integrated teacher education program that allows students to simultaneously earn a bachelor's degree and the preliminary teaching credential within 135 units (compared to the usual 120 units for a bachelor's degree plus 35 or more units for the preliminary teaching credential). As with the inclusion in the Natural Science minor, the STEP requirement bodes well for the continuing existence of the course.

The support from local sources has extended to significant financial commitments. The CSUF department of Chemistry and Biochemistry renovated an existing laboratory classroom to suit the instructional methods of Phys/Chem 102, and this room is now dedicated exclusively to the course. The course has received approximately \$21 000 in support from a variety of intramural sources to purchase equipment and supplies. In particular, the College of Education allocated \$10 000 from a Stuart Foundation grant to purchase notebook computers used for data acquisition in some of the experiments done in the classroom.

After the first year of Phys/Chem 102, a Peer Instructor program was created, with initial support coming from the Stuart grant in the College of Education. Each semester high performing students in Phys/Chem 102 were selected and hired to be peer instructors for the course the following semester. These students attended class on a regular basis as teaching assistants, interacting with students as they worked in their collaborative groups and also helping with administrative and logistical tasks including equipment setup. In contrast to a more formal Learning Assistant model, the training for these peer instructors was typically limited to a weekly meeting with course faculty focusing on course content and suggested instructional strategies [29]. This experience has proven to be extremely beneficial to the participating students, who improve their own understanding of the course material and have a chance to practice their teaching skills. Further, these students serve as useful role models and resources for students who are taking the course for the first time. Often students find the perspective of a peer who has recently learned material to be a useful supplement to that of more experienced instructors.

The Departments of Physics and Chemistry and Biochemistry continued to share support for the Peer Instructor program for two more years after the expiration of the Stuart grant. In 2005, we secured grant funding from the Boeing Corporation, which has totaled \$47 000 over three years. This grant funded the purchase of additional equipment and supplies as well as the continuation of the peer instructor program.

The peer instructor program has attracted a number of strong students and influenced some of them to change their career goals. For example, one student who served as a peer instructor for several semesters graduated and is now a full-time fifth grade teacher. She completed the Master of Arts in Teaching Science (MAT-S) degree at CSUF in part in order to be able to teach an evening section of the 102 course as a part-time instructor.

B. Challenges

While the course has largely been successful, there have been a number of challenges, some ongoing, that in some cases threaten the very existence of the course. The most significant issue is the cost of the course. Compared to the large lecture format, the small-group collaborative pedagogy makes the course very labor intensive and very expensive to run. As already noted, California has entered another cycle of budget cuts, and the cost of the course has made it a target for cuts.

Staffing the course can be difficult. Many full-time faculty are unwilling or unable to teach the course because they are not comfortable with the inquiry-based pedagogy. In addition, the joint nature of the course can be problematic for potential instructors. Though the content is relatively elementary, some instructors are not comfortable outside their own discipline: chemists are not used to teaching about electric circuits and physicists are not used to using glassware and teaching about chemical reactions. In some cases, assignment of part-time faculty has led to compromising pedagogical issues and the continuity of student experience.

Another staffing difficulty is related to student ratings of instruction. Some faculty in the course have found that average scores on student evaluations are lower than for other lower-division courses. Students are often unreceptive to the science content to start with and are not comfortable having to take a greater responsibility for their own learning. Strategies such as passive listening in a lecture, memorization, and reading and underlining in a textbook that may work in a traditional lecture class do not work well in this course. Students often express this dissatisfaction by saying: ‘‘I do not like it when the instructor answers a question with another question.’’ This type of student response is similar to that reported in the literature on reform efforts in science education [30]. Halpern and Hakel [31] reported that, although active learning strategies may result in significantly greater learning gains, the learning tasks may take longer and require greater student effort, may be less enjoyable for the student, and may lead to lower student ratings of their instructor. At CSUF, the retention, tenure, and promotion process for faculty relies heavily on student ratings of instruction, making Phys/Chem 102 a potentially risky teaching assignment for untenured faculty. Even experienced instructors may have a steep learning curve to adapt to the pedagogical demands of guided inquiry and some have experienced more student dissatisfaction than in comparable traditional courses.

V. RESEARCH QUESTIONS

As we have taught the course, we have sought to examine several aspects of the course in terms of physics and chemical education research. Data on students in the course have been presented as part of numerous presentations and papers. For the purpose of this paper, we will describe a subset of the research that we have conducted, with a view to research questions whose results will inform instructors and departments that are considering developing or adopting courses of this nature.

The primary research questions that we consider in the paper are as follows.

To what extent have prospective teachers entering university science courses mastered the K-8 California physical science standards that they will be expected to teach?

To what extent does student understanding of science content change as a result of instruction in this format?

How does the initial level of understanding for prospective teachers in this course compare to those in more traditionally taught physical science courses serving broader student populations?

In the sections below we will examine data bearing on these questions. While we have not performed strictly controlled experimental studies of student learning, we have gathered data on pretest and posttest instruments in this course and, where possible, given matched questions in Phys/Chem 102 and the comparable general education courses offered in physics and chemistry. A colleague has collected data on student responses to pretest and posttest questions while using this curriculum at another university [28]. Those data show conceptual gains in six different content areas and are broadly consistent with those that we report below.

In several of the examples below, we show comparison data from a CSUF general education physics course taught at a similar level. This course, which we describe as ‘‘Survey of Physics’’ or ’’the survey course,’’ is a fairly typical lecture course intended for a general education audience. Particularly important is to note that this course is often taken by prospective teachers instead of Phys/Chem 102 [8]. The course includes 3 hours per week of lecture instruction with either two or three weekly meetings. Currently there are two sections each semester of 70–90 students each. The course text is a locally produced set of lecture notes produced by R. Nanes, so it shares some influences with Phys/Chem 102 as well as the Conceptual Physics courses common for such a course level [32]. The course emphasizes conceptual understanding and covers much of the same material as the physics portion of Phys/Chem 102: underpinnings, energy, heat and temperature, global warming, kinematics and dynamics, and electricity and magnetism. The survey course does not require calculus or high school physics, and the most difficult mathematics used is ratio reasoning or very simple algebra. The majors of students taking this course span the university, though there are very few science, math, or engineering majors. Approximately a third of the students take a corresponding lab course.

The corresponding general education course offered in the Department of Chemistry and Biochemistry is also a survey course. There are usually two to three sections of the course taught each semester in a traditional lecture format for 60–100 students three hours per week in two or three weekly class sessions. The pedagogy for survey chemistry is fairly traditional and the preparation of prospective K-8 science teachers is not necessarily a factor in its curriculum. Prerequisites for the survey chemistry course are the equivalent of high school algebra and high school science required for admission to the university. The survey chemistry course does not fulfill requirements in chemistry for science majors; thus, most of the students are nonscience majors from across the university. A corresponding lab course fulfills the general education laboratory requirement, but its curriculum is not linked to the survey lecture course.

A. Example: Entering students’ understanding of mass, volume, and density

As we teach the various content areas in the course, we make an effort to document the initial level of student understanding, particularly of those topics from the California science standards that prospective teachers are likely to teach in their future classrooms. As an example, we present a small selection of sample data from questions on mass, volume, and density that we pose on an ungraded pretest given on the first day of class, as students begin

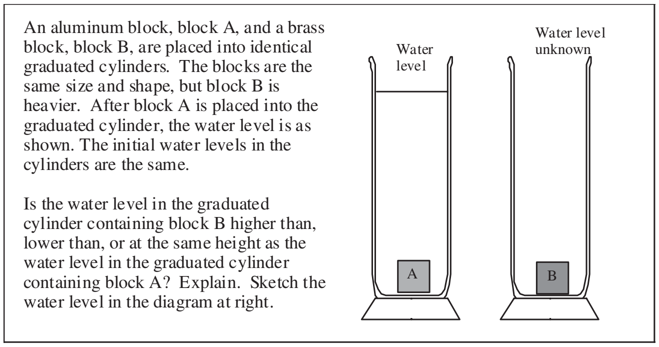


FIG. 1. Water displacement problem posed before instruction on an ungraded quiz in Phys/Chem 102 as well as a comparison course.

their study of the Underpinnings section. This pretest comes before any instruction in Phys/Chem 102, so it reflects the incoming knowledge of students. The California Science Standards require that students in grade 4 understand how to measure volume, and that students in grade 8 understand density and its relationship to sinking and floating behavior, so any high school graduate would certainly be expected to know this material [33].

The question illustrated in Fig. 1 is the first part of the ungraded pretest. Students are asked to compare the volume of water displaced by two blocks of the same size and shape but different mass. In order to avoid potentially memorized responses, the question is not phrased in terms of displaced liquid, but rather asks students to sketch the water surface in a container. The results on the water displacement problem are shown in Table I and are roughly consistent with those from previous studies [34]. A little more than half of the students answer correctly, with a large fraction of the students stating that the heavier block will cause a greater change in the water level. We also see a significant edge in performance among the students in the Survey of Physics course, which will be discussed in Sec. V D below.

Another portion of the first pretest is shown in Fig. 2. In this question, adapted from a similar problem on electric charge density, a solid block of plastic is cut into two smaller pieces [35]. Students are asked to compare the masses of the original block and the two parts, then to

TABLE I. Student responses to the water displacement problem (Fig. 1).

	Phys/Chem 102 CSUF 9 sections $N = 222$	Survey of Physics CSUF 3 sections $N = 151$
Same water levels (correct)	56%	72%
Heavier block displaces more liquid	39%	21%
Other incorrect or blank	5%	7%

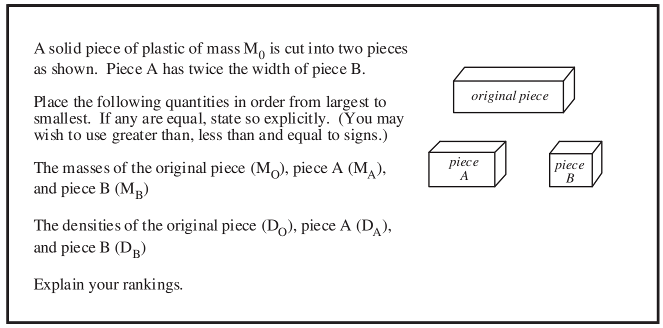


FIG. 2. ‘‘Broken-block’’ density problem posed before instruction on an ungraded quiz in Phys/Chem 102.

compare the densities of the three pieces. Students are expected to recognize that density is the ratio of mass to volume, and a characteristic property of materials, so that the three pieces will all have the same density.

As shown in Table II, the broken-block problem in Fig. 2 is quite challenging for students. Only approximately a third answer correctly. The largest group of students give answers in which the larger pieces have larger densities (i.e., $D_0 > D_A > D_B$). The explanations given by students in this category typically refer to the size of the object: ‘‘D_0 is the most dense because it is the largest piece.’’ A significant fraction of the students give exactly the opposite answer, in which smaller blocks have a greater density. A sample student response reads, ‘‘D_B is more dense than D_A because it is smaller in size and thus weighs less as well.’’ In addition, a number of the explanations supporting correct answers were incomplete or incorrect, seemingly reflecting a failure to recognize the definition of density as the ratio of mass to volume: ‘‘$D_0 = D_A = D_B$. The size does not change the density. It is the weight that changes it.’’

After the pretests, students complete several in-class activities on mass, volume, and density. (See the Appendix.) Students perform an activity that is essentially identical to the water displacement question in Fig. 1. In most semesters, we give additional ungraded quizzes after instruction including the questions from Figs. 1 and 2, to help students to document the progression of their understanding for the MERIT essay. After seeing a demonstration and observing the water displaced by two metal bars of the same volume but different mass, approximately 100% of the students answer the water displacement question

TABLE II. Student responses to the broken-block density problem (Fig. 2).

	Phys/Chem 102 9 sections ($N = 222$)
All densities equal (correct)	30%
Larger piece has greater density	54%
Smaller piece has greater density	12%

correctly. That is reassuring, but the demonstration is essentially the same physical situation as the pretest and posttest. The activity on density is not as closely related to the pretest question in Fig. 2. Students measure mass and volume for several objects constructed from a set of plastic cubes and measure masses and volumes for various samples of the same liquid, finding in each case that the ratio is very similar for samples of a given material. Shortly after completing these activities, approximately 80% of students answer the density question in Fig. 2 correctly.

In addition, we have posed a number of multiple-choice and free-response questions testing these concepts on course examinations, after students have completed homework on this material and used the idea of density in later activities. In several exam questions, students were asked to compare the density of a small chip removed from an object to the density of the larger object from which the chip was removed. In others, this concept was extended to the sinking and floating behavior of the objects. For example, see the multiple-choice question in the Appendix. Student performance on these questions in course examinations suggests very strongly that student understanding has improved. For example, on several different density-only questions posed over the course of three sections ($N = 78$), 94% of students answered correctly that the densities of a small piece and the larger body would be the same. Given the improvement over the success rate on the pretest, these data indicate that the Phys/Chem 102 course has a positive impact on student understanding of this topic. On the more involved questions involving sinking and floating ($N = 54$), 74% of students answered correctly that the larger and smaller objects would behave in the same way. Although we have not asked this sinking and floating question directly on a pretest, results in the next section illustrate that the connection between density and sinking and floating were quite difficult for students before the corresponding activities, with pretest success rates of under 35%.

B. Example: Student understanding of sinking and floating

In this section we refer to a study of student understanding of sinking and floating, described in greater detail elsewhere [36]. On a written pretest, students are asked a series of questions about a small sealed bottle containing pieces of metal shot. The pretest begins by asking students to consider a situation in which the bottle floats in a beaker of water. They are then asked to predict what would happen if a piece of metal were removed and the bottle were returned to the water. The problem continues with the question shown in Fig. 3, which we describe as the Shot problem. These questions were posed in Phys/Chem 102 as well as the Survey of Physics course, again at a point in the course before any explicit classroom instruction on the topic of sinking and floating (but after the instruction on

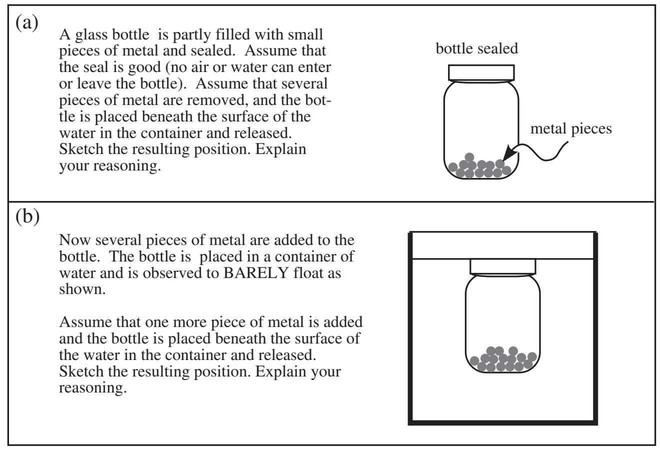


FIG. 3. The Shot problem. Panel (a) gives the initial setup and a preliminary question. Panel (b) is the part referred to in the text and data tables. This problem is given on an ungraded quiz in Phys/Chem 102 and a comparison course after instruction on density but before instruction on sinking and floating. This task is also now used as an instructional activity.

density described above). Results from the second part of Shot problem [Fig. 3(b)] are shown in Table III.

In contrast to most of the examples in this paper, student performance in Phys/Chem 102 and the survey course was very similar, with about a third of the students in each class answering correctly and about half giving the same common incorrect answer.

After some initial research, the curriculum for the Underpinnings section of Phys/Chem 102 was altered to include an activity based on the Shot task (see part 2 of activity 1.6.1 in the Appendix). First, the students examine the bottle filled with shot as it barely floats and predict how the system would behave in the water after a single piece of metal was removed. After discussion the instructor performs the demonstration. Very few students are surprised by this result. Then the students are asked to consider the question in the written version of the task. They predict the behavior of the system after one additional piece of shot is added, and then discuss their prediction with peers. As indicated in the pretest results, many students predict that the bottle will float just below the surface of the water. The instructor then performs this demonstration. If the initial

TABLE III. Student responses to the second part of the Shot problem [Fig. 3(b)] in Phys/Chem 102 and Survey of Physics.

	Phys/Chem 102 12 sections $N = 316$	Survey of Physics 4 sections $N = 177$
Sink to bottom (correct)	33%	35%
Float below surface	53%	49%
Other (e.g., make no difference)	14%	16%

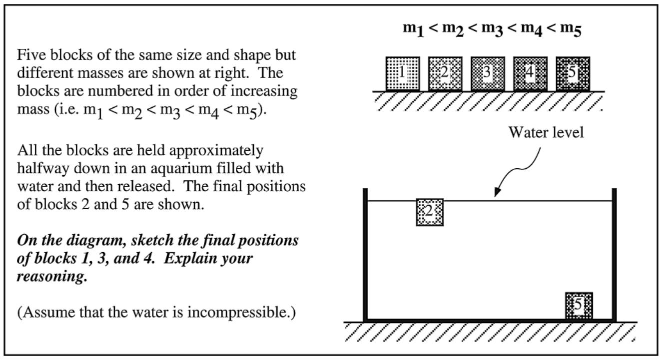


FIG. 4. The Five Blocks problem.

state of the system is indeed just barely floating, the addition of even a small piece of paper is enough to make the bottle sink to the bottom. This outcome is typically surprising for many students and provokes a rich and thoughtful discussion.

As a posttest for this activity, we have posed the Five Blocks problem (Fig. 4) developed in previous studies [37]. As students have not seen this problem before, we feel it is a more rigorous test of student understanding than a repeated administration of the Shot task. Results are shown in Table IV. Before the revision of the activity on sinking and floating, the Phys/Chem 102 course included a hands-on lab activity on sinking and floating including a Cartesian diver demonstration. In these sections of the course, only about 15% of the students answered the Five Blocks question correctly after all instruction on density and sinking and floating. In the unmodified lecture-based Survey of Physics course, the success rate is somewhat greater, but still low. In sections of Phys/Chem 102 completing a revised activity including the Shot task, success on the Five Blocks question after instruction was over 70%. For completeness, we include data from sections of the Survey course using a lecture demonstration version of the Shot activity. This activity was similar in structure to the activity in Phys/Chem 102, with the cycle of prediction, observation, discussion, but did not include written worksheets for students to record predictions and explanations; the success rate on the Five Blocks question in these sections was also high but a bit below that of Phys/Chem 102.

The results on these problems provide a strong signal that the instructional strategies used in Phys/Chem 102 can help to improve student learning as compared to traditional lecture instruction, as students would encounter in the Survey of Physics course. However, they also suggest that hands-on activities by themselves do not necessarily improve student learning; the sections of Phys/Chem 102 using the early version of the density activity showed results that were less successful than the traditional course. Thus we believe that the details of the activities in a course of this type are crucial and often require an iterative development cycle including repeated classroom tests, assessment, and revision of the materials [38].

C. Example: Student understanding of physical and chemical changes

State science standards for fifth grade include the idea that chemical reactions require that atoms rearrange to form substances with different properties [39]. As part of ongoing research into student understanding of physical and chemical changes, students in six sections of Phys/Chem 102 ($N = 157$) were given an ungraded ten-question survey, the Physical-Chemical Change Assessment (PCA), during the first few weeks of the course. The PCA includes a variety of representations of substances undergoing changes, including text, chemical symbols, and macrosopic and particulate-level illustrations (see sample items using each of these four representations in the Appendix). Entering students had an average success rate of 67% prior to instruction, again suggesting deficiencies in the entering content preparation of students. The questions involving the particulate-level representations were the most difficult for students, with a success rate of 62%.

Physical and chemical change is a topic that is specifically addressed in an activity in the Kitchen Science volume of the Phys/Chem 102 curriculum. In order to measure the extent of student learning of this topic, the PCA was administered again at the end of the semester. Student performance was significantly better, with an average success rate of 79%, including 76% correct responses for the problems involving particulate representations [40].

D. Comparison of student population to general education science courses

As noted above, if Phys/Chem 102 were not available, preservice teachers would likely end up taking more traditional lecture-based courses to satisfy their science

TABLE IV. Percentages of students giving correct answers on the Five Blocks problem after all instruction on density and its connection to sinking and floating, for different course types and instructional interventions. Each row in the table below except the first includes at least two different instructors.

Phys/Chem 102 (4 sections)	Hands-on lab-based including Cartesian diver	15%	$N = 94$
Phys/Chem 102 (12 sections)	Shot demonstration with worksheet	71%	$N = 316$
Survey of Physics (2 sections)	Standard lecture	36%	$N = 121$
Survey of Physics (6 sections)	Shot demonstration without worksheet	65%	$N = 280$

TABLE V. Comparison of fractions of students giving correct responses on a variety of common problems in Phys/Chem 102 and the corresponding survey courses in physics and chemistry at CSUF. The problems in all cases were posed at similar points in instruction, typically after reading and brief introductory lecture but before any research-based instruction.

	Phys/Chem 102	Survey of Physics
Pendulum questions	$N = 48$ (two sections)	$N = 53$ (one section)
Kinetic energy comparison	58%	87%
Grav. potential energy comparison	54%	92%
Total energy conservation	50%	71%
Heat & temperature questions	$N = 51$ (two sections)	$N = 57$ (one section)
Temperature prediction	84%	88%
Heat lost = heat gained	25%	43%
	Phys/Chem 102	Survey of Chemistry
Particulate representations	$N = 22$ (one section)	$N = 110$ (one section)
Solid	27%	50%
Gas	27%	49%

requirements. We have performed some research to compare the initial content understanding of the student populations in the two course types. Our intent here is twofold. First, we wish to characterize the level of science understanding in the two groups, to get a sense of how the preservice teachers compare to a broader audience of college students at a given institution. Second, we hope to gauge the extent to which preservice teachers would be in a position to "compete" with the student population in the more traditional courses.

We have given a handful of pretests in Phys/Chem 102 that are matched with pretests given in the corresponding survey course in physics or chemistry. In each case, the pretests were given at similar points in instruction. In the first two cases described in this section, students had been assigned reading on the subject matter of the pretests, but had not begun formal instruction, so in practice the pretests are essentially measuring the incoming level of student understanding. In the third example, the questions were posed prior to instruction. As in the more in-depth examples in the two previous sections, the questions chosen are quite simple by most standards, reflecting the level of material that might be covered in precollege science courses. Each item tests material included in the state content standards for precollege science, as well as those for preservice teachers [41]. Here we show data from three additional examples of content questions that are representative.

The first example involves pretest questions on potential and kinetic energy in the context of a pendulum [42]. These questions were common to Phys/Chem 102 and Survey of Physics, and required fairly straightforward comparisons involving the application of the definitions of kinetic energy and gravitational potential energy, plus the energy conservation law. (See the Appendix for all research questions referenced in this section.) In both cases, students had been assigned reading on the material, but the pretest would largely reflect prior knowledge. As shown in Table V, in each of the questions, the students in the survey course were fairly successful in answering correctly, but those in Phys/Chem 102 had more difficulty.

A second example is drawn from heat and temperature, a topic addressed in both courses. Students were given a pretest with several questions involving straightforward predictions in the context of a mixture of a sample of cold water with a sample of hot water of twice the mass. Students were asked to predict the final temperature of a water mixture and to state whether the heat lost by the hot water in the process was greater than, less than, or equal to that lost by the cold water. While most students are able to predict that the final temperature will be closer to the hot water temperature, most students have difficulty with the heat transfer question.

A third example is drawn from chemistry and involves particulate models of matter. Students were shown a macroscopic illustration of a substance and asked to draw a particulate-level representation of the substance (see Fig. 5). Students should identify from the given chemical

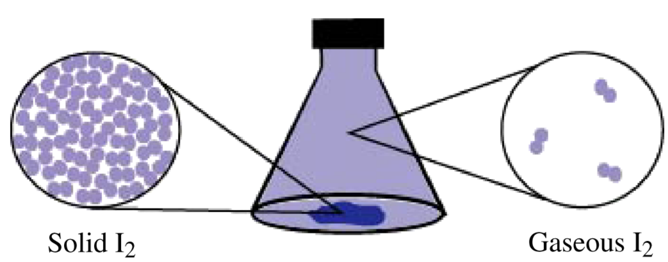


FIG. 5 (color online). Students are asked to draw particulate-level representations of solid and gaseous I_2 (iodine). One potentially correct answer is shown.

formula the diatomic nature of iodine as an element. This is depicted as a symbol for an iodine atom connected to another identical symbol. The molecules of iodine as a gas would be depicted as separate from one another and filling all of the available space in the box. The solid molecules will be shown in the box as aggregated (localized). Both groups struggled with this problem, but the survey chemistry students were approximately twice as likely to draw an appropriate particulate-level illustration of a solid or gas as the students in Phys/Chem 102.

These data and those in the previous sections indicate that even fairly straightforward physical science content is not well understood by a healthy fraction of the students entering Phys/Chem 102. From reports of colleagues using the course materials at other institutions, we feel comfortable in claiming that this phenomenon is not restricted to CSUF. Although these questions cover material that is normally taught in precollege science courses, and is covered in K-12 science standards, a large fraction of the students did not display a deep understanding, and it seems clear that these students would face challenges when teaching this material.

In most of the cases in this paper, we see better performance among students in the survey courses than in Phys/Chem 102. This apparent edge is consistent with our subjective impression that the survey course students on average have stronger science and mathematics backgrounds. It may also reflect self-selection. For example, students in the Survey of Physics course have chosen to take physics as opposed to other GE offerings, often because of their interest in physics and/or a strong high school physics background. In contrast, most Phys/Chem 102 students do not have the same latitude in course selection.

While the trend on these problems is strikingly consistent, we do note that there are other problems on which both groups of students do very poorly. For example, on pretest questions involving subtractive color, the success rate for students in Phys/Chem 102 and the survey course was essentially 0%. Similarly, on questions involving particulate representations of a chemical reaction with a limiting reagent, the success rates in Phys/Chem 102 and the survey chemistry course are between 10% and 15%, with a slight edge for the survey course.

The difference in performance only reinforces the need for special courses. Many previous studies have shown that traditional physics lecture courses do not produce deep understanding of physics content or the nature of science. Our data suggest that if the prospective teachers in Phys/Chem 102 were in a more traditional course, many of them would be relatively poorly prepared compared to their peers, in an environment that would neither encourage deep learning nor provide opportunities to reflect on one's understanding. It is very unlikely that this combination of factors would result in preparing teachers to teach physical science effectively.

VI. CONCLUSION

The development and implementation of Phys/Chem 102 at CSUF required a multiple year commitment on the part of several faculty. The course is viewed as a success locally and has become institutionalized. While several outside funding sources were instrumental in the conception and initial development of the course, the course continues even without this external funding. The initial development process was an exemplar of interdisciplinary cooperation, including not only the two departments directly involved in the course but also our colleagues in the College of Education. We are particularly proud of the Peer Instructor program and the reports we have of its influence on the students participating in the program.

Despite these achievements, there have been challenges along the way, and the continuing success of the course may be threatened, as its special character requires small enrollments and the ongoing collaboration of two academic departments with distinct characters and financial constraints. Staffing of the course has often been a challenge for the two departments involved. As of Fall 2009, local budgetary concerns have led to the cancellation of multiple sections of the course, and there is no guarantee that these sections will be reinstated. Because of the enrollment cap required by the lab classroom and the pedagogy, a course like Phys/Chem 102 is relatively expensive to operate, and our experience suggests that such a course will always be a potential target when budgets are tight.

We have performed some research on several aspects of the course. Our work suggests that the students entering Phys/Chem 102 often have significant difficulty with material that is covered on state science standards, including relatively basic material like mass, volume, and density that they will be expected to teach in K-8 classrooms. The students in this course seem to have even less preparation in physical science on average than the typical nonscience majors in large lecture survey courses intended to satisfy general education requirements. We believe that special courses like Phys/Chem 102 are particularly important for those students who have relatively weak science backgrounds. These students would likely be among the weaker students in a large survey lecture course, and in such a course they would have little opportunity to reflect upon their learning or discuss the content with other students.

Our results suggest that the instructional strategies in Phys/Chem 102 course do have some successful impact on student learning. Student performance on density questions improves dramatically, for example. However, our work on sinking and floating suggests that the details of the activities are very important. Early versions of activities failed to have the desired impact on student learning, despite the fact that students were in a small-group setting doing activities focusing on conceptual understanding, and only after the activities were revised based on research did student performance improve to the desired levels. In the cases described above, an iterative approach to course development informed by research on student learning has led to significant improvements, but such an effort is quite intensive and time-consuming, and well beyond the typical expectations of course instructors.

In conclusion, we believe that we have learned a great deal from the experience of developing, implementing, and assessing Phys/Chem 102. This course is relatively unusual as an example of continuing interdepartmental collaboration that appears to be sustainable. We are hopeful that our description of these experiences and selected research findings can be of use to colleagues at other institutions.

APPENDIX: EXAMPLES OF THE INQUIRY-BASED COURSE

See separate auxiliary material for the assessment, MERIT essay, performance task, curriculum sample, interactive demonstration, research problems, and Table of Contents for the Inquiry into Physical Science.

[1] See, for example, L. C. McDermott, A perspective on teacher preparation in physics and other sciences: The need for special courses for teachers, Am. J. Phys. **58**, 734 (1990); L. C. McDermott and P. S. Shaffer, in *The Role of Physics Departments in Preparing K-12 Teachers*, edited by G. Buck, J. Hehn, and D. Leslie-Pelecky (American Institute of Physics, College Park, MD, 2000); V. Otero, N. D. Finkelstein, R. McCray, and S. Pollock, Who is responsible for preparing science teachers?, Science **313**, 445 (2006); See www.ptec.org for an example of the involvement of professional societies is the Physics Teacher Education Coalition; A chemistry example is illustrated in L. L. Jones, H. Buckler, N. Cooper, and B. Straushein, Preparing preservice chemistry teachers for constructivist classrooms through the use of authentic activities, J. Chem. Educ. **74**, 787 (1997).

[2] S. M. Wilson, R. E. Floden, and J. Ferrini-Mundy, Teacher preparation research: An insider's view from the outside, J. Teach. Educ. **53**, 190 (2002).

[3] D. D. Goldhaber and D. J. Brewer, Evaluating the effect of teacher degree level on educational performance, in *Developments in School Finance*, edited by William J. Fowler, Jr. (NCES, Washington, DC, 1996), pp. 197–210.

[4] D. D. Goldhaber and D. J. Brewer, Does teacher certification matter? High school teacher certification status and student achievement, Educ. Eval. Policy Anal. **22**, 129 (2000).

[5] D. H. Monk, Subject area preparation of secondary mathematics and science teachers and student achievement, Econ. Educ. Rev. **13**, 125 (1994); D. H. Monk and J. King, Multilevel Teacher Resource Effects on Pupil Performance in Secondary Mathematics and Science, in *Choices and Consequence*, edited by Ronald G. Ehrenberg (ILR Press, Ithaca NY, 1994).

[6] L. Shulman, Those who understand: A conception of teacher knowledge, Educ. Researcher **15**, 4 (1986); L. Shulman, Teacher development: Roles of domain expertise and pedagogical knowledge, J. Appl. Dev. Psychol. **21**, 129 (2000).

[7] H. Hill, B. Rowan, and D. L. Ball, Effects of teachers' mathematical knowledge for teaching on student achievement, Am. Educ. Res. J. **42**, 371 (2005).

[8] For example, one study in mathematics illustrated the lack of mathematical understanding among teachers: L. Ma, *Knowing and Teaching Elementary Mathematics: Teachers' Understanding of Fundamental Mathematics in China and the United States* (Erlbaum, Mahwah, NH, 1999).

[9] R. Yopp Edwards, "Study of California State University Fullerton multiple subject credential candidate transcripts" (to be published).

[10] There is a wide body of research literature showing that traditionally taught physics courses do relatively little to improve student content understanding. See, for example, many of the articles in the annotated bibliography L. C. McDermott and E. F. Redish, Resource letter: PER-1: Physics education research, Am. J. Phys. **67**, 755 (1999); There is also evidence that these courses seem to negatively impact student beliefs about the nature of science and the learning of physics; see E. F. Redish, J. M. Saul, and R. N. Steinberg, Student expectations in introductory physics, Am. J. Phys. **66**, 212 (1998).

[11] California Department of Education, Standards for California Public Schools, Kindergarten Through Grade Twelve, 2000, http://www.cde.ca.gov/be/st/ss/.

[12] Candidates can complete a series of courses, but at this point more choose to take a series of standardized tests known as California Subject Examinations for Teachers (CSET), http://www.cset.nesinc.com/.

[13] R. Nanes and J. W. Jewett, Jr., Southern California Area Modern Physics Institute (SCAMPI): A model enhancement program in modern physics for high school teachers, Am. J. Phys. **62**, 1020 (1994).

[14] R. diStefano, The IUPP evaluation: What we were trying to learn and how we were trying to learn it, Am. J. Phys. **64**, 49 (1996).

[15] R. McCullough, J. McCullough, F. Goldberg, and M. McKean, *CPU Workbook* (The Learning Team, Armonk, NY, 2001).

[16] J. K. Ono, M.-L. Casem, B. Hoese, A. Houtman, J. Kandel, and E. McClanahan, Development of faculty collaboratives to assess achievement of student learning outcomes in critical thinking in biology core courses, in *Proceedings of the National STEM Assessment*

Conference, Washington, DC, 2006, edited by D. Deeds and B. Callen (National Science Foundation and Drury University, 2008), pp. 209–218.

[17] For example, the biology course originally used Biological Sciences Curriculum Study, *Biological Perspectives* (Kendall-Hunt, Dubuque, IA, 1999).

[18] Neither the biology nor geology course curricula are nationally published, but the courses are still active.

[19] L Pryde Eubanks, C. H. Middlecamp, C. E. Heitzel, and St. W. Keller, *Chemistry in Context* (American Chemical Society, Washington, DC, 2009), 6th ed.

[20] The representations include some that are similar to the energy bar charts described in A. Van Heuvelen and X. Zou, Multiple representations of work-energy processes, Am. J. Phys. **69**, 184 (2001).

[21] The sequence of activities described in this section comes from Vol. 1, chapters 2–4 of the course text, which is described later in Sec. III B (see Ref. [26] for a full citation). The full table of contents is included in Appendix for readers who wish to see how these activities fit into the course as a whole. In particular, this paragraph references activities 2.4.1 (representation of energy), 3.4.1ff (water mixing), and 4.1.1ff (dynamic thermal equilibrium).

[22] R. diStefano, Preliminary IUPP results: Student reactions to in-class demonstrations and to the presentation of coherent themes, Am. J. Phys. **64**, 58 (1996).

[23] L. C. McDermott, and the Physics Education Group, *Physics by Inquiry* (John Wiley & Sons, Inc., New York, 1996), Vols. I and II; F. Goldberg, V. Otero, and S. Robinson, *Physics and Everyday Thinking* (It's About Time, Armonk, NY, 2008); American Association of Physics Teachers, *Powerful Ideas in Physical Science* (AAPT, College Park, MD, 1996), 2nd ed.

[24] In addition to the state K-12 content standards in Ref. [9], see National Committee on Science Education Standards and Assessment, National Research Council, *National Science Education Standards* (The National Academies Press, Washington, D.C., 1996); California Commission on Teaching Credentialing, Standards of Program Quality and Effectiveness for Subject Matter Requirement for the Multiple Subject Teaching Credential (2001).

[25] The activities are not intended for use with K-8 students, and have not been tested with this population, but some former Phys/Chem 102 students have nevertheless used them to prepare lessons.

[26] F. Goldberg, V. Otero, S. Robinson, R. Kruse, and N. Thompson, *Physical Science and Everyday Thinking* (It's About Time, Armonk, NY, 2009); See also the LEPS curriculum currently under development, F. Goldberg, E. Price, D. Harlow, S. Robinson, R. Kruse, and M. McKean, AIP Conf. Proc. **1289**, 153 (2010).

[27] R. Nanes, *Inquiry Into Physical Science: A Contextual Approach* (Kendall-Hunt, Dubuque, IA, 2008), Vols. 1–3, 2nd ed.

[28] Some aspects of the implementation at Cal Poly Pomona are described in H. R. Sadaghiani and S. R. Costley, The Effect of an Inquiry-Based Early Field Experience on Pre-Service Teachers' Content Knowledge and Attitudes Toward Teaching, in *Physics Education Research Conference*, AIP Conf. Proc. No. 1179 (AIP, New York, 2009) pp. 253–256.

[29] A more formal learning assistant model with extensive accompanying curriculum is described in V. Otero, N. D. Finkelstein, R. McCray, and S. Pollock, Who is responsible for preparing science teachers? (Ref. [1]).

[30] See, for example, R. R. Hake, Interactive-engagement versus traditional methods: A six-thousand-student survey of mechanics test data for introductory physics courses, Am. J. Phys. **66**, 64 (1998); Y. J. Dori and J. L. Belcher, How does technology-enabled learning affect undergraduates' understanding of electromagnetic concepts?, J. Learn. Sci. **14**, 243 (2005).

[31] D. F. Halpern and M. D. Hakel, Applying the science of learning to the University and beyond: Teaching for long-term retention and transfer, Change **35**, 36 (2003).

[32] The course has in the past used the popular text P. Hewitt, *Conceptual Physics* (Addison-Wesley, Reading, MA, 2001).

[33] Science Content Standards for California Public Schools, Kindergarten through Grade Twelve. The standards are available online at http://www.cde.ca.gov/be/st/ss/documents/Sciencestnd.pdf Standard 6b for Grade 2 (p. 13) includes the measurement of volume. Standards 8a-d for Grade 8 (p. 28) include density and sinking and floating.

[34] See, for example, M. E. Loverude, Investigation of student understanding of hydrostatics and thermal physics and of the underlying concepts from mechanics, Ph.D. thesis, University of Washington, 1999; M. E. Loverude, C. H. Kautz, and P. R. L. Heron, Helping students develop an understanding of Archimedes' principle, Part I: Research on student understanding, Am. J. Phys. **71**, 1178 (2003); P. R. L. Heron, M. E. Loverude, and P. S. Shaffer, Helping students develop an understanding of Archimedes' principle, Part II: Development of research-based instructional materials, Am. J. Phys. **71**, 1188 (2003).

[35] The original problem on electric charge density is described in S. E. Kanim, Investigation of student difficulties in relating qualitative understanding of electrical phenomena to quantitative problem-solving in physics, Ph.D. thesis, University of Washington, 1999; Questions on mass density adapted from this problem are included in, for example, G. White, Pre-Instruction State of Nonscience Majors—Aspects of Density and Motion, in *Proceedings of the 122nd AAPT National Meeting, San Diego, 2001* (Rochester, NY, 2001) and M. E. Loverude, S. E. Kanim, and L. Gomez, Curriculum design for the algebra-based course: Just change the "d's to deltas?," in *Physics Education Research Conference*, AIP Conf. Proc. 1064 (AIP, New York, 2008), pp. 34–37.

[36] M. E. Loverude, A research-based interactive lecture demonstration on sinking and floating, Am. J. Phys. **77**, 897 (2009).

[37] M. E. Loverude, Investigation of student understanding of hydrostatics and thermal physics and of the underlying concepts from mechanics (Ref. [34]); M. E. Loverude, C. H. Kautz, and P. R. L. Heron (Ref. [34]).

[38] See similar findings by K. Cummings, J. Marx, R. Thornton, and D. Kuhl, Evaluating innovation in studio physics, Am. J. Phys. **67**, S38 (1999); L. G. Ortiz,

P. R. L. Heron, and P. S. Shaffer, Investigating student understanding of static equilibrium and accounting for balancing, Am. J. Phys. **73**, 545 (2005).

[39] See the state science content standards (Ref. [28]), content standard 1a for grade 5, p. 14.

[40] A paired-samples t test showed a statistically significant gain in the mean percent accuracy on the total PCA and for each stimuli format ($t = 10.45$, $df = 211$, $p \leq 0.05$).

[41] See state standards, Ref. [8]. The energy questions are covered by grade 9-12 physics standards 2a-c, p. 32. Heat and temperature are covered by grade 6 standard 3, p. 19. Particulate models of matter are included as early as grade standard 1a, p. 8, with particulate models of different states of matter appearing in grade 8 standard 3d-e, p. 27.

[42] This problem and related data are also shown in M. Loverude, Student understanding of gravitational potential energy and the motion of bodies in a gravitational field, *Physics Education Research Conference*, AIP Conf. Proc. No. 790 (AIP, New York, 2004), pp. 77–80.

Appendix 1—Assessment

1.A. Sample Examination Questions

1. A block of metal is held halfway down in a container of water and then released. It is observed that the block barely floats as shown in Figure 1 to the right. A very small chip is then carved out of the block and held halfway below the surface and released. In Figure 2 to the right, which letter best describes the final position of the chip after it is released? Explain your answer.

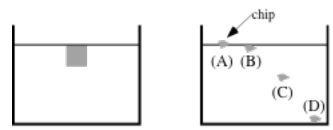
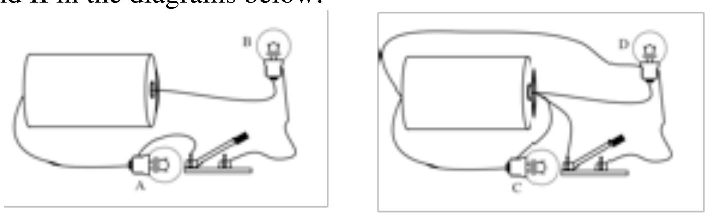


Figure 1 Figure 2

2. Consider circuits I and II in the diagrams below:



Circuit I Circuit II

   A. Draw a standard circuit diagram for each circuit and label the light bulbs A – D.
   B. For each circuit, state whether the circuit is open, closed, or short when the switch is open. Briefly explain the reason for your choice.
   C. Repeat the process from part B for the case with the switch closed.

1.B. Sample "Making Connections" (Homework) Questions

1. The following question is from an assignment given to students after their investigations of heat and temperature by means of hot- and cold-water mixing experiments:
   A. While working on Exercises 1 B (8 g of water at 30˚C) and 1 C (4 g of water at 40˚C) in the previous activity (3.4.2-Part II), a student is confused. She disagrees with the solutions reached by her partners and she argues that:

      In exercise 1B, since 1 calorie raises the temperature by 1ºC, 19.2 calories will raise the temperature by 19.2ºC making the final temperature 49.2ºC, not 2.4˚C, which is what her partners claimed. Also, in exercise 1C, a 15ºC temperature drop should result from a loss of 15 calories, not 60 calories as agreed to by her partners.

      If you were one of her partners, how would you clarify this issue for her?

   B. After receiving clarification from her partners in A above, the student makes the following claim:

      "*It seems as though there is a relationship between the total amount of heat gained or lost by a sample of water and the temperature change of the sample*."

      However, she is having some difficulty figuring out what that relationship is. Use Exercises 1B and 1C from Activity 3.4.2 to help her state the relationship between the total heat gained or lost by a water sample and its temperature change.

2. The following question is taken from a "Making Connections" assignment about the greenhouse effect, after students have studied the solar input and the infrared radiative output components of the Earth's thermal equilibrium and the effect of greenhouse gases such as CO_2 in the atmosphere:

Our studies in the Global Warming unit focused on Earth, but the physics we discussed is also relevant to other planets. Robotic spacecraft that have landed on Venus have given us a great deal of information about the planet. The following table summarizes some of the things that we know about Venus, compared to Earth:

Property	***Earth***	***Venus***
Distance to sun	93 million miles	68 million miles
Temperature	15˚C	472˚C
% CO_2 in atmosphere	0.03%	96.5%
Color of atmosphere	None (transparent)	Slight orange color

A. Scientists have suggested that Venus has experienced a "runaway greenhouse effect". Using the information given in the table, explain why you think that scientists have made this suggestion.

B. Why do you think the equilibrium temperature for Venus is so much higher than that of Earth?

Appendix 1. C—MERIT Essay

Annotated MERIT Essay on Density

Note: No errors in spelling and/or grammar are noted here but would be part of the evaluation of the MERIT Essay under the "Writing Mechanics" component of the evaluation rubric.

A topic we have learned about this semester is about density. I thought I understood density when I started this unit but I was wrong. *[Can she document her preliminary ideas and show her poor initial understanding?]*

In Chapter 1 I learned by doing the experiments *[Which experiments? Although this may be clarified later, avoid these general statements]* that the density of an object determines if it will sink or not. *[Not really correct. The density of the object relative to that of the liquid it is in determines if the object will sink or float in that liquid.]* Before starting this unit we were given a pretest where we are supposed to figure out which block make the water level rise higher. I stated that, "the water level in the graduated cylinder containing block B will be higher because <u>block B is heavier</u>." *[This is good that the student quotes directly what she had written.]* After doing the experiment *[What experiment? The student does not describe anywhere what was done and how he/she learned from it.]* in class I learned that although block B is heavier, the water level raised exactly the same for both cylinders *[Both cylinders? Again very confusing references to what was done.]* because mass does not matter, density does. *[The experiment that the student is talking about is the measurement of volume by water displacement. It is correct that "mass does not matter" in determining volume by displacement, but it is completely incorrect to say that "density does". The student is clearly confused by these terms and their connection to the experiment.]*

Activity 1.6.1 *[specifically, which part of 1.6.1?]* was very helpful to me because it proved to me that no matter how big an object, made of a certain material, is it will still have the same density as a smaller piece of the same object. We were given a number of plastic cubes that measure 1 cm on an edge. We were to construct an object of any shape from these plastic cubes. We then determined the mass and recorded it. Then we had to break this object into smaller pieces of different size by separating some cubes and then finding the mass of this shape. We did this about five times. Finally, we found the mass of a single cube and recorded it. The volume of each cube is 1 cm *[units!]*. Therefore, the shape with 20 pieces had a volume of 20 cm *[units!]*, and so on. We then found the density of the different shapes by dividing mass into volume. *[All of this paragraph to this point was spent describing the details of the experiment that was done. This is unnecessary and irrelevant here. It adds no insight whatever to the question of how it helped the student understand the concepts.]* After doing this I found that given the marginal error the mass/volume ratio (density) is the same for all the shapes. I learned that as you add more cubes to a shape the mass does increase but the density will always remain the same. The density remains constant because density is a property of a particular material, not the property of size or shape. *[True, but the student shows no understanding of the fact that changes in the mass in this experiment was accompanied by proportionate changes in volume, thereby resulting in a constant ratio, the density.]* Therefore, no matter how heavy the object the density remains the same.

A pretest given in class showed that I understood density a little more after doing Activity1.6.1 but still needed a little clarification. When asked what I thought would happen when several pieces of metal are removed and the bottle is placed beneath the surface of the water in the container and released I stated that, "the bottle will float and come up higher because the metal pieces that was weighing it down were removed from the bottle making it less dense"
which was correct and supported by the demonstration in class. *[Although the student makes the claim that the prediction was correct and supported by the demonstration, the student's understanding is clearly not correct. To say that removing the metal pieces that were weighing down the bottle makes it less dense implies that the reduced mass makes the bottle less dense. However, why did reduction in mass result in constant density in the early part of 1.6.1 that the student discussed in the previous paragraph, but gives a lower density here? The answer is that the volume is constant here. The student fails to recognize this.]* When asked what I thought would happen when several pieces of metal are added to the bottle I stated that the bottle would go down just a little bit because it is more dense than the first time which was confirmed by the demonstration. But when asked ot predict what would happen to the container if one more small piece of metal is added and the bottle is place beneath the surface of the water in the container and released, I predicted, "that the bottle would go down a little more because by adding a piece of metal the weight is increased therefore the density also increases." The demonstration proved me wrong because the unit sank to the bottom of the container. If these small pieces of metal were all the same density *[they were!]* they would all float the same in the container *[float in the container?]* but both the metal pieces and the bottle caused it to sink to the bottom which proves that the density of the metal piece and the bottle together is greater than 1.00 g/cm^3. *[The student has clearly documented incorrect predictions but has not demonstrated how his/her understanding changed after making those predictions.]*

These activities have helped me understand density. *[I don't think so. If so, the student has not successfully conveyed that understanding nor how he/she obtained it. The essay was mostly a description of a couple of activities but did not focus very well on the student's learning.]* I have learned that the mass of an object does not necessarily determine whether an object will float or sink. The density determines that, if an object is less dense than water, which is 1.00 g/cm3, then it will float but if the object is more dense than water then it will sink. *[Student is summarizing what was supposed to be learned but has not done a very good job of showing that he/she learned it or how that learning occurred.]*

MERIT Essay Evaluation Guidelines

1. Documentation of thinking including quotes from pretests / activities / posttests:

Indicator	Value
Thorough documentation of ideas (≥2 examples per stage)	5
Adequate documentation (≥1 and ≤2 examples per stage)	4
Some documentation (only one example for each stage)	3
Incomplete documentation (less than one example for each stage)	2
No documentation	1

2. Inference of conceptual understanding from written evidence:

Indicator	Value
Describes model of own thinking consistent with evidence (Identifies model abstracted from responses and identifies how predictions are consistent with model. Ex: "I thought when something was bigger, mass, volume and density would all be bigger. Thus, I predicted the density of the	5

larger block in Pre-Test 1 would be greater, and that the heavier block would displace more volume.")	
Describes model of thinking with little evidence (Identifies a model without connection to predictions. Ex: "I thought heavier things would have more density.")	4
Describes thinking without coherent model (Refers to specific concept as right or wrong without a model. Ex: "I didn't know the difference between mass and volume.")	3
States answers are right or wrong with little interpretation (No relationship to a specific concept-complete generalization. Ex: "I was wrong and I don't know what I was thinking.")	2
(No analysis of own thinking)	1

3. Trace change in understanding:

Indicator	**Value**
Initial understanding compared with intermediate & final ideas consistent with scientific theory (Discusses/compares all three stages)	5
Initial understanding compared with final, no intermediate but consistent with scientific theory (Discusses/compares at least two of the stages)	4
Evaluation of learning based only on final understanding but consistent with scientific theory (Discusses/compares at least one stage)	3
Vague assertion of learning, no specific comparison or inconsistent with scientific theory	2
No comparisons of understanding	1

4. Identification of important activities and description of role in learning:

Indicator	**Value**
Makes appropriate connections between activities and learning (≥2 relevant tasks identified and related to Pre-/Post- ideas)	5
Make some appropriate connections between activities and learning (One relevant task identified and related to Pre-/Post- ideas)	4
Incomplete connection between activities and learning (Tasks identified without connection to ideas.)	3
Activities identified with little connection to learning (Mere mention of activity without specific reference to tasks within activity)	2
No activities identified	1

5. Writing mechanics:

Indicator	**Value**
Clearly written, good connections, very few minor mechanical errors (0-1 minor errors of all types per page)	5
Clearly written, connections need improvement, some mechanical errors (1-2 minor errors of all types per page)	4
Vaguely written, disjointed, or many mechanical errors (3-4 minor errors of all types/page or 1-2 major grammatical/style errors/page)	3
Very vague, disjointed, multiple mechanical errors (5-7 errors of all types/page or fewer minor errors plus 2-3 major grammatical errors)	2
Writing very difficult to follow, usage non-conventional	1

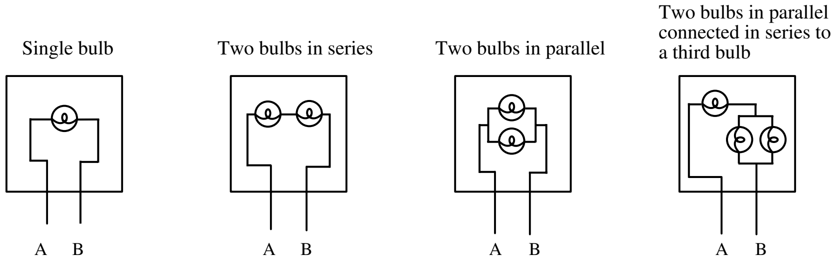
6. Peer Review:

Indicator	**Value**
Indication of serious effort to inform classmate of ways to improve Essay.	5

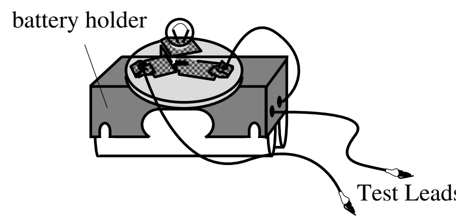
TOTAL SCORE (30 points possible)	

Appendix 1.D—Performance Task

You will be given four "mystery" boxes numbered 1 - 4. The contents of the boxes are not visible, but each box has two protruding wires, labeled A and B. The boxes contain various combinations of light bulbs connected to terminals A and B by conducting wires inside the box as pictured below:

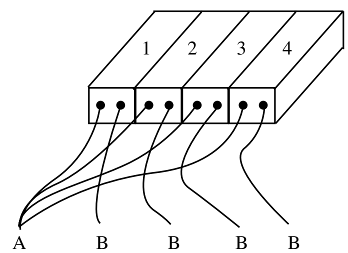


You cannot see what is in the boxes—all you can see are the terminals, A and B, protruding from the box. You will also be given a “tester” which consists of a battery and a bulb and two test lead wires as shown to the right. (Although the battery and bulb are arranged slightly differently, this is the same as the “circuit tester” that you learned about in a previous Making Connections assignment.)



YOUR TASK WILL BE TO USE THIS TESTER TO IDENTIFY THE CONTENTS OF THE FOUR BOXES.

To make it easier to connect your tester to the boxes, the terminal wires A for all four boxes are connected together as shown to the right. You can connect one lead from the tester to this common “A” junction and leave it connected as you connect the second tester lead to the terminal B wire for each individual box.



You will do this performance task in three steps:

Step 1. BEFORE DOING ANY MEASUREMENTS, think about a plan to identify the contents of each of the mystery boxes without opening the boxes. Your plan should consider what you will be looking for when you connect the tester to the mystery boxes to enable you to decide which circuit pictured above is in which box. (Note: It will not be acceptable to explain how you find the contents of three boxes and then use the argument “by elimination” for identifying the fourth box. You must explain how the tester is used to identify the contents all four boxes.) ***On your answer sheet***, describe your plan and ***explain the reasoning that you used*** in arriving at this plan. You must write this plan on your answer key before moving to step 2.

Step 2. After writing down what your plan is, execute your plan and determine the contents of each box.

Step 3. It may be that your strategy for determining the contents of the boxes changed as you began to make measurements. If so, that is fine, but write down (***on your answer sheet***) how you had to change your approach relative to what you planned in step 1.

Appendix 2—Curriculum Sample

Sample of curriculum for Phys/Chem 102, activity 1.6.1 from the *Underpinnings* section of the *Global Warming* volume.

Your Name:___________________________ Partner's name(s):____

Underpinnings—Activity 1.6.1
Understanding Density

1. A. You will be given a number of plastic cubes that measure 1 cm on an edge. Measure the mass of a single cube and enter both the mass and volume of the cube into the following table. Divide the mass by the volume and enter this ratio into the last column of the table.

# of cubes in piece	Mass (g)	Volume (cm^3)	Ratio of mass/volume (g/cm^3)
1 (single cube)			
2			
5			
12			
18			
25			

B. Join two plastic cubes together and repeat the process done for the single cube in part A, i.e., measure the mass of the piece made by joining together two cubes and enter its mass and volume into the table along with the ratio of its mass divided by its volume.

C. Now construct larger pieces by joining together the indicated number of plastic cubes and complete the table given above in part A.

2. A. Are there any pieces for which the mass/volume ratio that you obtained in part 1 is the approximately the same? Explain your observations.

B. In part 1, you started with a single plastic cube and built a larger structure by adding cubes. Each time an additional cube was added, the mass increased. How is it possible that the density remained essentially constant, regardless of how many plastic cubes were in each piece? Explain.

C. Give an interpretation of the meaning of the mass/volume ratio that you tabulated in the last column of the above table, i.e., what does this number tell you about the object to which it applies? (The <u>name</u> for the ratio of mass/volume is the *density* of an object, but this does not explain the <u>meaning</u> of the ratio.) (*Hint:* Refer to section 1.5 in your text.)

3. ***Exercises:***

   A. The volume of an object is measured to be 120 cm^3. If we measure the mass of the object to be 340 g, what is the interpretation of the ratio 340/120? ("Density" is not the answer being sought here.)

   B. The density of aluminum is 2.7 g/cm^3. Imagine that, in doing the experiment in part 1, you had used aluminum cubes measuring 1 cm on an edge rather than plastic cubes. How would your results have been different? Complete the following table assuming that you had used aluminum cubes.

# of cubes in piece	Mass (g)	Volume (cm^3)	Ratio of mass/volume (g/cm^3)
1 (single cube)			
2			
5			
12			
18			
25			

4. You will be given a set of 2 cubes and 2 cylinders from your instructor.

   A. Describe two ways to measure the volume of the cubes and cylinders that have been given to you. Which method do you think is more accurate? Why do you think so?

   B. Measure the mass and volume of each of the cubes and cylinders that you have and determine the density of each. Enter your data into the following table:

Object	Mass (gram)	Volume (cm^3)	Density ($gram/cm^3$)
Cube #1			
Cube #2			
Cylinder #1			
Cylinder #2			

   C. Do any of the objects have the same density? What similarities do you see between these objects?

   D. Some properties of matter are specific to a given object while other properties (known as *characteristic properties*) are the same for any object made of a particular material. Circle which of the following quantities you think are characteristic properties?

   mass volume density

   What evidence do you have to support your thinking?

5. A. You will be given a plastic container or beaker deep enough to submerge a soda can that does not have a graduated scale of volume markings (as did the graduated cylinder used to measure the volume of the rectangular blocks in Activity 1.4.1). With your partners, devise an experiment to determine the density of a full, unopened soft drink can. Write down your plan and specifically include details of how you would determine the volume of the can using the unmarked container provided. Before executing the plan, discuss it with your instructor.

B. Once you get the go ahead from your instructor, execute your plan to measure the density of the soft drink can. Enter your group's value for the density of the soda can into the table below. You will be asked to share your group result for the density with the class by writing your result on the board. When the data for all groups is on the board, copy the class results into the following table:

Class Data for the Density of a Soft Drink Can

Group	**Type of Soda (Diet or Regular)**	**Mass**	**Volume**	**Density**
Your group				

C. Do you think that there should be a difference between the density of diet soda compared to that of regular soda? Why, or why not?

D. (*i*) Compute the average density of the regular soft drinks using the data in the table in part B and, separately, compute the average density of the diet drinks.

(*ii*) Was your prediction in part C confirmed, i.e., is there a difference between the density of diet soda compared to that of regular soda?

E. Ideally, the class data should have shown that the density of diet soda is slightly smaller than the density of regular soda? What would explain this difference?

6. A. In the table to the right are the densities of various materials— some that typically float and some that typically sink in water. If the density of water is 1.00 g/cm^3, what can you conclude about the densities of objects that float or sink, when compared with the density of water?

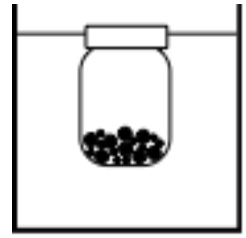
Substance	Density (g/cm^3)
Gold	19.3
Lead	11.3
Aluminum	2.7
Granite	2.7
Glass	2.4-5.9
Ice	0.92
Wax	0.9
Oak wood	0.6-0.9
Bamboo	0.3-0.4
Balsa wood	0.1

B. Will a filled soda can sink or float in water? Explain your thinking.

Part II
Interactive Demonstration

(The author is grateful to Dr. Michael Loverude for contributing this Activity.)

1. A. A glass bottle is partly filled with small pieces of metal and sealed so that no air or water can enter or leave the bottle. The bottle is placed in a container of water and is observed to float as shown in the figure to the right.



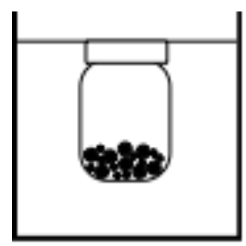
Imagine that several pieces of metal are removed, and the bottle is placed beneath the surface of the water in the container and released. ***Predict*** the resulting position of the bottle by drawing a sketch in the space below. Explain your reasoning.

B. Your instructor will now perform the demonstration. Was your prediction confirmed? If there is a difference between the observed results and your prediction, reconsider your explanation!

C. (*i*) If you consider the bottle and its contents as a unit, what can you say about the density of this unit? Explain.

(*ii*) How is the density of this unit related to the behavior of the bottle? Explain.

2. Now the pieces of metal in the bottle are adjusted so that when the bottle is again placed in a container of water, it is observed to BARELY float, as shown.



A. If you consider the bottle and its contents as a unit, what can you say about the density of this unit? Explain.

B. ***Imagine*** that one more small piece of metal is added and the bottle is placed beneath the surface of the water in the container and released. ***Predict*** the resulting position of the bottle by drawing a sketch in the space below. Explain your reasoning.

C. Your instructor will now perform the demonstration. Was your prediction confirmed? If there is a difference between the observed results and your prediction, reconsider your explanation?

D. (*i*) If you consider the bottle and its contents as a unit, what can you say about the density of this unit? Explain.

(*ii*) How is the density of this unit related to the behavior of the bottle? Explain.

3. A. Considering the bottle and its contents as a single unit, which of the following quantities *increase, decrease,* or *remain the same* as a result of the addition of the piece of metal to the bottle?

    Mass

    Volume

    Density

    B. In the beginning of this Activity, you joined plastic cubes together to construct larger pieces. Which of the following quantities *increase, decrease,* or *remain the same* when two or more cubes are joined together?

    Mass

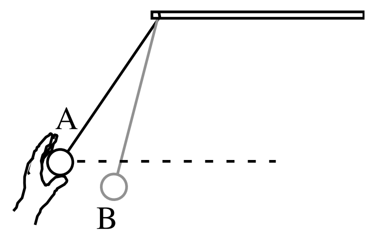
    Volume

    Density

    C. Are your answers to questions 3A and 3B the same? Explain any differences.

Appendix 3: Research Problems for Section VD

3.A: Questions on pendulum and energy (see Loverude 2004).



A ball is hanging at the end of a string, forming a *pendulum*. A student holds the ball at position A and then releases it. Answer the following questions about this situation. In all cases consider a system including the ball and string (and assume that the process takes place on Earth).

A moment after it is released, the ball swings past position B (and continues beyond this point). For the quantities below, state whether the quantity is *greater at instant A, greater at instant B,* or *equal at the two instants*. If you are unable to compare the quantities, state so explicitly.

Kinetic energy of the pendulum (circle one and explain briefly)

Gravitational potential energy of the pendulum (circle one and explain briefly)

Total stored energy of the pendulum (circle one and explain briefly)

3.B: Questions on heat and temperature.

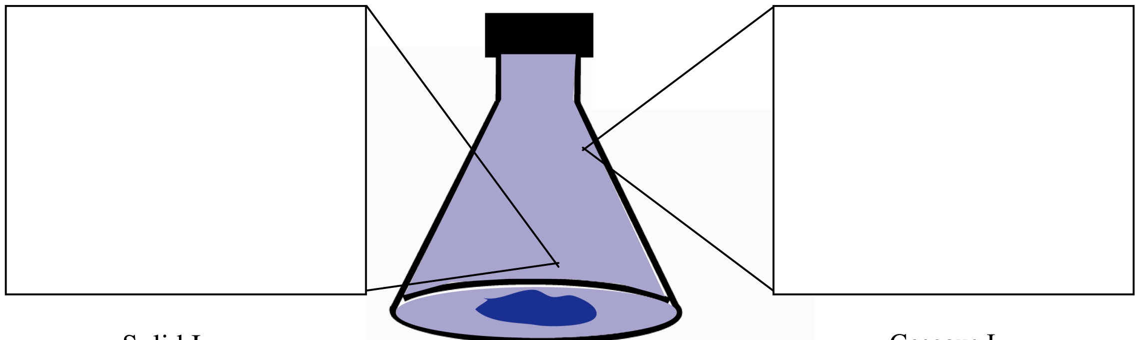
Imagine that 500 grams of hot water at 60 ˚C are mixed with 250 grams of cold water at 20 ˚C. The mixture is stirred and its final temperature is measured.

Will the final temperature of the mixture be *greater than, less than* or *equal to* 40 ˚C? Explain.

Is the quantity of heat lost by the hot water in this process *greater than, less than,* or *equal to* the quantity of heat gained by the cold water? Explain.

3.C: Questions on particulate representations of matter.

Iodine, I_2, is a solid that sublimes at room temperature; it exists in the solid and gas phases simultaneously. A macroscopic-level representation of iodine in a closed flask is shown below.



Solid I_2 | Closed flask containing I_2 | Gaseous I_2

Draw particulate-level representations of iodine in the solid phase and in the gas phase in the boxes below.

Is the content in the flask a pure substance or a mixture? Explain your reasoning.

Is iodine an element or a compound? Explain your reasoning.

3.D: Sample questions from the PCA.

1. Which of the following represents a physical change?
Circle the letter of the *best* answer.
A. Toast burning black when overheated in a toaster.

B. Water evaporating into the air from a puddle on the hot concrete.

Explain why your choice is a physical change.

4. Which of the following represents a chemical change?
Circle the letter of the *best* answer.

A. $2H_2(g) + O_2(g)\ ) \rightarrow 2H_2O(g)$

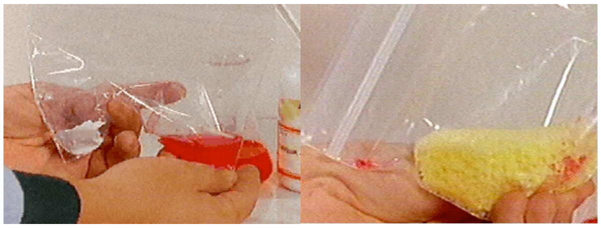
B. $H_2O(g) \rightarrow 2H_2O(l)$

Explain why your choice is a chemical change.

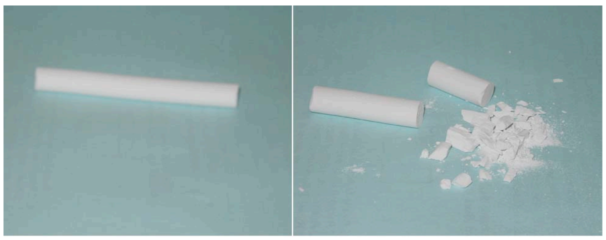
5. Which of the following represents a physical change?
Circle the letter of the *best* answer.

Explain why your choice is a physical change.

A.



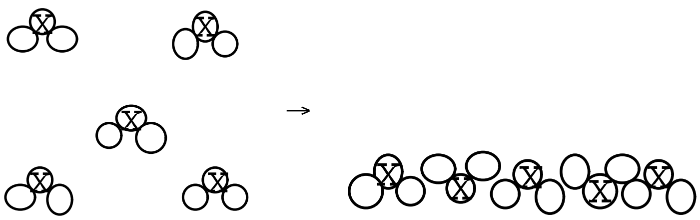
B.



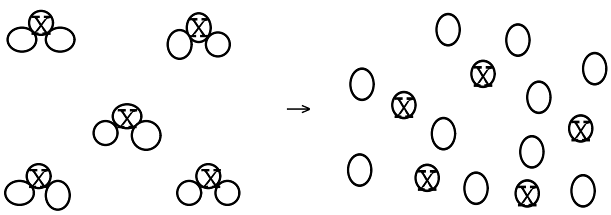
6. Which of the following represents a chemical change?
Circle the letter of the *best* answer.

Explain why your choice is a chemical change.

A.



B.



Appendix 4—Table of Contents for *Inquiry into Physical Science*

Contents — Volume 1 - Global Warming

Leading Question: Is Global Warming Really Occurring?

Chapter 1. Introduction—Underpinnings

Chapter 2. What is Energy?

Chapter 3. Heat and Temperature

Chapter 4. Thermal Equilibrium of the Earth

Chapter 5. The Role of the Atmosphere

Contents — Volume 2 - Kitchen Science

Leading Question: Will Science Be a Guest At Your Next Dinner?

Chapter 4. The Foods We Eat

Contents — Volume 3 - The Automobile

Leading Question: Will the Gas-Driven Automobile Ever Become a Thing of the Past?

In addition, the following excerpts from Volume 1 are included as an appendix in both Volumes 2 and 3, in case adopters choose to use one or both of the later volumes without Volume 1.

Appendix 1—"Underpinnings" (from Chapter 1, Volume 1)

Appendix 2—"Energy" (Excerpted from Chapter 2, Volume 1)

A physics department's role in preparing physics teachers: The Colorado learning assistant model

Valerie Otero
School of Education, University of Colorado, Boulder, Colorado 80309

Steven Pollock and Noah Finkelstein
Department of Physics, University of Colorado, Boulder, Colorado 80309

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In response to substantial evidence that many U.S. students are inadequately prepared in science and mathematics, we have developed an effective and adaptable model that improves the education of all students in introductory physics and increases the numbers of talented physics majors becoming certified to teach physics. We report on the Colorado Learning Assistant model and discuss its effectiveness at a large research university. Since its inception in 2003, we have increased the pool of well-qualified K–12 physics teachers by a factor of approximately three, engaged scientists significantly in the recruiting and preparation of future teachers, and improved the introductory physics sequence so that students' learning gains are typically double the traditional average.

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I. INTRODUCTION: THE U.S. EDUCATIONAL CONTEXT

Physics majors are typically not recruited or adequately prepared to teach high school physics. One needs only to look at reports,[1] international[2,3] and national[4] studies, and research on student learning[5] for evidence. Two out of three U.S. high school physics teachers have neither a major nor a minor in physics,[6] and there are no subject matter specialties that have a greater shortage of teachers than mathematics, chemistry, and physics.[7] Many undergraduates are not learning the foundational content in the sciences,[8,9] and average composite SAT/ACT scores of students who enter teaching are far below scores of those who go into engineering, research, science, and other related fields.[10] The effects may be dramatic. For example, only 29% of U.S. eighth grade students scored at or above proficient on the National Assessment of Educational Progress in 2005.[11] What is worse is that only 18% of U.S. high school seniors scored at or above proficient.[11] With few exceptions, universities and research universities in particular, are producing very few physics teachers.[12] And some universities are sending the message, usually implicit but often explicit, that such a career is not a goal worthy of talented students.[13]

Recently, the National Academies listed four priority recommendations for ensuring American competitiveness in the 21st century. The first recommendation, in priority order, is to "increase America's talent pool by vastly improving K–12 science and mathematics education."[1] Who will prepare the teachers? Physics teacher preparation cannot be solely the responsibility of schools of education.[14] Studies point to content knowledge as one of the main factors that is positively correlated with teacher quality.[15] Yet, those directly responsible for undergraduate physics content, physics faculty members, are rarely involved in teacher preparation.

II. THE COLORADO LEARNING ASSISTANT MODEL

At the University of Colorado at Boulder (CU Boulder), we have developed an model that engages both physics faculty and education faculty in addressing the national challenges in science education. Talented undergraduate physics majors are hired as *learning assistants* (LAs) to assist interested faculty in redesigning their large-enrollment introductory physics courses so that students have more opportunities to articulate and defend their ideas and interact with one another. In our redesigned courses, we employ findings of research on student learning, utilize nationally validated assessment instruments, and implement research-based and research-validated curricula that are inquiry oriented and interactive.[16] To this end, we have implemented *Peer Instruction*[17] in lectures and *Tutorials in Introductory Physics*[18] in recitations. These innovations have been demonstrated to improve student understanding of the foundational concepts in introductory physics.[8,9]

The Learning Assistant program in physics is part of a larger campus-wide effort[19] to transform science, technology, engineering, and mathematics (STEM) education at CU Boulder and has now been implemented in nine science and mathematics departments. The program uses undergraduate courses as a mechanism to achieve four goals:

(1) improve the education of all science and mathematics students through transformed undergraduate education and improved K-12 teacher education;
(2) recruit more future science and math teachers;
(3) engage science faculty more in the preparation of future teachers and discipline-based educational research; and
(4) transform science departmental cultures to value research-based teaching as a legitimate activity for professors and our students.

These four synergistic goals are illustrated in Fig. 1. *Undergraduate Course Transformation* is highlighted because it also serves as the central mechanism by which the other three goals are achieved within the Learning Assistant model.

Since the inception of the program in Fall 2003 through the most current data analysis (Spring 2010), we have transformed over 35 undergraduate mathematics and science courses using LAs with the participation of over 48 science

Fig. 1. Synergistic goals of the Colorado Learning Assistant program.

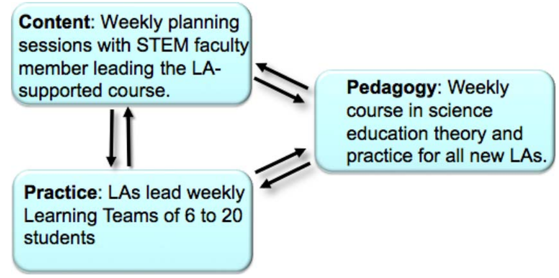

Fig. 2. The LA experience triad for developing pedagogical content knowledge.

and mathematics faculty members including two Nobel Laureates and several National Academy members. More than 15 physics faculty members have been involved in transforming a course or in sustaining previous transformations.[19] The program impacts roughly 2000 introductory physics students per year and is still growing. Recent efforts are focusing on the transformation of upper-division courses.[20,21]

The LAs are instrumental in initiating and sustaining course transformation by taking active roles in facilitating small-group interaction both in large-enrollment lecture sections and in interactive recitation sections. Because the LAs also make up a pool from which we recruit new K–12 teachers, our efforts in course transformation are tightly coupled with our efforts to recruit and prepare future K–12 science teachers.

Each semester, the physics department typically hires 18 LAs from a pool of roughly 60 applicants. These LAs predominantly support transformations in the introductory calculus-based physics sequence for majors and engineers but have also supported transformations in nonmajor introductory courses such as Light and Color, Sound and Music, and Physics of Everyday Life, and upper-division courses such as Electricity and Magnetism. In the Introductory Physics I and II courses, faculty members work with both undergraduate LAs and graduate teaching assistants (TAs) on a weekly basis to prepare them to implement research-based approaches to teaching and to assess the effectiveness of these instructional interventions. Participating faculty members also work with each other to provide support and advice for implementing various innovations, trying out new ideas, and discussing their research findings regarding the course transformations.[22] Some of these research results are presented in Sec. III.

LAs engage in three major activities each week, which support all aspects of course transformation (see Fig. 2). The LAs in each department meet weekly with the instructor of the class to plan for the upcoming week, reflect on the previous week, and examine student assessment data in these courses. LAs from all the participating STEM departments attend a course in the School of Education, *Mathematics and Science Education*, which complements their teaching experiences. In this course, the LAs reflect on their teaching practices, evaluate the transformations of courses, share experiences across STEM disciplines, and investigate relevant educational literature. In addition to weekly meetings with instructors and attending the Education seminar, LAs assume one or two main roles to support changes in lecture-based courses. First, LAs lead learning teams (sometimes in recitation sections) in which students work collaboratively to make sense of physical problems posed in curriculum activities (see Fig. 3). Second, LAs work within the large lecture setting where they facilitate group interactions by helping students engage in debates, arguments, and forming consensus around conceptual questions that are posed roughly every 20 min of lecture typically through personal response systems (clickers) used to poll the class.

Through the collective experiences of teaching as a LA, instructional planning with a physics faculty member, and reflecting on their teaching and the scholarship of teaching and learning, LAs integrate their understanding of content, pedagogy, and practice, or what Shulman[23] calls *pedagogical content knowledge*, which has been shown to be a critical characteristic of effective teachers. Putnam and Borko[24] described why pedagogical training is more beneficial when it is situated in practice—teachers have the opportunity to try out and revise pedagogical techniques by implementing them with real students. Eylon and Bagno demonstrated the effects of situating physics-specific teacher professional development in practice.[25] This reflective practice is a feature of the LA program because LAs take their Math and Science Education course during the first semester in which they serve as LAs. Those LAs who decide to seriously investigate K–12 teaching as a possible career option are encouraged to continue as LAs for a second and third semester. Those who commit to becoming teachers and are admitted to our CU-Teach teacher certification program are eligible for NSF-funded Noyce Teaching Fellowships.[26]

There are several elements that distinguish the Learning Assistant program from other programs that use undergraduates as teaching assistants. First, although course transformation is a key element of the LA program, the target population of the program is the LAs themselves. The LA program is an *experiential learning program*; the learning is embod-

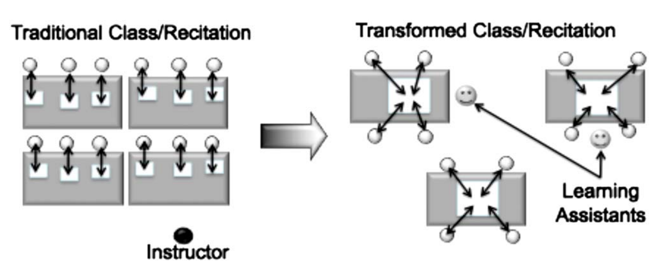

Fig. 3. Traditional versus transformed educational environment for recitation sections. The new recitation environment depicts one LA and one TA working together with students in lieu of a TA working problems solo at the chalkboard. (Lectures are still held in a 350 seat hall.)

ied in the *experience* of serving as an LA. Second, the LA program serves as a K–12 teacher recruitment program. Throughout the LA experience, LAs learn about the complexity of the problems involved in public science education and their potential roles in generating solutions to these problems. Although only approximately 12% of LAs are actually recruited to K–12 teaching careers, the program is valuable to all students as they move into careers as research scientists and college professors or into industry and have opportunities to improve science education more broadly.

III. RESULTS OF THE LA PROGRAM

The LA program has been successful at increasing the number and quality of future physics teachers, improving student understanding of basic content knowledge in physics, and engaging research faculty in course transformation and teacher recruitment.

A. Impact of the LA program on teacher recruitment

Since its inception in Fall 2003 through Spring 2010, 186 LAs positions have been filled in the physics department (120 individual LAs, 66 for more than one semester), and 123 positions have been filled in the astronomy department (82 individual LAs, 41 for more than one semester); 40 physics LAs were female (80 male) and 45 astronomy LAs were female (37 male). Of the 120 individual LAs in physics, 68 were physics, engineering physics, or astrophysics majors, and 45 were other STEM majors (such as mechanical engineering, aerospace engineering, and math); among the remaining seven, four had undeclared majors at the time that they served as LAs, and three were finance or communications. In astronomy, 27 of the 82 individual LAs were astronomy majors, three were physics majors, 17 were other STEM majors, and six had undeclared majors. The remaining 29 LAs hired in astronomy were majors such as economics, international affairs, finance, and political science. The large number of nonscience majors in astronomy should be expected because some of our astronomy course transformations take place in courses for nonscience majors, which is one of the places from which LAs are recruited. In some cases, students changed their majors to STEM majors as a result of participating in the LA program. For example, a political science major who served as a LA in astronomy changed her major to biochemistry, became certified to teach secondary science, and is now teaching science in a local high needs school district. The average grade point average of physics majors was 3.6 (the department's average is 3.0) and 3.2 for astronomy majors. Nine physics and seven astronomy/astrophysics majors have been recruited to teacher certification programs.

The impact of the LA program is demonstrated by a comparison of the total enrollments of physics/astrophysics majors in teacher certification programs in the entire state of Colorado to those at CU Boulder since LAs began graduating from teacher certification programs. In AY 2004/2005, the state of Colorado had only five undergraduate physics majors enrolled in teacher certification programs (out of almost 11000 certification students at 18 colleges and universities).[27] For comparison, in AY 2007/2008, CU Boulder's enrollment of physics/astrophysics majors in certification programs was 13. As of Fall 2009, ten physics/astrophysics majors that were former LAs were teaching in U.S. schools (mostly in Colorado), and an additional six was enrolled in teacher certification programs. Before the LA program began recruiting, CU Boulder had an average of less than one physics/astrophysics major per year enrolled in our teacher certification programs.

Most of the LAs who decided to become teachers report that they had not previously explored teaching as a career until participating as LAs. Our surveys of LAs indicate that one of the factors influential in helping students to consider teaching has been the encouragement and support of participating STEM faculty members.[13] Another frequently reported reason for deciding to become a teacher is the recognition of teaching as an intellectually challenging endeavor. A typical LA (Physics, Fall 2004) stated,

> "It would have been weird at first when I first started [to consider teaching]…. But now [the LA program] is really affecting the way a lot of us think…. So now it's kind of a normal thing to hear. Oh yeah, I'm thinking about K–12…. It's not out of the ordinary, whereas a couple years ago it would have been strange for me to hear that."

B. Impact of the LA program on physics content knowledge

Students learn more physics as a result of the course transformations supported by the LA program. In this section, we present sample results from our introductory calculus-based physics courses where most physics LAs are employed. These classes are large (500–600 students) with three lectures per week, implementing *Peer Instruction*[17] and now including the *Tutorials in Introductory Physics*.[18] The LA program in physics was established due to one faculty member's (Pollock) intention to implement the *Tutorials* after visiting the Physics Education Group at the University of Washington. At that time, the LA program was being piloted in four departments and Pollock took advantage of this opportunity to use undergraduate LAs alongside graduate TAs. We therefore have no course transformation data that isolate the use of LAs (or TAs) from our implementation of the *Tutorials*. This type of isolation would be difficult because the *Tutorials* require a higher teacher to student ratio, which was made possible at CU Boulder through the LA program. We do not argue that LAs are more effective than graduate TAs when the *Tutorials* are used. In the following, we demonstrate the value that the LA experience has on the LAs themselves and on faculty using LAs.

Each semester, we assess student achievement in the transformed courses using conceptual content surveys (in addition to traditional measures). Specifically, we use the Force and Motion Conceptual Evaluation[28] (FMCE) in the first semester and the Brief Electricity and Magnetism Assessment[29] (BEMA) in the second semester. Figure 4 shows BEMA results for all of the students enrolled in second semester introductory physics. The data demonstrate that LA-transformed courses result in greater learning gains for students and, in even greater learning gains, for students who participated as LAs. The histogram shows pre- and post-test scores for the fraction of a 600-student class within each range. The average pretest score for this term was 27%, the post-test was 59% (which corresponds to a normalized learning gain of $(\langle\text{post}\rangle - \langle\text{pre}\rangle)/(100\% - \langle\text{pre}\rangle) = 0.44$). For com-

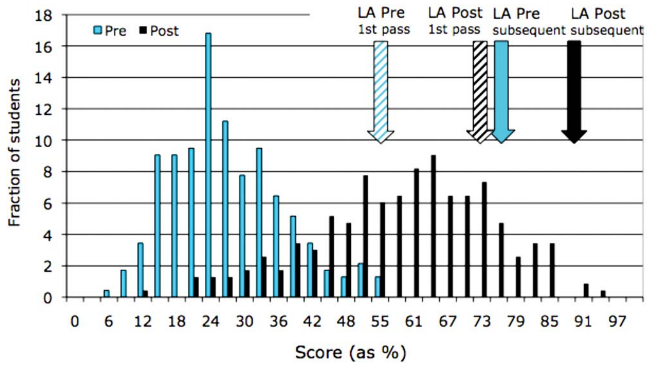

Fig. 4. Pre/postscores on the BEMA instrument for enrolled students compared to LAs. Histogram bars show data for students enrolled ($N=232$) in a representative term of Calculus-based Physics 2 (Spring 2005). Hashed arrows indicate LA pre/postscores the first semester LAs were used ($N=6$). Solid arrows indicate LA pre/postscores ($N=6$) from the following semester.

parison, a recent national study[31] shows that typical post-test scores in traditionally taught courses at peer institutions are around or below 45% (and normalized gains of 0.15–0.3). The dashed arrows in Fig. 4 show the BEMA pre- and post-test scores for LAs during the first semester that LAs were used in the physics department. All of these LAs had taken a non-transformed introductory electricity and magnetism course preceding their service as an LA. The solid arrows near the top of Fig. 4 show the average BEMA pre- and post-test scores for LAs in the first semester for which all LAs were recruited from transformed classes. That is, most of the LAs from the subsequent semesters had taken an introductory course that was transformed using LAs. The average normalized learning gains for all students in the transformed courses have consistently ranged from 33% to 45%. The normalized learning gains for the LAs averages just below 50%, with their average post-test score exceeding the average incoming physics graduate-TA's starting score.

The data in Fig. 5 show the scores of students enrolled in upper-division Electricity and Magnetism. The bin labeled F04-F05 is the average BEMA score for students who were enrolled in upper-division E&M in the three consecutive semesters from Fall 2004 through Fall 2005 ($N=71$). None of these students had enrolled in an introductory physics course that was transformed using LAs. The three bins labeled S06-S07 represent the average BEMA scores for three different groups of students who were enrolled in upper-division E&M during the next three semesters from Spring 2006 through Spring 2007: (1) those who had a traditional introductory experience with no LAs ($N=18$), (2) those who did take an introductory course that was transformed using LAs ($N=36$), and (3) students who had been LAs themselves ($N=6$). The scores of the students who did not take a transformed course are comparable in both F04/05 and S06/07. The students who had taken a transformed introductory E&M course scored significantly higher than those who did not, and the LAs scored even higher. These data suggest that the LA program produces students who are better prepared for graduate school and for teaching careers and that the LA experience greatly enhances students' content knowledge.[30] Note that although some students from each group in Fig. 5 have taken the BEMA multiple times, the average change from post-freshman score to post-junior score (after taking the BEMA for a second time following upper-division E&M) is zero.[30] Also, repeated testing of individuals on the BEMA shows no impact on their scores.[30]

In addition to increased content gains, LAs show strong evidence of attitudinal gains. The Colorado Learning Attitudes about Science Survey[32] (CLASS) is a research-based instrument intended to measure students' attitudes and beliefs about physics and about learning physics. As is the case with the Maryland Physics Expectations Survey[33] and other instruments of this type, students' attitudes and expectations about physics tend to degrade over a single semester.[33] The arrows in Fig. 6 show results from a recent semester. First semester physics students showed large negative shifts in their overall views about physics and in their personal interest as measured by the CLASS, consistent with national findings.[33] The second semester course showed smaller negative shifts (possibly due to a combination of instructor and selection effects). Both of these courses were transformed and show high levels of conceptual learning. The LAs started with much more expertlike views and high personal interest, both of which increased greatly throughout a semester of serving as LAs.

Although there is a contribution from selection effects associated with the LA data shown in Fig. 6, students who are serving as LAs shift in a dramatically favorable manner during the semester. These students make up the pool from which we are recruiting future K–12 teachers and exit the LA experience with more favorable beliefs about science, greater interest in science, and greater mastery of the content than their peers.

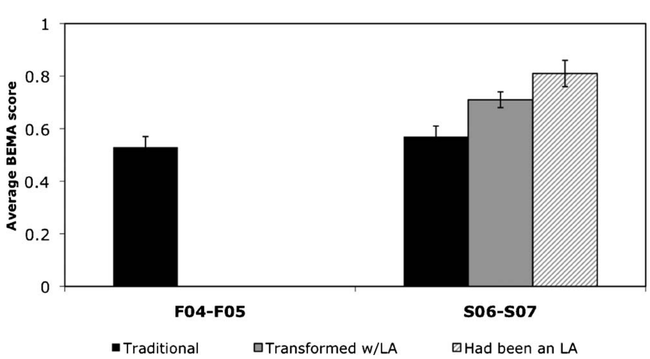

Fig. 5. BEMA scores of physics majors after taking upper-division Electricity and Magnetism, binned by semester and freshman (Physics II) background.

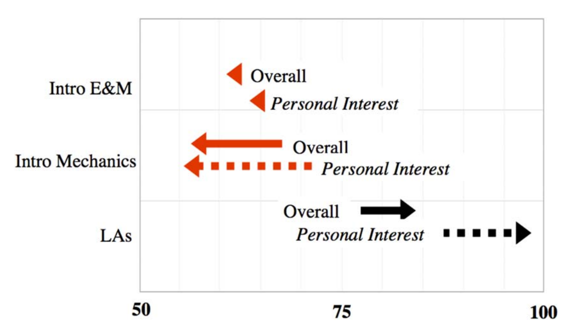

Fig. 6. Shifts by non-LA and LA students in attitudes about learning physics and in their interest in physics over one semester. The horizontal axis represents percent favorable scores on the CLASS instrument. The LA scores are an average for the LAs in both courses combined.

C. Impact of the LA program on faculty

As a result of transforming courses and working with LAs, participating faculty members have started to focus on educational issues that they had not considered previously. Faculty members report increased attention to student learning. All of the 11 faculty who were involved in the LA program from 2003–2005 were interviewed and reported that collaborative student work is essential, and LAs are instrumental to change. One typical faculty member noted,

> "I've taught [this course] a million times. I could do it in my sleep without preparing a lesson. But [now] I'm spending a lot of time preparing lessons for [students], trying to think 'OK, first of all, what is the main concept that I'm trying to get across here? What is it I want them to go away knowing?, which I have to admit I haven't spent a lot of time in the past thinking about."

This statement was drawn from the group of 11 faculty members who are now perceived by students as caring about student learning and supporting their decisions to become K–12 teachers.

Impacts on faculty are also observed in the scaling of the program at CU Boulder. Increasingly, faculty members are working together to implement the LA program in the physics department as well as in other departments. Faculty members seek out one another for support and meet weekly in informal "Discipline-Based Educational Research"[34] meetings to discuss their teaching and the use of LAs and to present data from their assessments and evaluations of their transformations.

The Learning Assistant model does not stop at the introductory level. Faculty members who teach upper-division courses are increasingly drawing on LAs to help them transform their courses, including third semester Introductory Physics[35] and upper-level Electricity and Magnetism[36] and Quantum Mechanics. In these environments, faculty members work with LAs (typically second- or third-time LAs or Noyce Fellows) to make research-based transformations to their courses. Typically, educational research regarding the efficacy of the transformation is conducted by the lead faculty member, a Noyce Fellow, and sometimes a postdoctoral scholar. In these contexts, LAs assume varying roles, all with the common theme of supporting educational practices that are known to improve student understanding.

IV. SCALING THE LA PROGRAM

We have studied the scaling of the program by examining the use of LA-supported *Tutorials in Introductory Physics* over a 6-year span, covering 15 different implementations of the tutorials by 15 faculty members.[22] We observe that it is possible to demonstrate strong and consistent learning gains for different faculty members. Table I summarizes the overall measures of students' conceptual learning gains in first semester courses. Although the listed courses span nearly the entire range of learning gains documented for interactive courses elsewhere,[9] all courses with the LA-supported tutorials led to learning gains higher than any classes that had traditional recitation experiences. All except two of the courses listed in Table I were taught by different instructors. Semesters F03 and S04 were taught by the same instructor, a faculty member who also engaged in physics education research. All of the other faculty members who taught the courses listed in Table I range from somewhat to vaguely familiar with physics education research.

Table I. Normalized gain on the FMCE for first semester Introductory Physics taught by different instructors.

Semester	Recitation	N (matched)	Average post-test score	Normalized gain $\langle g \rangle$
F01	Traditional	265	52	0.25
F03	Tutorials	400	81 (FCI data)	0.63
S04	Tutorials	335	74	0.64
F04	Workbooks[a]	302	69	0.54
S05	Traditional	213	58	0.42
F05	Traditional	293	58	0.39
S06	Tutorials	278	60	0.45
F06	Tutorials	331	67	0.51
S07	Tutorials	363	62	0.46
F07	Tutorials	336	69	0.54

[a]Students worked in small groups on problems in a workbook that came with their text. No LAs were used (Ref. 37).

The data suggest that the transformations are transferable among faculty members at CU Boulder, even among faculty members who have little or no experience with physics education research. This finding suggests that such LA-supported tutorials are transferable to faculty at other institutions.

The development of an LA program in physics departments at other institutions requires the commitment of dedicated faculty and administration within the department. Currently, at least five universities in the U.S. are funded to emulate the Colorado LA program as a part of their work with the Nationwide Physics Teacher Education Coalition.[38] Many other institutions are also emulating the Colorado LA model. Although the Colorado LA program is a campus-wide program spanning nine departments, other institutions have successfully developed and managed LA programs in the physics department alone.[39] Successful LA programs have started in the physics department with a buy-in from the department chair and a handful of interested faculty members.

Departments considering implementing an LA program need to identify sources of financial and pedagogical support for the undergraduates who will be enrolling. Implementation of an LA program requires funding of a few thousand dollars per LA per year.[40] An alternative to this cost is to provide course credit in a service-learning model,[41] where LAs receive course credit for time spent supporting course transformation. Although pedagogical support for LAs may be challenging, it is a critical component of the program. LAs must be supported both in weekly content preparation such as the tutorial preparation we have discussed and in their acquisition and implementation of pedagogical techniques through a forum such as the Mathematics and Science Education course. We encourage physics departments to partner with their Schools of Education to offer such a specialize course and have sample course materials available for those interested.

V. SUSTAINING SUCCESSFUL LA PROGRAMS

Can the Learning Assistant model be sustained? Is it possible to scale this model without significant external funding? We believe so. Currently, 85% of our LAs are funded by our administration and private donations, although these are temporary funds and the university is working toward stable institutional funding.

At CU Boulder, the Learning Assistant program is university-wide and benefits from such scale. We bring together a variety of interested faculty members, department heads, deans, and senior administrators, each of whom has a stake in and benefits from increasing the number of high-quality teachers, improving our undergraduate courses, and increasing the number of math and science majors. Because teacher recruitment and preparation are tied to the improved education for all students through the transformation of undergraduate courses, many members of the university community have a vested interest in the success of the Colorado LA program. CU Boulder recently received funding to replicate the University of Texas at Austin's successful UTeach certification program.[35] The new CU-Teach certification program utilizes the Colorado LA program as one of two methods for recruiting students to careers in teaching.

With the commitment of physics departments to the enhanced education of all students and to the recruitment and preparation of future teachers, we can collectively enhance the status of education both for the students considering teaching careers and for the faculty teaching these students. As scientists, we can take action to address the critical shortfall of science teachers by improving our undergraduate programs and engaging more substantively in evidence-based solutions in education and teacher preparation.

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PHYSICAL REVIEW SPECIAL TOPICS - PHYSICS EDUCATION RESEARCH **7**, 010108 (2011)

Preparing future teachers to anticipate student difficulties in physics in a graduate-level course in physics, pedagogy, and education research

John R. Thompson,[1] Warren M. Christensen,[2] and Michael C. Wittmann[1]

[1]*Department of Physics and Astronomy and Maine Center for Research in STEM Education, University of Maine, Orono, Maine, USA*
[2]*Department of Physics, North Dakota State University, Fargo, North Dakota, USA*
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We describe courses designed to help future teachers reflect on and discuss both physics content and student knowledge thereof. We use three kinds of activities: reading and discussing the literature, experiencing research-based curricular materials, and learning to use the basic research methods of physics education research. We present a general overview of the two courses we have designed as well as a framework for assessing student performance on physics content knowledge and one aspect of pedagogical content knowledge—knowledge of student ideas—about one particular content area: electric circuits. We find that the quality of future teachers' responses, especially on questions dealing with knowledge of student ideas, can be successfully categorized and may be higher for those with a nonphysics background than those with a physics background.

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I. INTRODUCTION

With the growth of physics education research (PER) as a research field [1,2] and the ongoing desire to improve teaching of introductory physics courses using reform-based approaches [3], there has been an opportunity to move beyond an apprenticeship model of learning about PER toward a course-driven structure. At the University of Maine, as part of our Master of Science in Teaching (MST) program, we have developed and are teaching two courses in *Integrated Approaches in Physics Education* [4]. These courses are designed to teach physics content, develop PER methods, and present results of investigations into student learning. The goal of our courses is to build a research-based foundation for future teachers at the high school and university level as they move into teaching.

Teachers must satisfy many, many goals in their instruction. In part, teachers must be able to understand from where their students are coming, intellectually, as they discuss the physics. Teachers need to know how their students think about the content. Such an agenda has a long history in PER [5] and is one part of pedagogical content knowledge (PCK) [6]. We want to help teachers recognize how investigations into student learning and understanding have led to what is known about student thinking in physics, and how the results of this research inform curricular materials development. In order to do this, we expose (future) teachers to, and let them participate in, the research on student learning; from this, they can learn to properly analyze instructional materials created based on research. And, to be consistent in our philosophy, we must attend to the future teachers' learning—of both physics content and pedagogy—as much as we wish for them to attend to students' learning. The activities described in this paper take part within a larger cycle of research, instruction, and evaluation, much as has been carried out in the PER community as a whole when developing instructional strategies to affect student learning.

In this paper, we propose to accomplish three tasks; the first two set the stage for the third. Before we describe our research, we first describe the two courses, the context in which they take place, and the activities that make up a typical learning cycle within the courses (elaborating on one such instructional unit from the course sequence in some detail). Second, we describe how we determine whether the future teachers have gained appropriate knowledge of student understanding and the role of different curricula. Finally, we draw from several semesters of data on future teacher learning of physics, pedagogy, and PER, looking at one topic that has been taught three times during this period. We present a framework for analyzing data on learning of physics content knowledge and of one aspect of pedagogical content knowledge—specifically, what conceptual difficulties a teacher might encounter among his or her students when teaching particular content. We then apply this framework to a small data set in order to provide a concrete example. All three of the tasks we have for this section are summarized in a single overarching research question: In a course designed to teach both content and pedagogy, how is future teacher knowledge affected by focused instruction with research-based materials and research literature documentation? In this paper, we present a method of assessment that we feel can be successfully used to address this question.

II. PEDAGOGICAL CONTENT KNOWLEDGE AND KNOWLEDGE OF STUDENT IDEAS

Much of the literature on PER in the U.S.A. over the past 30 years deals with identification of student difficulties with specific physics concepts, models, relationships, or representations [7]. Past results of PER on student learning at the university level have led to the development of curricular materials designed to address common incorrect or naive student ideas using various pedagogical strategies [8–16]. These curricular innovations have helped improve student learning of physics concepts, as measured by performance on specific diagnostic assessments and/or surveys. In light of the history of PER, we believe that we must prepare future physics teachers to have an awareness of how their students might think about various topics, as well as an awareness of the kinds of curricular materials available to help guide students to the proper scientific community consensus thinking about the physics. This attention to student ideas in the classroom is one component of what Shulman labeled as ''pedagogical content knowledge'' [6]. Shulman describes PCK as ''the particular form of content knowledge that embodies the aspects of content most germane to its teachability''; this includes knowledge of representations, analogies, etc. that make the content comprehensible, and ''an understanding of what makes the learning of specific topics easy or difficult.'' The component of the description most relevant to our work, however, is ''the conceptions and preconceptions that students of different ages and backgrounds bring with them to the learning of those most frequently taught topics and lessons.'' In teaching in a field such as physics, the use of analogies and representations are often helpful, if not essential, in developing a coherent and sensible understanding by students [17,18]. The ways in which students misunderstand, misinterpret, or incorrectly apply prior knowledge to common pedagogical tools need to be recognized by teachers who will be using these tools to teach and want to teach effectively.

In the larger science education research literature, research on science teachers' PCK has focused on the nature and the development of PCK in general, rather than investigating science teachers' PCK about specific topics in a discipline. van Driel and colleagues noted this issue in an article a decade ago [19]. In the context of results on a PCK-oriented workshop, the authors describe their own interpretation of and framework for PCK. The authors argue that PCK consists of two key elements: knowledge of instructional strategies incorporating representations of subject matter and understanding of specific learning difficulties and student conceptions with respect to that subject matter. They state that ''the value of PCK lies essentially in its relation with specific topics.'' Our work speaks directly to this recommendation and emphasizes the second of their two key elements.

van Driel *et al.* also suggest, based on their work and the literature review, what features a discipline-based PCK-oriented course should contain, including exposure to curricular materials and the study of what they refer to as ''authentic student responses.'' Through specific assignments and discussions, participants may be stimulated to integrate these activities and to reflect on both academic subject matter and on classroom practice. In this way, participants' PCK may be improved.

In addition, van Driel *et al.* lament the contemporary state of research into teachers' PCK and make recommendations for a research agenda on teachers' PCK. From their review of the literature, they call for more studies on science teachers' PCK with respect to specific topics. Despite the apparent specificity of this approach, they argue that the results would benefit teacher preparation and professional development programs and classroom practice beyond any individual topic. As an example of such work, Loughran and colleagues [20] have conducted longitudinal studies of teachers in the classroom, and used the results to develop a different two-piece framework for PCK, involving content representations and teaching practice. We seek to advance this agenda in physics.

Magnusson *et al.* [21] present an alternate framework and discussion. They conceptualize PCK as pulling in and transforming knowledge from other domains, including subject matter, pedagogy, and context. They argue that this enables PCK to represent a unique domain of teacher knowledge rather than a combination of existing domains. They state that ''... the transformation of general knowledge into pedagogical content knowledge is not a straightforward matter of having knowledge; it is also an intentional act in which teachers choose to reconstruct their understanding to fit a situation. Thus, the content of a teacher's pedagogical content knowledge may reflect a selection of knowledge from the base domains'' ([21], p. 111).

Magnusson *et al.* break down PCK for science teaching further than van Driel *et al.*, into five components. Their first component is ''orientations toward science teaching and learning,'' dealing with views about the goals of science teaching and learning, and how that perspective guides the teacher's instructional decisions. In PER one might classify this domain as the metacognitive and epistemological aspects of physics education. For example, Magnusson *et al.* describe the *didactic* orientation, whose goal is to ''transmit the facts of science''; the accompanying instructional approach would be lecture or discussion, and questions to students would be used for the purposes of accountability for the facts. The importance of the *orientation* component is that it acts as the lens through which any teacher—or teacher educator, as they point out—views other aspects of PCK, especially curricular materials, instructional strategies, and assessment methods. Magnusson *et al.*'s main argument here is that a teacher's orientation influences, and may even determine, his or her pedagogical choices and perspectives. In PER one would present this argument in terms of a teacher's epistemological framing of their science instruction [22], where epistemological framing describes one's (in this case the instructor's) expectations for what it means to teach science and how their students learn science, and how these expectations influence their behavior within the classroom.

The other four components deal with knowledge and beliefs about science curriculum; students' understanding of specific science topics; science assessment, including methods and referents against which to assess; and science-specific instructional strategies. Most directly relevant to our work here is the *student understanding* category. This is further broken down into two parts. The first deals with requirements for student learning, which includes prerequisite knowledge as well as developmental appropriateness of particular representations. "Developmental appropriateness" refers to the degree to which students of varying abilities can successfully work with representations that require higher-order reasoning (e.g., three-dimensional models of atoms). The second component of understanding concerns areas of student difficulty, which includes difficulties with the abstract or unfamiliar nature of the concepts, with needed problem-solving skills, or with alternate (prior) conceptions (or specific difficulties) held by students. Magnusson *et al.* argue that knowledge of these student ideas, as we are referring to them, will help teachers interpret students' actions and responses in the classroom and on assessments. From their research and the literature they cite, they find that even teachers who know about student difficulties may lack knowledge about how to address these difficulties.

In the domain of mathematics, Ball and colleagues have developed a framework for what they have labeled "mathematics knowledge for teaching" [23,24]. They envision a set of knowledge split between subject matter knowledge (broken down further into common and specialized knowledge) and pedagogical content knowledge. PCK contains three subgroups of knowledge and content: those of teaching, students, and curriculum. This framework has only recently been established but is quite similar to the one we have used implicitly. In particular, we have focused on the knowledge of student ideas (KSI), described by Ball and collaborators as the knowledge of ideas about the content that students have been documented to have.

Within the PER community, Etkina discussed the building of physics-specific PCK—described as "an application of general, subject-independent knowledge of how people learn to the learning of physics"—as a central goal in building an ideal physics teacher preparation program [25,26]. Etkina emphasizes the domain specificity of PCK, underscoring the need for each discipline to have content-tailored PCK learned in teacher preparation programs. She points out that learning about PCK should be conducted in the same manner as effective content learning, via active learning, or in this case, active teaching. In [26], Etkina describes an entire graduate program for high school physics teacher preparation that embodies the principles of learning PCK, and in which students learn about many aspects of PCK and put them into practice. Etkina's necessary and careful work is consistent with the agenda of building a large-scale framework for PCK as described above. The lack of available PCK literature in PER is reflected by its absence in Etkina's references, and indicates the need for explicit attention within this community.

Knowledge of student ideas about specific concepts and representations is common to all of the definitions of PCK employed by the researchers cited above. The course goal that we focus on in this paper is to improve future teacher KSI in physics. We have chosen to concentrate on assessing this aspect of PCK that everyone agrees on as a necessary feature. By investigating future teacher ideas about student ideas about physics, and through teacher preparation curriculum development informed by previous education research, we are attempting to improve future teachers' understanding of this aspect of the learning and teaching of physics. Our work is not aimed at building a complete, large-scale framework for PCK in physics, although hopefully our results could be useful in helping inform researchers who wish to do so.

The need to include KSI and the results of PER in teacher preparation courses is justified by the analogy to the past use of PER to inform curriculum development in physics courses. Many PER studies have challenged the assumptions that physics instructors held about their students' understanding of basic physics concepts, representations, and reasoning. There has been a long history of the rich interplay of research, instruction, and evaluation. Early versions of research-based curricular materials were implemented by physics education researchers or the curriculum authors themselves running pilot studies at their home institutions. Similarly, there is great value in having research on KSI in physics take place in an instructional setting that is designed to help physics teachers develop KSI. Trained physics education researchers who are familiar with the literature, pedagogy, and research methods are necessary for such a course to provide teachers with the full spectrum of skills and knowledge. Such a mind-set is consistent with the ideas promoted by targeted conferences on preparing K–12 teachers [27] and the recommendations of the American Institute of Physics. [28].

The work we describe here addresses only the most basic elements of instruction on KSI, namely, content knowledge as learned during instruction in a one-semester course. It would, of course, be useful to follow future teachers from this course into their teaching positions and study how and to what extent they apply their KSI or other PCK in their teaching. Similarly, one could focus on the conceptual and

TABLE I. Course I instructional units.

Physics content	Curriculum emphasized	Research method studied
Electric circuits	*Tutorials in Introductory Physics* [12] and materials from Gutwill *et al.* [31]	Analysis of free-response pretest and posttest responses [32,33]
Kinematics	*Activity-Based Tutorials* [13,14], *Real Time Physics* [11], and *Powerful Ideas in Physical Science* [10]	Free-response questions, multiple-choice surveys [Test of Understanding Graphs—Kinematics (TUG-K)] [34] and Force and Motion Conceptual Evaluation (FMCE) [35]
Forces and Newton's laws	*Tutorials in Introductory Physics* [12] and *UMaryland Open Source Tutorials* (as described in Ref. [36])	Multiple-choice surveys [Force Concept Inventory (FCI) [37] and FMCE [35]]

epistemological development of the students of our program's graduates. We hope that the research described here forms the basis for such future studies.

III. CONTEXT FOR RESEARCH

Our PER courses exist under several constraints due to the population targeted for the MST program. This population includes in-service physics teachers, either in or out of field; professional scientists or engineers transitioning into careers in education; physics graduate students, most (but not all) of whom are doing PER for their Ph.D.; and MST students from other science and mathematics fields. As a result of this variety, the class spans a wide range of knowledge of both physics and pedagogical content. Many students enrolled in the course were concentrating in mathematics, chemistry, or biology, so took the course as an elective; others were moving into physics teaching from another field (e.g., math, chemistry, biology, etc.).

A great deal of the literature and curricular materials that we cover in the course are based on the generalizations that have been made regarding the results in physics education research, especially as is related to the improvement of students' conceptual understanding [29,30]. Our goal, as stated previously, is to have the future teachers recognize, through reading and discussion of the literature, experiencing the curricular materials, and learning to use the basic research methods of PER, the importance of reflection on and discussion about physics content and student knowledge thereof, in order to gain a more coherent understanding of both the content and how best to teach it. Additionally, students encounter general issues of learning and teaching in science and mathematics primarily drawing on the literature in educational psychology and the learning sciences. However, that is beyond the scope of the course described in this paper and is addressed in a different course that is required of all MST students.

It should be mentioned that the course(s) described here have far more modest goals than the full graduate program described by Etkina [26]. There are only two discipline-specific courses for each discipline in the MST program, as well as an educational psychology course and various seminar courses. Given the span of the preparation of our candidates, the fact that these courses are not taken exclusively by future physics teachers, and our emphasis on including a research component, our courses are necessarily broader in scope and thus unavoidably less thorough at accomplishing the many goals of a full graduate program specifically designed for physics teachers.

To show the coherence of instructional materials, research methods, and research literature, we split our PER courses into content-based units. Instructional units for one course are presented in Table I, and those for the other in Table II.

TABLE II. Course II instructional units.

Physics content	Curriculum emphasized	Research method studied
Mechanical wave pulses, sound; mathematics of exponential functions	*Activity-Based Tutorials* [13,14]	Analysis of interview data [38,39]; comparing multiple-choice to free-response questions [40]
Work-energy and impulse-momentum theorems	*Tutorials in Introductory Physics* [12]	Individual student interviews [41]; assessment question formats: free-response, multiple-choice, multiple-choice-multiple-response [42]
Various, primarily kinematics	Excerpts from *Ranking Tasks* [43], *Tasks Inspired by Physics Education Research* [44]	Various forms of assessment—formative or summative
Thermodynamics	*UC Berkeley laboratory-tutorials* [45], *Physics by Inquiry* [8]	Classroom interactions; curriculum development and modification

The first course contains the most studied topics in the PER literature for which effective instructional materials exist, as demonstrated in the research literature: electric circuits (dc), kinematics, and dynamics. We use these areas to demonstrate various research methodologies, including the analysis of pretests and posttests, and the development of broad assessment tools and survey instruments. We use electric circuits before mechanics because our experience, and that of others, is that thinking about electric circuits qualitatively is often difficult for people regardless of their physics backgrounds, and so starting with circuits would put the different student populations in the class on a more equal footing at the outset.

The second course contains topics with less literature on learning and teaching at the college and high school level: mechanical waves and sound, the work-energy and impulse-momentum theorems, and basic thermodynamics. We use these topics to expose the class to more qualitative research methods, including interviews, design of different kinds of assessments and the difference in student responses between those assessments, classroom interactions, and guided-inquiry curriculum development and modification.

A typical cycle of instruction lets future teachers experience the use of several common teaching and research tools: (1) pretests on the physics that will be studied, to explore the depth of understanding of our future teachers (many are weak in physics, and we need to know how best to help them); (2) pretests on what introductory students might believe about this physics, to see how good a picture the future teachers have of student reasoning about the topic; (3) instruction on the physics using published, research-based curricula, as listed above; (4) discussion of the research literature on the physics topic, typically based on papers directly related to the instructional materials, but often set up to complement and create discussion; (5) homework dealing primarily with the physics, and sometimes also the pedagogy; and (6) posttests on all three areas of physics, pedagogy, and research and how they intersect.

Students practice clinical interview skills, and as part of an in-class research project, design a short set of instructional materials to use. There is no formal practical teaching component in our course such as microteaching.[1]

[1]MST students seeking certification carry out student teaching at the secondary level, and are observed and scored using an observation protocol partly based on the Reform Teaching Observation Protocol [46,47]. Many of our students are also teaching assistants in reform (and traditional) courses at the university level. They are also observed and scored with the protocol, after which the observers and the student discuss the observed ''lesson.''

IV. ASSESSMENT OF FUTURE TEACHER PEDAGOGICAL CONTENT KNOWLEDGE IN THE COURSE

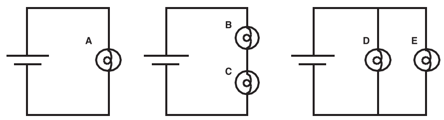
Our assessments match our course goals. We probe conceptual understanding of content by asking questions from, or based on, the research-based and -validated curricular materials used in class. To assess the grasp of the research findings and methodologies, we ask for comparative analysis of literature, or of analysis of data in light of discussions in specific papers. We assess understanding of pedagogy and curricular effectiveness by asking for comparisons between different research-based instructional strategies, and comparative analysis of different curricular materials to address a specific difficulty. Finally, we assess the development of an understanding of student ideas by asking the future teachers themselves to generate hypothetical student responses to questions unfamiliar to the future teachers.

We present one example from the context of electric circuits. Before instruction, the future teachers answer the ''five-bulbs'' question [32] and also predict what an ''ideal incorrect student'' might answer in a similar situation (Fig. 1).[2] A reasonable incorrect response on the five-bulbs analysis task would match results from the research literature and be self-consistent throughout the response, although students are often inconsistent when giving incorrect answers. As part of the unit lesson, the future teachers analyze typical responses by categorizing 20 anonymous student responses before reading the research results [32,33] on this question. One class period is spent on discussions of different categorizations. Next, the future teachers work through research-based instructional materials that begin with simple series and parallel circuits and progress through *RC* circuits. Students consider several curricula that they might use for teaching their own future students about current (see Table I) and discuss the merits and weaknesses of each. Finally, they are tested on their understanding of the physics and the research literature on student learning and possible instruction choices. To show understanding, they must refer to the correct physics and the literature as appropriate.

Tests typically have in-class and take-home components to allow for the evaluation of more time-consuming analyses of student thinking. The in-class component is demonstrated in Fig. 2. The take-home component (see Appendix) typically includes analysis of data that are new to the future teachers—it could be an interview excerpt, a set of student free responses, or a series of multiple-choice responses from a group of students—that

[2]We should point out that while the circuits unit focuses on incorrect student ideas, and on interpreting incorrect student responses to identify specific difficulties—which is how the literature addresses the issue—in a later unit on forces and motion we include curricular materials that are designed to build on student intuitions about the content [33].

1. The three circuits below contain identical bulbs and identical batteries. Assume the batteries are ideal.



Rank the brightnesses of the five bulbs above, from greatest to least. Explain how you determined your answer.

2. Consider a student giving an incorrect response to question 1. Give this "student's" response in the space below and explain which pieces of the student's reasoning are incorrect. Assume that the rankings and models are consistent (*i.e.* that the student is "ideal"). If your answer does not sufficiently explain the ranking, include the additional assumptions that the "student" might be making in giving this response.

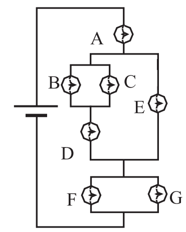
FIG. 1. "Five-bulbs" question (1) [32] and extension to assess knowledge of student ideas (KSI) (2). Correct response (for ideal batteries and bulbs): A = D = E > B = C. Common incorrect responses (meaning, "correct KSI responses") include A > B = D = E > C for current-used-up explanations and A > B = C = D = E for fixed-current, current-sharing models.

is then analyzed so they can respond to specific questions or issues, and discuss the data in light of the literature covered in the class. In sum, we test whether our students learn the correct physics concepts and whether they can predict, analyze, and classify incorrect responses they are likely to encounter when teaching, to better understand their students' thinking about the content. In later parts of the course we also ask students to suggest, design, or critique instructional materials that address typical incorrect responses.

Our emphasis on having future teachers discuss student reasoning in homework assignments in our class has increased since the creation of our courses. In the first few years, we explicitly avoided asking about student ideas on the homework, focusing instead on the future teachers' understanding of the relevant physics. More recently we have added some questions that include KSI into the homework, to allow future teachers the opportunity to practice what they have learned in our class. KSI questions were included on the exams in the course. Our instruction was therefore better aligned with our assessment.

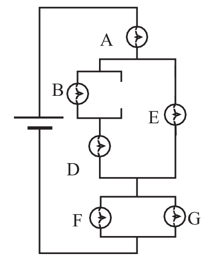
Having described the course format and sources of data on future teacher reasoning about student learning and understanding, we now discuss the data we have gathered and how we analyze it. We provide data on student understanding of concepts through responses to seminal questions and conceptual surveys from the PER literature. As stated previously, data on future teacher KSI understanding come from responses to questions on the same physics concepts assessed by the content questions. After asking future teachers to provide responses to content questions, we then ask them to provide example(s) of incorrect student responses to these same questions. Figure 1 shows an

A. Consider the circuit shown at right. Predict the relative brightness of the bulbs within the circuit. Attempt to decide bulb brightness in the circuit by reasoning on the basis of current **and also** by reasoning on the basis of voltage. Which method is better suited for analyzing the circuit? Explain.



B. Bulb *C* is now removed from the circuit, as shown in the new circuit diagram at right.

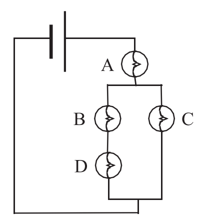
i. How, if at all, has your *ranking* from part A changed? (Not changes in the actual brightnesses, just the ranking.) Explain how you know using *either* the current model *or* the voltage model (whichever you decided works better).



ii. After bulb *C* is removed, is bulb *F brighter than, dimmer than or as bright as* bulb *F* was before bulb *C* was removed? Explain using your model for current.

iii. After bulb *C* is removed, is bulb *E brighter than, dimmer than or as bright as* bulb *E* was before bulb *C* was removed? Explain your reasoning.

C. The circuit at the right contains a battery and four bulbs. Give *three* different possible student responses that rank the relative brightness of these bulbs *and* give a model that accounts for the ranking. Only *one* of your models may be a correct model – at least two models must be incorrect and appropriately based on our readings on common student responses. Assume that the rankings and models are consistent (e.g. that students are "ideal"). If your model does not sufficiently explain the ranking, include the additional assumptions that a student might be making in giving this response.



Your responses should be consistent with the research literature and/or with observations you have made in class.

FIG. 2. Posttest questions for content (A), (B) and KSI (C) for electric circuits. (A) is based on a homework question in *Physics by Inquiry* [8]; (C) is based on unpublished posttest data. The instructions in italics at the bottom were not included until the third time the course was taught. [Correct KSI responses to question (C) are shown in Figs. 6 and 7.]

example of the paired questions we asked before instruction on electric circuits. After instruction, the questions are more focused: the content questions are more difficult, and the KSI question has the added requirement of consistency with literature or evidence. The pretest question (which was used every semester) was the five-bulbs set shown in Fig. 1; while different posttests were used for different semesters, features of these questions were similar. One version of a post-test question is shown in Fig. 2.

The results obtained are analyzed for several factors. We sought correct content understanding. We also judged responses on the extent to which the future teachers demonstrated knowledge of incorrect student models as documented in the literature. Some future teachers were quite specific about the way a student would be thinking to justify a particular response, while others gave reasoning that was less rigorous, but still reasonable. This led to a third level of analysis to account for any errors or vagueness in the KSI responses, that is, the consistency of those responses with the PER literature. We now proceed to discuss this phase of the analysis.

During the first few years of the course, the posttests contained no explicit mention of tying any incorrect responses to the PER literature. Unfortunately, this led to some responses that could be considered reasonable incorrect solutions, but had not been identified in the literature as either a single common conceptual difficulty or a combination of difficulties (i.e., a seemingly plausible incorrect answer that is unlikely to be encountered by the future teacher in a classroom of students). Eventually we added the instructions seen in italics at the bottom of Fig. 2 to individual questions; more recently we have put a more general pronouncement on the exam paper about the need for consistency with research literature. These changes have helped us receive answers more aligned with our assessment goals, though the low numbers of students in a given course preclude us from a meaningful analysis of how student responses have changed over time.

Tables III and IV show preliminary results for electric circuits. Before instruction, the future teachers themselves displayed an array of incorrect responses consistent with the published literature on electric circuits [32,33] on the content portion of the pretest (see Fig. 3). After instruction, students performed very well despite substantially more difficult questions.

In our analysis of the future teacher responses in content and in KSI, we were specifically looking for those "conceptual difficulties" that are documented in the research literature. Therefore "correct" or "nearly correct" answers were defined by the omission of any incorrect conceptual thinking. For example, on the content question, if there was one minor error (for example, one reversal in the ranking and/or reasoning of a six- or seven-bulb circuit, analogous to, say, the dropping of a factor of 2 in a long numerical solution)—rather than evidence of a more serious and pervasive specific difficulty—it implied a procedural error rather than a deep-seated one, and we classified that response as being "nearly correct" in that area. We similarly classified a future teacher response as "nearly correct" on KSI if their generated student response(s) were consistent with literature but lacked explicit descriptions of

TABLE III. Correct responses on content: Performance comparison of graduate students in displaying appropriate content knowledge on electric circuits as a result of instruction in the graduate course. (See Fig. 1 for before instruction and Fig. 2 for after instruction questions.)

	$N = 26$ (matched sample)
Before instruction	58%
After instruction	85%

TABLE IV. Appropriate KSI. Performance comparison of graduate students in displaying appropriate KSI on electric circuits as a result of instruction in the graduate course. (See Fig. 1 for before instruction and Fig. 2 for after instruction questions.)

	$N = 26$ (matched sample)
Before instruction	54%
After instruction	96%

student reasoning or student models, e.g., the ranking of bulbs was consistent with a well-documented incorrect student idea but the model was not articulated precisely, or their reasoning was a bit perfunctory. Examples of correct and nearly correct responses are shown in Figs. 4 and 5, respectively.

In the KSI analysis, before instruction most students were unfamiliar with the published research material on common student ideas about circuits, and therefore most of their examples about common incorrect student thinking were described from a more intuitive point of view. In Fig. 4, a response given on a pretest is shown; the future teacher described brightness due to "electricity," but also went on to carefully describe the ranking for each bulb. By contrast, the ranking shown in Fig. 5 is inconsistent with the accompanying explanation, which focuses on power rather than current or voltage. However, in general the response is consistent with common student reasoning, so it was classified as nearly correct.

Postinstruction testing covered several questions. We felt the need to make a distinction between some of the

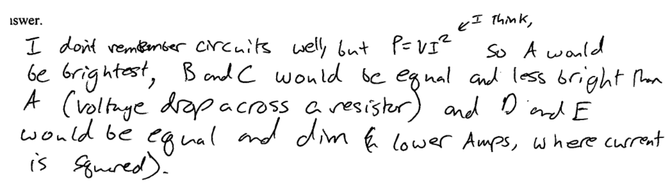

swer.
I don't remember circuits well, but P=VI² ←I think, so A would be brightest, B and C would be equal and less bright than A (voltage drop across a resistor) and D and E would be equal and dim (& lower Amps, where current is squared).

FIG. 3. Incorrect future teacher pretest response to five-bulbs question (Fig. 1). In this response the future teacher uses voltage reasoning correctly for ranking bulbs A, B, and C; their ranking and reasoning for D and E suggests the idea that the battery acts as a constant current source, consistent with results seen in the literature [13,14].

A > B = D > C = E
A is the brightest because all the electricity goes to it.
B & D are the next brightest because they're closest to the battery in their respective circuits. C & E are dim since B&D use up some electricity before it gets to C&E.

FIG. 4. Future teacher response modeling student response to five-bulbs question, before instruction. This response was classified as "correct" with respect to PCK.

A<B=C<D<E

A has the most power, B+C have half the power, and D has more power than E, but less than A.

FIG. 5. Future teacher response modeling student response to five-bulbs question, before instruction. This was classified as "nearly correct" for PCK.

2. Ranking: A>B=C>D
Model: current is used up, with distance "downstream" from the battery determining how much is left.

FIG. 6. Future teacher response modeling student response to posttest question (C) in Fig. 2. This was classified as correct for PCK.

A > C > B > D
A gets all current, C gets most current, B gets the current before D so B is brighter.

FIG. 7. Future teacher response modeling student response to posttest question (C) in Fig. 2. This was classified as "nearly correct" for PCK.

student responses that were reasonable but primarily intuitive as opposed to those that seemed to be informed by the literature. As mentioned previously, it may seem initially to be desirable for a future teacher to think up a novel and viable incorrect student response, but it is not pedagogically useful if a student is extremely unlikely to come up with such a response.

The circuit used in part C on the posttest question shown in Fig. 2 was deliberately chosen because it has been administered in introductory courses after tutorial instruction, and while the question itself has been presented in a peer-reviewed conference proceedings [48], the responses have been analyzed but not published other than in a doctoral dissertation [49]. This circuit leads to an interesting pedagogical situation: it is possible to obtain the correct ranking of the bulbs using incorrect reasoning that couples two different conceptual difficulties. A student who uses the incorrect idea that current splits in half at any junction (documented in [32]) *and* the incorrect idea that bulbs in series "share" or split current evenly (documented in [49]) would provide the correct ranking ($A > C > B = D$); approximately 10% of students in the study in Ref. [49] provide reasoning suggesting ideas related to sharing of current in series. This question thus provides the opportunity for future teachers to anticipate this response based on their reading of the literature combined with their own insight.

The response in Fig. 6 includes a brief but precise description of student thinking, in this case "current is used up"; this response was scored correct for PCK. In the nearly correct posttest response shown in Fig. 7, the ranking and explanation are given, but the future teacher fails to describe which incorrect student model is being described, and therefore this looks more like a pretest description, where the incorrect student explanations are determined from intuition rather than the research literature. So while the answers in both cases would be scored correct for course evaluation purposes, the attention to informed knowledge of student ideas, rather than what appear to be a more intuitive ideas, is reflected in the difference in our assessment scores.

Figure 8 shows results of future teacher knowledge on both content knowledge [Fig. 8(a)] and knowledge of student ideas [Fig. 8(b)] for the electric circuits questions shown in Figs. 1 and 2. For the data presented in this paper, the course enrolled twice as many students with a physics background ($N = 16$) as those with a nonphysics background ($N = 8$). Analysis of performance by physics background shows one distinct feature and the potential for

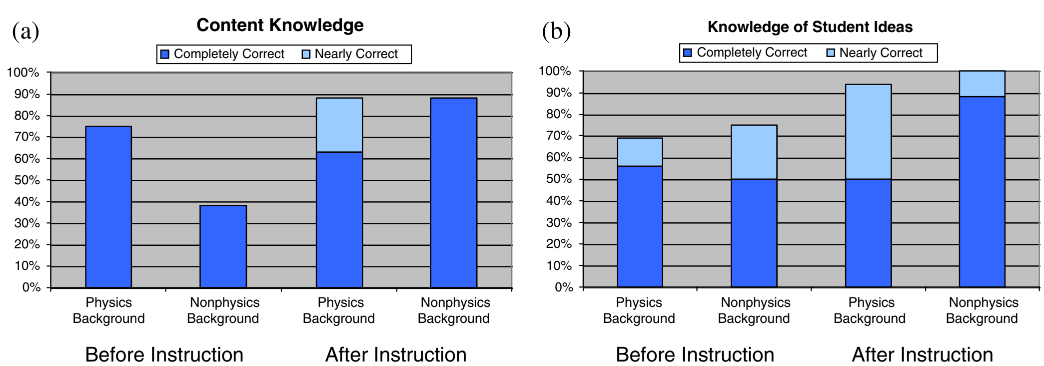


FIG. 8 (color online). Preinstruction and postinstruction results for multiple semesters of the class ($N = 24$; $N_{\mathrm{physics}} = 16$; $N_{\mathrm{nonphysics}} = 8$) on (a) content knowledge and (b) pedagogical content knowledge for the electric circuits unit. "Nearly correct" responses are those that contain one minor error over several questions (CK) or explanations that were somewhat vague (PCK), but still technically correct.

another. First—and unsurprisingly—future teachers with a nonphysics background performed far worse on content knowledge questions before instruction than those with a physics background. The second is plausible but inconclusive at this point due to an insufficient sample size. It would seem that a higher proportion of students with a nonphysics background were coded as completely correct for KSI than were students with a physics background ($p < 0.13$ using a test of binomial proportions).

V. DISCUSSION OF PRELIMINARY RESEARCH FINDINGS

Although our investigation is still in its initial phase and thus our findings are tentative, we discuss several possible implications of our analysis. The results presented above suggest a hypothesis that may be borne out with further study: a larger proportion of future teachers with a nonphysics background provide model student responses consistent with documented student difficulties in electric circuits than do those with a physics background. This result coincides with the finding that both groups end up with similar overall performance on content knowledge.

These findings are somewhat surprising—one expects stronger content knowledge to lead to better KSI. We offer a few interpretations of these findings. One possibility is that the nonphysics future teachers are being more careful in crafting their responses on the posttests than the physics future teachers, since the content is somewhat unfamiliar to them. In that light, this result suggests a need to vary assessment strategies in order to obtain multiple readings of KSI and content knowledge. A second interpretation is that the future teachers without a background in physics are more aware of incorrect or naive student ideas about the content, since they themselves may have harbored similar ideas at the beginning of the course. This is consistent with pretest responses we see from future teachers who have no physics background, in which they tell us to consider their own response to the content question as a model incorrect student response. These types of responses are absent in the pretest responses of the future teachers with a background in physics and the posttest responses from either group.

VI. CONCLUSION

We have designed a course that uses the literature and products of physics education research to deepen future teachers' content knowledge while also developing their abilities to recognize and understand the common student ideas that exist in the classroom. Our course contains features of a discipline-based PCK-oriented course, as suggested by van Driel *et al.*, and our efforts to assess the effectiveness of the course to improve PCK advances the agenda of increasing the research base on the role of discipline-specific PCK in teacher preparation put forth by these researchers [19,20]. Our focus within the very broad area of PCK on knowledge of student ideas is common to many PCK frameworks in science education. This focus is also a central component of the framework described by Ball and collaborators in mathematics education research [23,24]. Magnusson *et al.* [21] point out that addressing common student ideas, even when teachers know that they exist, is not trivial. Having future teachers work through curricular materials that contain instructional strategies explicitly designed to target specific student difficulties can provide touchstone examples from which teachers can build, thus strengthening that aspect of their pedagogical content knowledge.

We have developed a methodology for investigating future teachers' content knowledge and knowledge of student ideas using a variety of assessments, both before and after instruction. We have analyzed performance on our assessments while paying special attention to differences in physics and nonphysics backgrounds among our future teachers. We find from our preliminary analysis that our course provides future teachers with tools to anticipate student thinking, to incorporate student ideas about the content into their teaching and assessment, and to analyze student responses from various types of assessments. While we acknowledge that our sample size at this time is still small, we argue that these findings nevertheless demonstrate the utility of the methodology that we are advocating. These findings are consistent with aspects of pedagogical content knowledge espoused by many different researchers in science and mathematics education, but they are not explicitly taught or assessed in most science and mathematics education research or physics teacher preparation programs. Our course design and commensurate research begin to address the need for the PER community to engage in helping future teachers develop both content knowledge and knowledge of student ideas, an essential part of pedagogical content knowledge.

We are interested in furthering this investigation with the continued collection of data which we hope will enable us to make more definitive claims about the evolution of student content understanding throughout this course and how that may or may not impact future teachers' PCK. As we focus on this narrow thread of PCK—knowledge of student ideas—we recognize that we do not make any attempt to map out the ways future teachers might use these ideas in the classroom, which is likely to be one of the most crucial aspects of this type of work. Nor have we tapped into how a teacher's development of PCK might affect their epistemological development as they encounter alternative ways of thinking and learning that might affect their view of their role in the classroom. We acknowledge these shortcomings of our work; however, as Etkina points out, there are limits to what can be done in the preparation years of a teacher's career, and an individual's PCK may need to develop over the course of many years [26]. We suggest that if we can successfully develop a methodology that proves fruitful even in a few small areas, it may give researchers some tools to use in other investigations.

ACKNOWLEDGMENTS

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APPENDIX: TAKE-HOME EXAM

See separate auxiliary material for a sample of the take-home component of the exam.

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Appendix A

Sample of Take-home component of exam

(student data not included with this Appendix, but it is included with the exam)

4. Pretest Analysis

Analyze the attached three “5-bulbs” pretests for the rankings and reasoning behind the rankings for each student.

Notice that in this version of the pretest there are <u>two</u> questions. *You will be analyzing both questions.*

A. Analyze Question 1. Decide what model(s) each student may be using to arrive at their ranking, and state whether their reasoning is a) complete and b) consistent with the ranking.

B. Analyze Question 2 *independently of* Question 1. Decide what model(s) each student may be using to arrive at their ranking, and state whether their reasoning is a) complete and b) consistent with the ranking.

C. Briefly discuss the utility of Question 2 in gaining insight into student reasoning. What purpose does this question serve that Question 1 does not (or assumes)?

D. Consider the pretests of students *2* and *3* in particular. For each of these two students, briefly discuss their responses to both questions *as a set*.
   - Are their responses consistent with their rankings within each question (i.e. are the rankings and models consistent with each other)?
   - More importantly, are these students consistent from Question 1 to Question 2, or does their model change from 1 to 2? If so, how? And how do you know?

   Discuss the models used in each question for each student, and comment on the consistency of that student.

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5. Prediction of student reasoning

You have been given two additional students’ responses to Question 1, but not their responses to Question 2. (Note that one of them is identical to one of the ivory-colored ones handed out in class last Wednesday.)

Based on your experience in this course, analyze each student’s response to Question 1, and then make *two different predictions* for their response to Question 2.

You may assume ideal students, but you don’t have to.

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Pedagogical content knowledge and preparation of high school physics teachers

Eugenia Etkina
Graduate School of Education, Rutgers University, New Brunswick, New Jersey 08904, USA
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This paper contains a scholarly description of pedagogical practices of the Rutgers Physics/Physical Science Teacher Preparation program. The program focuses on three aspects of teacher preparation: knowledge of physics, knowledge of pedagogy, and knowledge of how to teach physics (pedagogical content knowledge—PCK). The program has been in place for 7 years and has a steady production rate of an average of six teachers per year who remain in the profession. The main purpose of the paper is to provide information about a possible structure, organization, and individual elements of a program that prepares physics teachers. The philosophy of the program and the coursework can be implemented either in a physics department or in a school of education. The paper provides details about the program course work and teaching experiences and suggests ways to adapt it to other local conditions.

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I. WHAT SHOULD THE TEACHERS KNOW?

A. Complex nature of teacher knowledge

Research in education demonstrates that the success of the current reform goals in K-12 science education depends on the preparation of teachers [1,2]. In addition to knowing the concepts and laws of physics and the methods of scientific inquiry (this knowledge is called knowledge of content), teachers should be able to create learning environments in which students can master the concepts and the processes of science. Teachers should know how people learn, how memory operates, and how a brain develops with age (this knowledge is called general pedagogical knowledge or the knowledge of how people learn). Most importantly, teachers of a specific subject should possess special understandings and abilities that integrate their knowledge of this subject's content and student learning of this content. This special knowledge, called pedagogical content knowledge (PCK), distinguishes the science knowledge of teachers from that of scientists. Pedagogical content knowledge, defined by Shulman as "the special amalgam of content and pedagogy that is uniquely the providence of teachers, their own special form of professional understanding…" [[3], p. 8], has become a key word in teacher preparation and assessment. Another important idea is that teaching science based on the methods advocated by current reforms is fundamentally different from how most teachers learned science themselves [4]; yet research indicates that teachers, unfortunately, tend to teach the way they have been taught [5,6]. The above arguments suggest that preparation of physics teachers should be a purposeful intellectual endeavor that needs to be carried out by professionals who possess strong expertise in the content area, can apply it to learning of physics and simultaneously have skills and experience in implementing the reformed way of teaching in a classroom.

B. Three pillars of teacher knowledge: content knowledge, knowledge of how people learn and pedagogical content knowledge

In the traditional path to becoming a teacher, preservice teachers are supposed to develop their content knowledge (knowledge of the discipline they will teach) and pedagogical knowledge (general knowledge of how people learn and how schools work). They learn the former while taking courses in the physics department. The latter knowledge is the domain of the schools of education. It includes the knowledge of psychology, general understandings of how people learn (for example, how memory works), how they work in groups, etc. However, in the past 20 years many teacher educators came to a conclusion that the most important aspect of teachers' practical knowledge, particularly for secondary teachers, is their pedagogical content knowledge [7,8]. Shulman [3,9] describes pedagogical content knowledge (PCK) as the knowledge of subject matter for teaching. It includes knowledge of students' difficulties and prior conceptions in the domain, knowledge of domain representations and instructional strategies, and knowledge of domain-specific assessment methods (see Fig. 1) [10]). Others have since then elaborated on the construct [11,12]. Where and how can preservice teachers develop this type of knowledge?

Much has been written about the nature and development of PCK [e.g., [13–20]]. One of the main ideas is that PCK is a personal construct and each teacher develops their own PCK over the years of teaching. Although some disagree that teachers' PCK can be developed during teacher preparation [8], Grossman, Schoenfeld and Lee [21] argue that there are some aspects of PCK that can be formed during teacher preparation years. Specifically, programs can help preservice teachers develop their PCK in regard to their understanding of student ideas in the domain and how to build on students' existing knowledge (see, for example, the work of Jim Minstrell on facets of student reasoning [22]). Obviously teacher preparation can only do so much, and a substantial building of PCK will occur during the formative induction years (first 3 years) of teachers' professional development. The first 3 years feature the greatest changes to teachers' practice until it stabilizes around the fourth year of teaching [20].

Magnusson, Krajcik, and Borko [12] suggest five aspects of PCK that preservice secondary science teachers can begin to develop during their preparation. Described briefly, those are: orientation to teaching, knowledge of curricula, knowledge of student prior understanding and potential difficulties, knowledge of successful instructional strategies, and knowl-

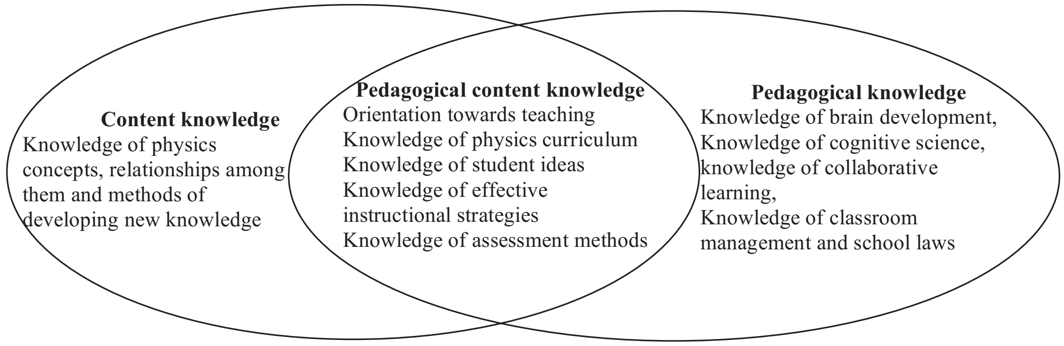

FIG. 1. The Structure of Physics Teacher Knowledge.

edge of assessment. Table I shows how the aspects of the model are related to physics teaching.

Three main points can be taken from the examples in the table:

(1) Deep content knowledge is a necessary condition for the development of PCK. If a teacher themselve does not understand the nuances of a concept, the deep relationships between this particular concept and other concepts, and the ways through which this concept was constructed by the physics community, then translating these nuances into student understanding is impossible. Therefore *it is critical that future physics teachers are skilled in the content and processes of physics* [3,6,12].

(2) Understanding of the processes of learning is crucial for the development of the orientation toward teaching, assessment methods, understanding of the role of student ideas, etc. For example, the awareness of the complex nature of brain activity should affect how teachers deal with what is widely perceived as "student misconceptions" [29].

(3) PCK is highly domain specific; therefore, it is *critical that future teachers develop teachers' PCK in the specific topics that they will be teaching*. This is particularly relevant in the sciences; the different disciplines such as biology, physics, and earth science have distinct teaching methodologies, curricula, and instructional sequences [30]. Each subject has its own PCK. Several books are dedicated to science PCK, one of them being [20]. In physics many aspects of PCK are explicitly and implicitly addressed in [31–33].

C. Course work to learn how to teach physics

As mentioned above, in the traditional approach to teacher preparation, future teachers learn the content of the disciplines they will teach in the arts and science departments and the teaching methods in the schools of education. Studies of teacher preparation programs in schools of education find that most of them have one course that prepares future teachers to teach their subject. In science education, teachers of all sciences (biology, physics, chemistry, and earth science) enroll in the same course, i.e., "Materials and Methods in Secondary Science," which cannot prepare them for the instruction of all the complicated topics of their discipline. In their review of methods courses, Clift and Brady reported that few teacher preparation programs were "preparing to teach distinctly different areas of science, such as physics or biology" [[34], p. 322]. They suggested that more content-specific methods courses where students learn how to teach the subject of their specialization are necessary to prepare high quality teachers. Moreover, the undergraduate coursework in their respective science disciplines leaves future teachers with gaps in their content understanding [6] and does not seem to prepare future teachers to teach in ways that follow the recommendations of the National Science Education Standards. Many future teachers do not experience the reformed, interactive-engagement pedagogy while learning the content. Thus, there is a need for preservice teachers to reconceptualize the content when they enter teacher preparation programs, not only to become familiar with the aspects of PCK such as outlined above but also to experience how science learning happens in reformed environments.

D. Physics specific clinical practice

If one cannot learn physics by just listening and reading but needs to engage in the active process of knowledge construction, the same should apply to PCK; one can only acquire PCK by actively constructing it in the process of teaching (called clinical practice). Thus an opportunity to model good teaching with learners becomes equally important for teacher preparation [3,7]. This modeling can happen either in the courses where students learn physics, if physics learning is followed by reflection on how one learned, or in content-specific methods courses. In these courses, preservice teachers first act as students learning a particular concept or procedure through a method that they are expected to use later when they start teaching; then later in the course they engage in microteaching. Microteaching is a technique where the preservice teachers teach their lessons and their peers act as high school students. Although it might seem that teaching a lesson to one's peers is not the same as teaching it to high school students, many elements of such practice are extremely useful: learning to plan the lesson, learning to choose the resources to achieve specific goals, learning to study research evidence on students' ideas, and finally learning to interact with "potential" students and revise the plan based on questions and comments that come up during the teaching of the lesson. Another way to engage future teachers in reformed teaching is for them to become Learning Assistants (Learning Assistants are talented undergraduate science majors with demonstrated interest in teaching; they

TABLE I. Five aspects of PCK and their relationship to teaching physics.

Aspect of PCK	How this relates to teaching physics	Specific example from physics
Orientation to science teaching.	Beliefs regarding the role of students' prior knowledge in their learning, the purpose of problem solving, the roles of experiments in the classrooms, what motivates students in the classroom, etc.	For example, 3 teachers have the following beliefs about the purpose of problem solving in physics: Teacher A: When students solve more textbook problems, students learn to apply physics principles and connect physics and math. Teacher B: Students learn to reason like scientists; they need to learn to represent problem situations in multiple ways. Thus students should learn to represent a particular situation in multiple ways without solving for anything. For example when studying circular motion students are provided with the pictures of three roller coasters—moving on a flat surface, at the bottom of the loop and on the top (upside down). They need to draw motion and force diagrams for each coaster and write Newton's second law for the radial direction [23]. Teacher C: To be proficient problem solvers students need to use a clear sequence of steps that will help them acquire the habit of drawing a picture, representing the situation, evaluating their answer, etc [24].
Knowledge of curricula.	The knowledge of the sequence of topics that allows a student to build the understanding of a new concept or skill on what she or he already knows.	One needs to understand the ideas of impulse and momentum in order to construct a microscopic model of gas pressure [25].
Knowledge of students' prior understandings about and difficulties with key concepts and practices in science.	Knowledge of students' preinstruction ideas when they are constructing a new concept. Knowledge of difficulties students may have interpreting physics language that is different from everyday language.	*Productive ideas:* Conservation and transfer of money can be related to such conserved quantities as mass, momentum, and energy. *Language:* Heat in everyday language is treated as a noun–a quantity of stuff–whereas in physics, heating is an active process involving the transfer of thermal energy. Also, force is often treated as an entity (an object has a weight of 50 N) as opposed to an interaction between two objects [26].
Knowledge of instructional strategies to scaffold students' learning of key concepts and practices in science.	Knowledge of multiple methods or specific activity sequences that make student learning more successful and an ability to choose the most productive strategy or modify a strategy for a particular group of students or an individual.	For example, when students learn Newton's laws, it is helpful to label any force with two subscripts indicating two interacting objects [25]; when students learn about electric current and potential difference, it is useful to know that an analogy between a battery and a water pump might not be clear for the students as many do not understand how pumps work [27].

are hired to facilitate interactive, student-centered approaches in large-scale introductory science courses after they themselves passed this course [35]) or laboratory or recitation instructors in the physics courses that follow reformed curricula. In most teacher preparation programs, students have to do student teaching in which they assume some of the responsibilities of the classroom teachers for a limited period of time. This is another opportunity for them to practice this new way of teaching. For both types of activities (microteaching with their peers as students and teaching "real" students) to contribute to the development of PCK, physics teacher educators need to constantly provide help and feedback to the future teachers and then slowly "fade" that feedback (that is, reduce its extent) as the future teachers become more and more skilled. Therefore learning and mastering PCK resembles "cognitive apprenticeship"—a process

TABLE I. (*Continued.*)

Aspect of PCK	How this relates to teaching physics	Specific example from physics
Knowledge of what to assess and specific strategies to assess students' understandings of key concepts and practices.	Knowledge of ways to assess student conceptual understanding and problem solving and general scientific abilities; knowledge of how to help students self-assess their work and to engage in a meaningful reflection.	For example, physics "Jeopardy" problems in which a student has to describe a situation that matches a given equation are an effective way to assess whether students understand the meanings of the symbols in mathematical equations that they use to describe physical processes and to solve problems [28]. An example of a Jeopardy problem is: A solution to a problem is described mathematically as $0.020\ \mathrm{N} = (0.020\ \mathrm{A})(0.10\ \mathrm{T})L(0.50)$. Draw a picture of a possible situation described by the equation and write the problem description in words.

of acquiring a cognitive skill with slowly fading coaching and scaffolding [36]. Scaffolding is a temporary support provided by the instructor to assist learners; it can be done through questions, prompts, suggestions, etc. [37,38]. The support is then gradually withdrawn, so that the learners assume more responsibility and eventually become independent.

In this paper, I describe a graduate program for preparing physics teachers, focusing mostly on how it helps them build physics knowledge and physics PCK through cognitive apprenticeship (there will be fewer details on how the program develops future teachers' general pedagogical knowledge). Although this particular program is housed in the School of Education, similar course work and especially the clinical practice can happen in a physics department.

II. BUILDING A PROGRAM TO HELP FUTURE TEACHERS LEARN WHAT THEY NEED

A. Cognitive apprenticeship and PCK

Cognitive apprenticeship is in many ways similar to traditional apprenticeships used in preparation of artists, musicians, tailors, etc. At first, the apprentices observe the expert as he or she models desired practices. Then the apprentices attempt the practice and the expert provides feedback (on past performance), coaching (advice and examples for future performance) and scaffolding (support during performance). The expert slowly removes scaffolding and finally provides apprentices with opportunities for independent practice. However, cognitive apprenticeship differs from regular apprenticeships because some of the processes and skills used by the expert are mental and thus cannot be observed directly. Thus it is necessary to make the process explicit and "visible" for the apprentices [39].

A similar approach is used in science research groups while training graduate students to become scientists. It is not enough for the students to simply observe other scientists doing their work; they need to understand the invisible thinking processes behind the scenes. At the same time, they need constant feedback when they start engaging in the practice themselves. And since the practice is very complex, multiple exposures in different contexts are necessary for a graduate student to become a scientist. The same is true for a teacher. The craft is complex and invisible, often subconscious for the teacher herself. Thus to learn to be a high-quality teacher, the person needs multiple exposures in different contexts and the explicit effort of an expert teacher to make her thinking and her basis for decision-making in the classroom visible to the novices. In addition, preservice teachers need to have opportunities to practice the skills of listening to the students, changing their plans depending on what students say, responding to specific student comments, planning what questions to ask, etc., first in "sheltered environments" and then gradually moving to independent teaching. Table II summarizes the opportunities a preservice physics teacher preparation program needs to provide for its students so they acquire PCK through cognitive apprenticeship.

B. Theory into practice: rutgers physics teacher preparation program

In this Sec. I will describe the physical science teacher preparation program at Rutgers, The State University of New Jersey, which is designed to provide preservice physics teachers with all of the opportunities described in Table II. As with every teacher preparation program, this program is tailored to the specific certification requirements of the state. In the state of NJ all high school teachers are required to have a major in the subject they are teaching or a 30-credit coherent sequence in that subject (with 12 credits at the 300–400 level) and pass the appropriate licensure exam(s). According to state requirements, there are separate certifications for physics teachers, chemistry teachers, and physical science teachers. A physics teacher needs to satisfy the requirements described above; a physical science teacher needs to be eligible for certification in either physics or chemistry according to the requirements for all subjects and then have 15 credits in the other subject. In addition, every certification program in the state has to show that its graduates satisfy NJ Professional Teaching Standards. If a teacher is certified to teach one subject, they can obtain another certification after satisfying the major requirements in this subject and passing the relevant licensure exam(s).

Because of the above, and because of the research done by the Holmes group [41] on the importance of strong undergraduate background for teachers, the program at Rutgers

TABLE II. Elements of the teacher preparation program.

What preservice physics teachers should learn	The program provides opportunities for a preservice teacher to	How this relates to PCK
Physics content and processes through which knowledge is acquired.	1) be a student in a classroom where physics (both content and the processes) is taught in ways that are consistent with the knowledge of "how people learn" [40], 2) engage in this way of teaching, and 3) reflect on their own learning of physics and on the learning of others.	Orientation to science teaching. Knowledge of curricula.
How their students learn physics and how to assess their learning.	1) read research literature on student learning; 2) observe and interview students learning physics, 3) reflect on classroom observations, 4) study different curriculum materials, and 5) interpret student work.	Knowledge of students' ideas and difficulties. Knowledge of instructional strategies. Knowledge of assessment methods.
How to actually be a teacher in a physics classroom, how to set goals for student learning, how to help the students achieve the goals, and how to assess whether students achieved the goals.	1) engage in teaching or co-teaching in environments that mirror the environments that we want them to create later (at first, without planning or assessment), 2) then add planning and assessment but with scaffolding and coaching, and finally, 3) engage in independent teaching that involves planning and assessment.	All of the above.

is a graduate level program. The Rutgers Graduate School of Education (GSE) has had a master's program in teacher preparation for the last 15 years; however before 2001, there was no special preparation program for physical science teachers. All science teachers were prepared together and based on their undergraduate majors they were certified to teach either biology or physical science (there was no special certification in physics in NJ at that time, there was only physical science). There were no content-specific methods courses where preservice teachers learned physics PCK. Before 2001 there were only 0 to 2 physical science teachers certified per year.

In 2001, the science program was reformed. It was split into two: life science and physics or physical science (by that time NJ had three separate certifications—for physical science, for physics only, and for chemistry only; Rutgers chose not to certify teachers in straight chemistry due to the absence of a chemistry education expert in the Graduate School of Education). Both physics or physical science and life science programs are offered as a 5-year program or a postbaccalaureate program. This paper only focuses on the physics or physical science programs. Appendix A shows the paths one can follow to get an Ed.M. degree and a physics certification at the Rutgers Graduate School of Education (GSE) and the details of different programs.

A short explanation might help the reader understand the difference between physical science and physics programs. The physical science program leads to a certificate in physical science. The prerequisite for admission is a physics major+15 chemistry credits or a chemistry major+15 physics credits. Students who receive physical science certification can be hired to teach physical science in middle schools and high schools (that involves a mix of physics and chemistry), and can also teach physics and chemistry. Students who receive physics certification (for which a physics major is a prerequisite) can be hired to teach high school physics only. Having the physical science certification not only allows physics majors to teach more subjects, but also allows chemistry majors to enroll in the program if they have a sufficient number of physics credits. Combining physics and physical science programs into one program is natural thing to do as in high school physical science, and even in chemistry, almost 50% of the content belongs to both chemistry and physics (gas laws, thermodynamics, atomic, and nuclear structure, etc.). However, due to the nature of the program, it attracts mostly physics majors. (In the last 2 years only one chemistry major went through the program; her teaching load now consists of one chemistry course, one physics course, and two physical science courses). What is important here is that the content of the programs once a students is enrolled is identical, the same is true for the 5-year and the postbaccalaureate programs.

The goals of both the 5-year and the postbaccalaureate programs stated in the program mission are to prepare teachers of physics or physical science who are knowledgeable in the content and processes of physics, who can engage students in active learning of physics that resembles scientific inquiry, and who can assess student learning in ways that improve learning.

To address these goals, the new program has multiple ways through which it prepares preservice teachers to teach physics or physical science. These can be split into three

TABLE III. Coursework and clinical practice.

	Coursework		Clinical practice	
Year/semester	General Education	Physics PCK and physics	As a student	As a teacher
1/Fall	1. Educational psychology 2. Individual and cultural diversity	1. Development of ideas in physical science	Teach (as a part of a 2–3 student team) 2 h in a class of peers who act as high school students	Work as an instructor in reformed recitations or laboratories with the full responsibility of a TA (no other instructor is present in the room).
1/Spring		1. Teaching physical science 2. Technology in science education 3. Upper level physics elective	Plan multiple lessons and one whole unit, teach a lesson in class (as part of a 2-student team). Observe 30 h of HS lessons (teach a lesson or two), reflect on experiences, conduct interviews with students.	
1/Summer	1. Assessment and measurement for teachers (2 credits)	1. Research internship in X-ray astrophysics	Observe HS students learning physics, astrophysics, and X-ray research in a summer program.	Teach sections in introductory physics summer courses (full responsibility).
2/Fall	1. Classroom management (1 credit)	1. Teaching internship seminar for physics students 2. Teaching internship (9 credits)	1. Observe high school physics instruction for 2 weeks, reflect on teaching experiences during the rest of the semester, write lesson and unit plans, tests.	2. Gradually assume individual responsibilities of a high school physics teacher. Plan, implement, and assess lessons. Plan, implement, and assess one unit.
2/Spring	1. Ethics	1. Multiple representations in physical science 2. Upper level physics elective	Plan multiple lessons and one whole unit; teach a lesson.	Work as an instructor in reformed recitations or laboratories.
After graduation	Participate in web-based discussions, attend meetings twice a month at the GSE, participate in professional development.		Work as a high school physics or physical science teacher and reflect on experiences.	

different categories: strengthening the physics content knowledge, preparing to teach physics or physical science, and practicing new ways of teaching in multiple environments (clinical practice). In addition the program builds a learning community of teacher candidates as they take courses in cohorts and continuously interact with each other during the two years of the program. What is extremely important here is that the Rutgers program does not end when preservice teachers graduate and become high school physics teachers. There is an infrastructure in place to help graduates continue to interact with program faculty and each other (maintaining and strengthening the community of all program graduates) and participate in a continuous professional development program.

Table III shows the structure of the program for the post-baccalaureate students. The students in the program take general education courses with other preservice teachers in the GSE; physics PCK courses and clinical practice are arranged so that the physics or physical science students are separate (in the technology course 50% of the work is with the preservice life science teachers). All courses are 3-credit courses unless otherwise noted.

Table III shows that there are six physics-specific teaching methods courses that students take. Since it is impossible to describe all of them in this paper, I focus on the similar elements in the structure of the courses in the following section and then describe three of them in detail in Sec. IV. The syllabi of all of them and examples of class assignments and student work are available in Appendix D at XX (URL will be provided by the PhyRev ST PER). The choice of these three is based on the premise that they can be taught in a physics department.

C. Rutgers program and PCK courses

All PCK courses have a similar structure. The theoretical foundation for the structure is cognitive apprenticeship. The content of the courses is a combination of physics (content and process) that teacher candidates will be teaching in a high school; knowledge of how to engage students in the learning of physics (science and physics education research) and how to plan and implement this instruction (science education and teacher preparation). Students attend a 3-h class meeting once a week. In the first half of the semester they learn physics and PCK through interactive-engagement methods (students who learn through these methods investigate physics phenomena with the guidance of instructor and devise and construct their own ideas as opposed to being told about them, for more information see Refs. [40,42]). Then they work individually at home reflecting on the class experience, studying additional resources, and writing either about how a particular physics idea was constructed by physicists or planning how they will teach a particular idea in a high school classroom. In addition, they work in groups on a comprehensive project that involves planning a unit of instruction and microteaching a lesson. The groups have two to three students. Each semester each student works with different partners, thus by the end of the program each student establishes working relationships with other students in the same cohort. In the second half of the semester all class meetings turn into lessons taught by the students. The assessment for the course is done multiple times through the feedback on weekly written homework and student projects, weekly class quizzes, and the final exam (in "Teaching Physical Science" and "Multiple Representations in Physical Science" courses). Students have an opportunity to improve their work as many times as needed to match the desired quality (usually the number of revisions ranges from 4 at the beginning of the semester to 1 at the end). Although the instructor gives formal grades at the end, they are often very high since all students redo and improve their work multiple times to meet course standards. Table IV provides the details for the courses and relates them to the elements of cognitive apprenticeship. Due to the nature of the assessment in the PCK courses and the intense work by the instructor with student groups preparing their lessons for microteaching, PCK classes cannot have large enrollment. Classes between 15 and 17 students are manageable.

Examples of Quiz questions in different courses show different foci and different levels of PCK sophistication (an example of a student's response to the quiz questions is in Appendix D, p. 35):

"Development of Ideas in Physical Science;" Week 7 Quiz question 2:

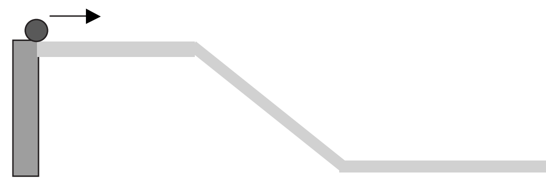

FIG. 2. Ball on track.

In his book Horologium Oscillatorium published in 1673, Christiaan Huygens described his method of controlling clocks with a pendulum. In this book one can find the following statement: "If a simple pendulum swings with its greatest lateral oscillation, that is, if it descends through the whole quadrant of a circle, when it comes to the lowest point of the circumference, it stretches the string with three times as great a force as it would if it were simply suspended by it."[1] What should Huygens have known to be able to make this statement? Explain how he came up with the number 3 for the problem. Draw a picture, a free body diagram, and an energy bar chart if necessary.

Teaching Physical Science Quiz Week 3 (complete Quiz, the first assignment is taken from the book "Five Easy Lessons" by R. Knight)

(1) Draw position, velocity and acceleration vs time graphs for the ball that is moving as shown in Figure 2.

Place the graphs under each other so the reading on the time axis matches the clock readings when the ball passes different sections of the track.

(2) Draw one possible graph that a confused student would draw and explain why they would draw it.

Multiple Representations in Physical Science, Week 4, Question 1

A student says: "I do not understand: what is the difference between $\vec{E}$ and V? Why do we need both?"

(a) How do you respond to these questions for yourself?

(b) What would you do in class when a student asks these two questions?

D. Nature of science foundation of PCK courses

Although preservice teachers have (or are finishing) an undergraduate degree in the discipline, many learned the subject through traditional lecture-based instruction and not through the methods that they will need to use when they themselves teach. (However, this is changing now that some of the Rutgers introductory courses have been reformed in collaboration with the GSE.) Therefore, in all physics PCK courses, preservice teachers re-examine physics ideas via the methods that they can later use with their students. The main focus is on how to engage students in the active construction of their own ideas [42]. In particular, the program uses the framework of the *Investigative Science Learning Environment* (*ISLE*) [29]. *ISLE* is a comprehensive physics learning system created for introductory physics courses (used in college and high school) that replicates some of the processes

[1]The text of the statement can be found W.F. Magie, *A Source Book in Physics* (McGraw-Hill, New York, 1935), p. 30.

TABLE IV. Repeated elements of physics PCK courses.

Course week	In-class work	Out-of-class work
Weeks 1–7: Instructor models good teaching practices and preservice teachers reflect.	Part 1: Preservice teachers act as students and participate in physics lessons that are conducted in an interactive, inquiry-oriented manner; they work in groups on questions and problems and present their solutions on white boards. Part 2: Preservice teachers act as teachers reflecting on the learning that happened in class and the actions of the instructor, analyzing them from the PCK point of view. Part 3: Preservice teachers act both as students and teachers by responding to the written formative assessment questions based on the content of the material and simultaneously on the responses given by high school students learning the same material. Even though students act as teachers reflecting on their learning and on the content of materials or quizzes, they do not lead the lessons.	Part 1: Students read original texts written by physicists (Galileo, Newton, Oersted, Joule, etc.), physics education research papers, textbooks, and other sources (which vary depending on the specific course) and use them to write a reflection on the process of construction of knowledge. The emphasis is on conceptual understanding, scientific reasoning, and high school student learning of specific topics. Students send their reports to the instructor who provides feedback after which students revise their work. Part 2: Students work in groups planning their microteaching and receive feedback from the instructor.
Weeks 8–14: Preservice teachers engage in microteaching their peers with immediate feedback from the instructor and reflect on their experience.	Part 1: A group of preservice teachers teaches a 2-h lesson to the class; the rest act as students. The instructor focuses "teacher" attention on student responses and asks them to "rewind" the lesson if they did not hear or respond to the comments or questions. Part 2: All students act as teachers. They reflect on the details of the lesson and discuss possible improvements.	Both parts 1 and 2 continue from above. Part 3: Students work together preparing for the final oral exam.
Week 15	Oral exam in which preservice teachers answer questions related to teaching specific physics topics, solve problems, and show interesting physics applications that would motivate their high school students to learn physics.	

that scientists use to construct knowledge and places a strong emphasis on the tools with which scientists reason. In each conceptual unit, introductory physics students construct concepts (ideas) by analyzing patterns in experimental data and then testing their ideas by using their own concepts to predict the outcomes of new experiments (that they often design) or applying their ideas to solve practical problems. When students first encounter a new phenomenon, they use their own language to describe and explain it, and only later, when they feel comfortable with their explanations, does the instructor tell them about the scientific language and accepted models. Curriculum materials to implement *ISLE* are in the published *Physics Active Learning Guide* [25] and are available on public websites http://paer.rutgers.edu/pt3 and http://paer.rutgers.edu/scientificabilities

ISLE uses a combination of inductive, hypotheticodeductive, and analogical reasoning, which are types of reasoning most commonly used by scientists. In addition, *ISLE* explicitly focuses on helping students learn how to represent ideas in multiple ways; multiple representations become the tools that they use to analyze physical phenomena and develop models. Many activities that students perform after they construct an idea require them to represent a physical process in different ways—sketches, diagrams, graphs, data tables, and mathematical equations—without solving for anything [see examples in (25)]. In the laboratories students design their own experiments without a cookbook recipe but with the help of questions that focus on the process of scientific reasoning [43,44]. In summary, the features of *ISLE* are closely matched with the guided inquiry-style teaching that the National Science Education Standards [1] and especially NJ state standards [45] encourage teachers to employ.

E. Rutgers program and clinical practice

The clinical practice is also organized on the principles of cognitive apprenticeship. Students observe and reflect on the lessons conducted by the program coordinator in the courses described above. They plan and implement their own "high school" lessons in those courses under close supervision and immediate feedback of the program coordinator. The also spend 10 half-days in high schools observing physics lessons and interacting with students during the second semester in the program. In addition for the first two semesters, preservice teachers work as instructors (either for laboratories or problem-solving sessions) in reformed physics courses similar to what physics graduate students would do. One can say that they are TAs except their teaching load is usually limited to one laboratory and/or one problem-solving session per week (which is about 2–3 contact hours, plus office hours, grading of homework or exams, and attendance at training meetings). The preservice teachers are fully and individually responsible for the learning of introductory physics students in the sections they teach. However, they do not plan their own recitations and do not design laboratory materials or write course exams. These plans and materials are provided for the preservice teachers by the course coordinator. Thus their teaching in the course is a very simplified and sheltered version of high school teaching where a teacher writes lesson plans, assembles equipment, writes tests, assigns course grades, etc. Preservice teachers' major responsibility is to implement instruction in a reformed atmosphere and reflect on what happened in class. This is possible as the physics course in which they teach is *ISLE*-based [29].

In problem-solving sessions undergraduate students work in groups on the assigned problem and then present their results to the class on a whiteboard and in laboratories they design their own experiments. The learning environment matches the national science standards and NJ state science standards and provides preservice teachers with an opportunity to practice teaching in ways they are expected to teach in a high school. The preservice teachers also have an opportunity to observe student responses and growth in such an environment. The instructor in that physics course is a physics education research (PER) expert who is deeply committed to working with preservice teachers.

In the second semester, preservice teachers spend 3 h/week for 10 weeks in local high schools observing high school physics lessons and reflecting on their observations (it is a part of the GSE structure for all teacher preparation programs). The program coordinator works closely with the GSE official who places the students to make sure that the teachers in the schools chosen for observations practice high quality, student active, inquiry-oriented teaching. To achieve this goal, the preservice teachers are only placed with teachers who either are graduates of the program or work with the program closely. These observations parallel the work in the "Teaching Physical Science" course, which has a set of weekly assignments to foster reflections on classroom observations. Also during this spring semester preservice teachers continue teaching in laboratories and recitations.

In the summer, they enroll in the Research Internship course in x-ray astrophysics. This course accompanies a year-long program for high school students (Rutgers Astrophysics Institute) who learn how to conduct authentic research (in the summer) and then carry out the research (during the following academic year) in x-ray astrophysics (more information about the program can be found in [46]). Preservice teachers observe high school students learning physics and astrophysics through the *ISLE* approach in the summer part of the program and then learn how to access NASA archival databases and interpret photon data to build models of x-ray sources (low and high mass binaries, bursters, supernovae remnants, etc.). This experience allows preservice teachers to not only watch how quickly and efficiently high school students learn when they are in an environment built on knowledge of how people learn, but they also see the "nature of science" at work and learn how to bring real science into the classroom.

In the fall of the second year preservice teachers do their student teaching internship (which is a part of the preparation of all preservice students in the GSE). For this teaching internship they are placed with the cooperating teachers who are graduates of the program (usually these are the same teachers who were observed by the interns in the spring of the previous year). This is both extremely important for the student teaching experience and makes the physics program unique in the GSE. These placements are only possible because of the continuous interaction of the program staff with the graduates (Table III). Placing the interns with the graduates of the program allows the interns to practice what they learned and avoid the conflict between how they are "supposed to teach" and "how real teachers teach." During the student teaching internship, they plan and execute their lessons with the supervision of the cooperating teacher and the university supervisor. Once a week they come to Rutgers for a course, Teaching Internship Seminar, where they reflect on what happened during the week, learn to interpret and assess student work, and plan their new lessons. In the spring, they return to teaching introductory laboratories and recitations at Rutgers. During this semester, they start interviewing for high school teaching positions. The interviews involve teaching a demonstration lesson. These lessons are planned together with the graduate advisor (the author of the paper). Because of these clinical experiences at Rutgers, the preservice teachers slowly build their skills and confidence as they move toward independent teaching. This section provided a general overview of the PCK-related courses; the details of two of them are given in the next section.

III. RUTGERS PROGRAM COURSE WORK DETAILS

This section describes two methods courses in detail ("Development of Ideas in Physical Science" and "Teaching Physical Science") and provides an overview of "Multiple Representations in Physical Science." Although a great deal of course work is based on science education literature, the "meat" of the courses is PER-based. During the two years in the program, preservice teachers read and discuss seminal papers of the founders and developers of the PER field (and their corresponding research groups) such as A. Arons, L. McDermott, F. Reif, E. Redish, A. Van Heuvelen, R. Beichner, F. Goldberg, J, Minstrell, D. Hammer, D. Meltzer, and many others. In the Rutgers program these courses are taught in the Graduate School of Education, however all of them can be offered in a physics department, provided that a person in charge is an expert in physics, general pedagogy and physics PCK. An important feature of the course content is that the preservice teachers learn how to teach every concept of the high school curriculum at least twice in different courses, from different angles. They also see how those concepts logically build on each other and how to structure the curriculum so students can benefit from those connections.

A. Development of Ideas in physical science (first year, fall semester)

1. Overview

"Development of Ideas in Physical Science" is a three-credit course that meets once a week for 160 min, fifteen times during the semester. The goal of the course is to help students learn how physicists developed the ideas and laws that are a part of the high school physics curriculum. "Ideas" that students investigate correspond to the major building blocks of physics and chemistry, such as motion, force, energy, molecular structure of matter, electric charge, electric current, magnetic field, light as a wave or a photon, and atomic and nuclear structure.

One might question why knowing the history of physics is important for future teachers. There are several answers to this question. One is that knowing the history allows preservice teachers to develop their content knowledge—the knowledge of the inquiry processes through which the discipline develops knowledge. In addition, it might help future teachers develop their PCK. Often student learning resembles scientists' grappling with ideas [47,48]. For example, it took thousands of years for scientists to accept the concept of a rotating Earth. A major obstacle was the concept of relative motion. High school students have a tremendous difficulty with this concept. How might our knowledge of the arguments made by Galileo help us convince our students that one is moving while sitting on a chair in class? Another example is the concept of heat as a flowing material substance. How did scientists come up with this idea and why did they end up abandoning it? What lessons can we learn from their experiences that will help our students understand that heat is not something that resides in the body? These examples by no means suggest that all student learning mirrors the history of science. However, knowledge of this history can be an important tool that strengthens teachers' content knowledge and such aspects of PCK as knowledge of students' ideas and knowledge of curriculum.

In the course, students use the elements of the *ISLE* cycle (observational experiments, patterns, explanations [hypotheses, relations], predictions, testing experiments[2]) as a lens through which they examine the historical process; they learn when this cycle actually worked and when it did not and why. They also examine the sequence in which the ideas were historically developed and determine which ideas were prerequisites for others. The textbooks used in the course are Refs. [49,50]; however students also read original scientific writings (for example passages from "Two Sciences" by Galileo; Newton's "Principia;" Joule's "Mechanical equivalent of heat;" Faraday's "Experimental researches in electricity") and physics education research papers on student learning of particular concepts. There are three distinct parts in the course.

2. Details

Part 1: Individual and group class work. During the first 7 weeks, students work in groups of three to four for about 20–40 min [per activity] on: (a) simple experiments and discussions in which students conduct observations, develop explanations and test them in new experiments (these activities are designed by the course professor and involve modern versions of historical experiments that served as initial puzzling observations or testing experiments for scientists); (b) reading and discussions of the original writings of scientists in which students identify the elements of the reasoning used in concept building by scientists, and reading and discussions of the PER papers that connect historical development of ideas to children's development of the same idea; (c) reflections and discussions of their own learning and comparing their conceptual difficulties to the struggles of scientists. Below we present an example of a class activity that occurs in the very first class of the semester.

Students receive a card with the following information:

"Eratosthenes was the first man to suggest how big Earth is. Here is a summary of the data that he possessed:

(1) The Sun rises and sets in Syene (now Aswan) and Alexandria at the same time.

(2) The Sun lights up the bottoms of deep wells in Syene on the day of summer solstice while the angle that the Sun's rays make with a vertical stick in Alexandria is 7.2°.

(3) It takes a Roman legion between 170 and 171 h of marching to cover this distance. The average speed of soldiers is 29.5 stadia/h.

Eratosthenes also assumed that Sun's rays striking Alexandria and those striking Syene were parallel."

The students need to use the information on the card to answer the following questions (they work in groups):

(a) On what experimental evidence could Eratosthenes base the assumption about parallel rays? Explain.

(b) How could he explain observations 1 and 2? Draw a picture.

(c) What could Eratosthenes conclude about the shape and the size of the Earth? Draw a picture.

(d) How could he convince others concerning his conclusion?

After preservice teachers answer questions (a)–(d) working in groups, they record their solutions on the white boards and engage in a whole class discussion. This is when they play the role of teachers and discuss the purpose of the activity, the issues of the continuity of knowledge, scaffolding, etc. Here the instructor shares her knowledge of student strengths and difficulties in this activity and the rationale

[2]Observational experiments are experiments that are used to create models or theories; when doing such experiments a scientist collects data without having a clear expectation of the outcome; testing experiments are the experiments that are used to test (reject) models and theories; while doing such experiments a scientist has clear expectations—predictions—of the outcome based on the model/theory she/he is testing [29].

behind the questions.

The goal of the activity described above is to contribute to the development of four different aspects of PCK. Of course, one activity cannot fully develop any of those aspects but the intent here is that development will occur through repeated exposure in different contexts over time.

(1) Orientation to teaching. By engaging in this activity as students, preservice teachers experience for the first time (and these experiences will repeat for the next 14 weeks of the semester) how high school students can construct an idea that they knew before as "fact" (how big Earth is) through a learning sequence that is built on processes that actually occurred in the history of science. As one of them commented at the end of class, "I heard in many classes that Eratosthenes measured the size of Earth but never knew how he did it and never thought that students could do the estimation themselves."

(2) Knowledge of curriculum. To answer question (a), preservice teachers need to go back to their knowledge of optics. Why is it important that Sun rays striking Earth are assumed to be parallel? In many of their former physics and astronomy classes, preservice teachers learned to assume that the Sun sends parallel rays of light. But why would we think this, especially when taking into account that all young children draw the Sun sending rays in all directions? Therefore, the goal of the class discussion of this first question is to help them reflect on their own knowledge of optics and to connect it to how children learn and how some ideas are necessary for other ideas to develop. This in turn relates to how one might think of structuring the curriculum.

(3) Knowledge of student ideas. High school students have to struggle with the following issues when responding to questions (b), (c), and (d): the relationship between the locations of two cities on Earth and the times of sunrise and sunset at the locations of the two cities on the surface of Earth (Earth science); the orientation of a well and a stick with respect to Earth's radius (physics); the parallel nature of the sun's rays hitting both cities (physics); the relationship between the angle and the circumference (geometry); proportional reasoning (algebra); unit conversion (algebra and physics). When preservice teachers perform the activity, they face similar issues and struggle with them (mostly with the orientation of a vertical stick and parallel Sun rays). Reflecting on their own progress and what they built on when solving the problem helps them think of what might be difficult for high school students and how they should or should not help. While the physics difficulties of preservice teachers in this example resemble high school students' difficulties, the former are much more skilled in mathematics. Here their instructor helps them see high school student difficulties by explicitly bringing them into the discussion "How do you think high school students will approach the proportional reasoning necessary for this problem? How would you help them set up the proportion? Do they need formal mathematics or can they reason by analogy?"

(4) Knowledge of instructional strategies. After preservice teachers complete the assignments as high school students, they discuss the following questions: Why is there an assumption about parallel rays in the handout? Why is asking students to draw a picture a helpful strategy? Why is it important to teach our students to represent their ideas in multiple ways?

There are multiple pedagogical reasons to do this activity on the first day of class. One is that future teachers start learning to question: "How do we know what we know?" When students study geometrical optics in their general physics courses, they see in books that Sun's rays are drawn parallel, but they rarely question how we know it. Next, the activity shows the preservice teachers the importance of appropriate scaffolding. In the activity above students have to think about several questions before they actually proceed to the calculation of the size of Earth. Removing the assumption about parallel rays from the activity makes it much more difficult and fewer students (I mean preservice teachers here) can complete it. The third reason is that it helps them learn the difference between a hypothesis and a prediction. A hypothesis is a statement explaining some physical phenomenon qualitatively or quantitatively (a synonym to "hypothesis" is "possible explanation"—there can be multiple hypotheses explaining the same phenomenon). A prediction is a statement of the outcome of an experiment based on a particular hypothesis; thus there can be only one prediction for a particular experiment based on the hypothesis under test. These words are used interchangeably in the discourse and even in textbooks. In their course textbook, the students read: "Eratosthenes predicted the size of Earth." However, his calculation was not a prediction, but a "quantitative hypothesis" that needed further testing. Discussions of these subtle differences help preservice teachers later construct their own lessons and design laboratory investigations (for example they ask their students to state which hypothesis they are using to make a prediction for the outcome of a particular experiment).

Part 2: Individual out-of-class work. The second part of the course involves student work with the text "Physics, the Human Adventure" [49] and original writings of the scientists [50]. Each week after a class meeting, students write a report in which they need to describe experimental evidence and the elements of inductive, analogical, and hypotheticodeductive reasoning that contributed to the development of a major "idea" of physics or chemistry using their class notes, the book material, and the original writings. Students need to reconceptualize the material in the book and in the original writings of the scientists in order to identify elements of scientific reasoning: for example, to separate observations from explanations, explanations from predictions, etc. A student sends this report to the course instructor via e-mail, the instructor reads it and provides feedback to the student, who then revises the report based on the feedback. In addition to writing weekly reports related to the material in class readings, students submit a "Popular science report" once a month. They need to find an article in the Science section of the New York Times about some recent development in science (not necessarily physics) and annotate it by identifying the elements of scientific reasoning such as original observations, a question that developed from these observations, proposed hypotheses, testing experiments, applications, etc.

Part 3: Out-of-class group work and microteaching. At the beginning of the course, students choose an idea (concept) that they will investigate working in groups of two to three for an extended period of time. They have to trace the development of that concept from first observations (if possible) to the stage when it was accepted by other scientists. They also need to prepare a story about one of the persons who participated in the development of the concept. The scientist has to become alive for the listeners—their family, a spouse, personal strengths and weaknesses, friends and enemies—all of the details that make their human are a part of the story.

Preservice teachers also need to design (and teach in class) a high school lesson related to one of the aspects of the concept. The concepts for the projects are: electric charge, electric current, magnetic field, models of light, and atomic and nuclear structure (transformation of elements and fission).

Students, working in groups outside of class, first make an historical outline; then they prepare a lesson that they will teach in class. For example, a group that is working on the history of the development of the concept of magnetic field will teach a lesson in which students develop a concept of magnetic interactions: they observe and devise explanations of the interactions of a compass with a magnet (this activity is similar to the experiments performed by Gilbert), a compass above, below and on the sides of a current-carrying wire (which is similar to Oersted's experiment), and finally design experiments to test their explanations (using an apparatus that has two parallel wires with the current in the same or opposite directions—similar to the experiment conducted by Ampere to test his hypothesis that a current carrying wire is similar to a magnet).

When the preservice teachers start planning their lesson, they tend to focus on the content that they will present instead of thinking about what goals the lesson will achieve. This is where the feedback of the course instructor is invaluable—she helps students think of a lesson as the means to achieve a particular learning goal(s). After the goals are established, the preservice teachers start thinking about how to achieve them. Here again, the main focus of the preservice teachers is what *they* will do in class as teachers, as opposed to what *their students* will do to learn. Another difficulty comes later: how will they know that the students learned? What questions will they ask? What possible answers will their students give? The goal of the course instructor is to help preservice teachers think of and plan these aspects of the lesson.

When preservice teachers teach their first few lessons to their fellow preservice teachers, they tend to stick with the plan they devised, without paying attention to the comments and questions of the lesson participants. During the actual teaching, the instructor plays multiple roles: a student who does not understand (to provoke a discussion), a team teacher (to help preservice teachers who are teaching to carry out their plan), and the course instructor, who might interrupt the flow of the lesson and focus the attention of the "teacher" on a student comment that might indicate a difficulty or misunderstanding or a possible need to change the order of the lesson. This latter role becomes more important as the program progresses since the skill of hearing what students are saying is the most difficult and the most important skill to acquire.

B. Teaching physical science (first year, spring semester)

1. Overview

Teaching Physical Science is a 3-credit course that meets once a week for 160 min. In this course, preservice teachers learn in greater depth and detail how to build student understanding of crucial concepts (velocity, acceleration, force, mass, Newton's laws, circular motion, momentum, energy, electric charge and electric field, potential difference, current and resistance, magnetic field and electromagnetic induction) and of a big picture of physics, how to engage the students in experimental design and complex problem solving, how to motivate them, and how to develop and implement curriculum units and lesson plans, including formative and summative assessments. The focus on listening to high school students and interpreting and explaining what they say and do becomes even stronger. To achieve this goal, preservice teachers practice listening to and interpreting the responses of their peers in class to specific physics questions, read physics education and science education research papers, and conduct clinical interviews with high school or middle school students.

In terms of physics content, the course focuses on mechanics, thermodynamics, electricity, and magnetism in the sequence that is normally used in a high school curriculum, so the preservice teachers see how the concepts should build on each other instead of just being developed as random lessons. The course has the same three components as the "Development of Ideas in Physical Science" (although there are differences in what is taught or what is expected from the preservice teachers) plus there are two additional components. For 10 weeks, students spend 3 h a day in a high school observing physics lessons and reflecting on their observations (this part was described in the Clinical Practice section). At the end of the semester, they have an oral summative assessment. Notice that some of the physics topics that preservice teachers work with in this course are the same as the ones that they encountered in the Development of Ideas in Physical Science course, but the focus is different. The purpose of using the same content is to have multiple exposures to the same ideas in multiple contexts [31].

2. Details

There are several fundamental enduring pedagogical ideas related to teaching physics (PCK ideas) in the course. One of them is the language (verbal, symbolic, etc.) that we use (both instructors and students) and how this language might help or hinder student learning. Another idea that permeates the course is that students learning physics should have "a taste" of what physics is and what physicists do. The focus on the "outcomes"—concepts, equations, laws—often prevents students from seeing the other integral part of physics as a science—its process. In other words, being able to explain how one knows something is as important as what one knows. The third idea is that listening to the students and being able to immediately respond during the lesson to students' needs is an important ability, but one that is extremely difficult to master and which needs time and effort to be developed.

Part 1: Individual and group class work. During the first eight weeks of the class, preservice teachers participate *as students* in *ISLE*-based physics lessons that mimic high school physics lessons, and they then reflect on their experiences. During these lessons, they work in groups on specific activities that involve: (a) qualitative and quantitative observational experiments, data collection, and analysis and identification of patterns; (b) devising multiple explanations for the observed phenomena and derivations of equations; (c) designing experiments to test their explanations; and (d) designing experiments to determine specific physical quantities. Preservice teachers conduct laboratory experiments that they design (this involves planning data collection and analysis) as opposed to performing cookbook laboratories in which students follow step-by-step instructions on how to set up the experiment, what data to collect, and how to analyze them, and they reflect on the laboratory handout scaffolding questions [43,44]. In other words, they experience the process of learning that they will later need to guide their own students to emulate.

As students work on the activities, many issues related to their own conceptual understanding arise despite the fact that they have physics or engineering degrees. In addition, in every course there are a couple of students who are not a part of the physics teacher preparation program but are, for example, middle school science teachers working on a masters degree or mathematics educators taking a course outside of their content area. Participation of those students in class discussions is invaluable as they bring more of a "physics novice" perspective, and make statements or ask questions that resemble, even more than those of the other class participants, the statements and questions of high school students. The instructor's actions when such moments occur are discussed in class from the teacher's point of view.

Class activities that resemble high school physics lessons last for about 2 h and the third hour is dedicated to the discussions of different teaching strategies, planning, assessment, student difficulties and productive ideas, instructor responses to their questions and comments, etc. Considerable time is dedicated to discussions of why a particular activity is structured in a particular way, what insights specific questions could provide about student learning, and so forth. Many of the class activities come from the Physics Active Learning Guide [ALG, [25,33]]. The learning guide has two editions—student [25] and instructor [33]; the preservice teachers use the student version in class and the instructor edition to complete their homework described below. Another resource used in the classroom is the video website, developed at Rutgers [51]. The website has more than 200

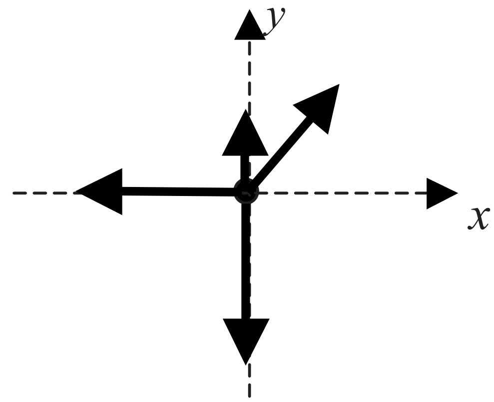

FIG. 3. Unlabeled force diagram.

videotaped physics experiments, many of which can be used for data collection when played frame-by-frame. Using the videos in class allows the students to see many more experiments than would be possible in 14 class meetings if the instructor had to assemble all the equipment; it also allows them to see in slow motion such simple processes as free fall, cart collisions, and projectile motion, or to see weather-dependent electrostatics experiments. Another resource that is used almost every day is the website with simulations developed at CU Boulder [52]. In addition students read and use other curriculum materials.

Below we show a sequence of activities in which preservice teachers engage as students in class no. 3 to learn how to help their students construct the idea of normal force. After performing the activities, they discuss the reasons for that particular order and possible student responses. The sequence is partially based on the research on student difficulties with normal force described in John Clement's paper on bridging analogies and anchoring intuitions [53]. After this class, students read Clement's paper at home and in the next class (no. 4) discuss the reasons for activity structures based on the reading. Finally, they take a quiz that assesses their PCK with respect to normal force. The sequence of student learning of PCK resembles the *ISLE* cycle—they start with engaging in the learning of a particular concept through a sequence of activities (observations), then devise multiple explanations for the content and structure of the activity, then learn about testing experiments for these different explanations with real students (the testing is described in the physics education research paper), and finally apply these new ideas to solve practical problems (the quiz in class next week).

Class 3 learning activities:

a. Observe and explain: Can a table push?. (a) Perform the experiments described in the first column. Then record your data and fill in the empty cells. Remember that the scale, as a measuring instrument, has an uncertainty of measurement associated with it.

Experiment	Draw a picture of the situation.	List objects interacting with the object of interest.	Draw a force diagram for the object.	Discuss what objects exert forces balancing the force that Earth exerts on the object. What is (are) the direction of the balancing force (forces)?	Write a mathematical expression for the forces exerted on the object. Specify your axis.
(a) Hang an object from a spring scale. Record the reading of the scale here ______________					
(b) Lower the object onto a platform scale so it touches the scale. Record the new reading of the spring scale ____________					
(c) You place the object on a tabletop. Record what happens ________________					
(d) You place the block on the platform scale and then tilt the scale at a small angle. Record what happens _____________________					

b. Test an Idea. A book rests on top of a table. Jim says that the force exerted by the table on the book is always the same in magnitude as the force exerted by Earth on the book. Why would Jim say this? Do you agree or disagree with Jim? If you disagree, how can you argue your case?

Class 4 quiz: Notice that the letter *C* next to the questions below indicates content knowledge. The numbers show the addressed dimensions of PCK (1-orientation to teaching; 2-knowledge of curriculum; 3-knowledge of student prior knowledge and difficulties; 4-knowledge of instructional strategies; 5-knowledge of assessment).

c. Quiz. Your students are learning Newtonian dynamics and are solving the following problem: An unlabeled force diagram for an object on a horizontal table is shown in Fig. 3. Sketch and describe in words a process for which the diagram might represent the forces that other objects exert on an object of interest.

You hear one of the students say: "There is a mistake in the diagram, the upward vertical force should always be the same as the downward arrow."

(1) Do you agree with the student? Explain your answer (*C*).

(2) Why do you think the student made this comment? (3)

(3) What activities done in class could have contributed to his opinion? (3, 4, 5)

(4) How would you respond to this comment in class? (1, 3, 4).

(5) If you were to test the student's idea, what experiments would you design? (*C*,5)

d. Individual work outside of class. Every week after a class session preservice teachers read a chapter in "Five Easy Lessons" by Knight [32], as well as reading the side notes (comments for teachers) in the ALG that are related to the class work. They also read the relevant physics education research papers (see the list in Appendix B). They then combine this information with the activities in class; they are told to "write a lesson plan for a lesson that will help your students master concept X. In this lesson plan make sure that you list student ideas related to concept X (use the ALG and "5 Easy Lessons" and the assigned readings) and provide questions that will allow you to assess the progress in student learning of the concept, provide possible student answers and examples of your feedback to the student." A template for a lesson plan is shown in Appendix C.

e. Group work outside class and microteaching. Beginning week 4, preservice teachers, in groups of two, start working on a curriculum unit and a corresponding 2-h lesson that they will teach in class starting week 8. The curriculum units are: static fluids, kinetic-molecular theory, vibrations, electrostatics, dc circuits, magnetism, and electromagnetic induction. Each unit takes about a month of instruction. The components of a unit that the preservice teachers have to address are: NJ state standards, learning goals, length of the unit, student prior knowledge and potential difficulties, the sequence of lessons (with short outlines), the laboratory (full text of one 2-h laboratory), the final test (full text), the equipment list, and list of resources. Writing a unit is not easy. Table V provides examples of the difficulties that students encountered in this assignment over the last 6 years and ways in which the instructor provided feedback (both difficulties and the feedback are taken from real unit plans and instructor responses).

In addition to the unit plan, students write a lesson plan for the lesson that they will teach in class. Before writing the unit, the preservice teachers read relevant literature and conduct an interview of a high school student using one of the questions or problems described in a research paper related to the unit. They also investigate other physics curricula and resources: tutorials, interactive demonstrations, workshop physics [54], TIPERs [55], on-line simulations [52,56,57], etc. The structure of the microteaching is the same as for the "Developing Ideas in Physical Science" class.

f. Observations of high school physics lessons (practicum). For these observations preservice teachers are carefully placed in the schools where physics teachers engage students in the construction of their own ideas, in group work and in the development of scientific abilities. In the last two years all of these teachers have been former graduates from the program. When preservice teachers conduct their observations (10 visits, each visit lasts about 3 h) they sit in the classroom taking notes, participate as facilitators when students work in groups, coteach several lessons, and informally interview the teachers about the lessons. Each week they write a reflection on their observations answering specific questions (see below); if the questions are not answered satisfactorily, the instructor returns the reflection for improvement. They also determine an RTOP [58] score for one lesson per observation (they learn to use this instrument during the Teaching Physical Science class). During the Teaching Physical Science class meetings there is a short period of time dedicated to discussion of their reflections.

Here are some examples of the questions that preservice teachers answer based on their observations:

Week 1: What were the goals of the lesson and how did the teacher make sure the goals were achieved?

Week 2: How did the teacher start and end the lesson? Did the beginning excite the students? Did the end provide a "hook" for the next lesson or a closure?

Week 3: What forms of formative assessment did the teacher use? What kind of feedback did they provide? How did student performance affect the continuation of the lesson?

Throughout: How did you know that students understood a particular idea or a procedure? Provide 3 examples by quoting what students said or describing what they did and explain how you know that they understood the concept or a procedure.

g. Final examination. The course ends with an oral exam during which preservice teachers need to (a) present in class their thoughts about helping and assessing high school student learning of a particular concept; (b) solve a complex physics problem chosen by the instructor and (c) demonstrate to classmates some exciting physics experiment that they can later use as a "hook" in their own teaching. A month prior to the exam they receive a list of 30 questions related to the teaching of physics that were or will be addressed in the course. For example, "What should your students know about friction? How will they learn it? How will you assess their learning?" During the exam, students are randomly assigned to present answers to two of the questions. The purpose of the exam is to engage preservice teachers in a cooperative preparation of the materials (as it is almost impossible for one person to prepare all 30 questions). Starting two weeks prior to the exam they meet on a regular basis, exchange their ideas, and share responsibilities to prepare the answers. They use the electronic discussion board and hold their own review sessions. Preparation for the exam usually starts the building of a community that will later support the future teachers when they do student teaching, search for jobs, go through the interview process, and later when they leave the program and become teachers.

C. Multiple representations in physical science (second year, spring semester)

"Multiple Representations in Physical Science" is a 3-credit course that meets once a week for 160 min. The physics content covered in the course is: waves and vibrations; thermodynamics and gas laws; electricity and magnetism; geometrical, wave and quantum optics; and atomic physics. The goal of the course is to help preservice teachers integrate different representations of physics knowledge into problem solving. Although preservice teachers have used representations such as motion diagrams, force diagrams, energy bar charts, and ray diagrams in the previous courses, here they learn to approach the representations systematically. Most importantly, they write rubrics for the high school students to help them self-assess their work with different representations. (A rubric is a table with the cells that describe different level of performance for a particular skill; students can use those to check and improve their own work—self-assess themselves, and teachers can use rubrics for grading. An example of a rubric for force diagrams is shown in Table VI. More about rubrics and how to use them see in [43].)

They also investigate opportunities provided by technology to aid students in learning abstract physics ideas. Some

TABLE V. Preservice teachers' difficulties with a unit plan.

Unit element	Difficulty	Feedback to the student
NJ state standards (or National standards)	Preservice teachers focus only on a particular piece of content (force or energy) and overlook the standards related to scientific reasoning, application of mathematics, technology, etc.	Think of what scientific abilities students should develop in this unit, what mathematical skills they will develop, and what applications of technology they will use. Then match these goals to the standards.
Learning goals	Preservice teachers limit the goals to the conceptual goals, missing procedural and epistemological goals and confuse learning goals with the class procedures.	Think of what other goals you might achieve. Should students learn how to write experimental results as intervals instead of exact numbers? Should students differentiate between a hypothesis and a prediction? How can "students will work in groups" be a goal? Did you mean that students will learn how to work in groups as a team? If yes, then how can you assess this goal?
Length of the unit	Preservice teachers underestimate the time needed for the students to master a particular concept or ability.	Think of how long it might take for the students to figure out the relationship between the width of the slit and the distances between diffraction minima. Will they be able to accomplish it in $\frac{1}{2}$ of a lesson?
Student prior knowledge and potential difficulties	1. Preservice teachers expect the students to know particular things when in fact these very ideas should be developed in the unit that they are planning. 2. Student difficulties documented in the literature are missing. 3. Students' productive ideas are missing.	1. Think of how you can help students learn graphing skills in this unit if they come without this prior knowledge. 2. How can you use R. Beichner's paper to summarize student difficulties with motion graphs? 3. How can you use J. Minstrell's facets to learn what productive ideas students might have about electric current?
The sequence of lessons	1. The lessons are not built on each other; a logical progression is missing. 2. Important ideas are missing which reflect gaps in the content knowledge.	1. Will your students understand the minus sign in Faraday's law if they have not yet learned about the direction of the induced current? 2. The idea of coherent wave sources is missing from the unit. Think of how this idea is related to the interference of light.
2-h laboratory	The laboratory in the unit is cookbook.	Think of how you can help students design the experiments instead of providing instructions step by step. Use the examples of design laboratories at: http://paer.rutgers.edu/scientificabilities.
Final test	1. The test problems and assignments do not assess the learning goals of the unit. 2. The test is too long. 3. All problems are difficult. 4. The test consists of multiple-choice questions only.	1. Number the learning goals and then put the numbers corresponding to the goals across each test problem. See which numbers are not addressed and revise the test. 2. Take the test and time yourself. Then multiply this time by 4 or 5. If you get more than 45 min, the test is too long. 3. Try to maintain a balance of the level of difficulty of the problems so students do not lose confidence during the test. 4. Try to balance between multiple choice and open-ended problems, having about 20% in m.c. You want to send your students a message that you value their thought process, not only the final answer.

TABLE V. (*Continued.*)

Unit element	Difficulty	Feedback to the student
List of resources	Preservice teachers list the internet sites and curriculum materials but not physics books and higher-level textbooks.	What resources related to the depth of the content did you use?

of the web resources that preservice teachers learn to integrate into their future instruction are the PHET simulations from the University of Colorado [52], Van Heuvelen's ActivPhysics [56], and NetLogo models from Northwestern University [57]. The big emphasis in the course is the connection between the use of multiple representations in physics and our knowledge of how the brain works [60]. In addition to reading research papers relevant to the weekly topics and using the book "Five Easy Lessons" by Knight [32], the students read the book "The Art of Changing the Brain" by Zull [61]; part of the class time is dedicated to discussing the connections between the biology of the brain and the learning of specific topics in physics.

The course has the same structure as the other two courses described above. For the first 6–7 weeks, the professor models problem-solving lessons; the preservice teachers participate as students and then reflect on the lesson. At home, they write a journal in which they describe how they will help students master a particular representation and devise a rubric for self-assessment. After week 7 or 8, they start doing microteaching. This time the lessons focus on problem solving instead of on concept construction (concept construction is the focus in the course "Teaching Physical Science"). At the end of the class, students submit another unit plan and take the oral exam.

IV. DOES THE PROGRAM ACHIEVE ITS GOALS?

A. Summary of goals

The program described above has several specific goals. The goals are to prepare a teacher of physics or physical science who:

(i) is knowledgeable in the content and processes of physics,

(ii) can engage students in active learning of physics that resembles scientific inquiry

(iii) knows how to listen to the students and assess their learning in ways that improve learning, and

(iv) stays in the teaching profession.

A fifth goal is to increase the number of teachers of physics graduating from the program.

B. What is the evidence that the program achieves these goals?

1. Evidence of learning physics content

For the last 3 years the students have taken FCI [62] and CSEM [63] as pretests when they enroll in the first course in the program. The scores range from very low (40–50 % on FCI to 30–40 % on CSEM) to very high (100% on FCI and 90% on CSEM). The preservice teachers who score low are usually those who received their undergraduate degree a long time ago ("postbac" students), have a chemistry major and are pursuing a physical science certification rather than straight physics, have an engineering major, or are students in the five-year program who are taking the bulk of their physics courses in the last year of their undergraduate degree (usually these are transfer students or students who decided to become physics teachers late in the undergraduate course of study). Sometimes those scores can be as low as 25–30 % on FCI. However, after two years in the program preservice teachers make huge improvements in their physics knowledge. The majority score 90–100 % on FCI and 80–90 % on CSEM when they take them in the last course of the program. Another way to assess their level of physics knowledge is to examine the artifacts that the students create while in the program, such as history projects, lesson plans, unit plans, and course assessments; this allows for a much more thorough assessment of preservice teachers' knowledge of the content of physics. As the same instructor teaches all of the PCK courses, these continuous physics-based interactions allow her to assess their current state of knowledge and

TABLE VI. Rubric for assessment of force diagrams [59].

Missing	Inadequate	Needs some improvement	Adequate
No force diagram is constructed.	Force diagram is constructed but contains major errors: missing or extra forces (not matching with the interacting objects), incorrect directions of force arrows or incorrect relative length of force arrows.	Force diagram contains no errors in force arrows but lacks a key feature such as labels of forces with two subscripts or forces are not drawn from single point.	The diagram contains all appropriate force and each force is labeled so that one can clearly understand what each force represents. Relative lengths of force arrows are correct. Axes are shown.

their progress. This is a subjective part of the assessment as the artifacts are not coded and there is no reliability check; however, the amount of evidence accumulated over the 7 years of the existence of the program allows me to describe some patterns that repeat year after year.

When students come into the program, many of them exhibit the difficulties described in the PER literature, despite the fact that they are completing or have completed a degree in physics or have an equivalent of a physics degree. In addition, their approach to problem solving resembles that of novices—when given a problem they search for equations and when they find the ones that they think are appropriate, they plug in the numbers right away instead of drawing a picture and thinking about relevant concepts, and then deriving the final equation in a symbolic form before plugging in the numbers.

By the end of the program, the graduates become Newtonian thinkers who understand the connections between the net force and the changes of motion of the object; they are also skilled in momentum and energy, electrostatics, DC circuits, and magnetism. In addition, they learn to approach problems in an expert way: represent the problem situation with a picture, a graph, derive an expression for the desired quantity and only then plug in the numbers. These conclusions are based on the quiz performance in the courses in the program and the homework assignments. For example, in the course Teaching Physical Science (TPS, spring of the first year) and in the course "Multiple Representations" (MR, spring of the second year), part of the homework assignment every other week is to solve standard physics problems relevant to the unit (dynamics problems, conservation problems, circuit problems, etc.). In the spring of 2010 in the TPS course on the first assignment for dynamics, of the nine preservice teachers only one person consistently derived the final expression for the answer before plugging in the numbers for all 12 assigned problems. At the same time in the MR course, five out of seven preservice teachers did it (the assignment was for electrostatics and had 13 problems).

Another source of data are the final unit plans and lesson plans. According to the scoring rubric developed for lesson plans adopted by the whole GSE, preservice teachers need to show an understanding of the content through the choice of appropriate NJ standards, goals, prerequisite knowledge, selection of concepts for the lesson and activities for formative assessments. The rubric scores range from 0 to 3 (0–missing; 1—does not meet expectations; 2—meets expectations; 3—exceeds expectations). Although the reliability in the scoring is not determined as only the course instructor does the scoring, again, multiple years allow us to see some patterns. For example out of 27 first drafts of the lessons that students submitted during the first three weeks of the TPS course in the spring of 2010, 12 were scored 1, 13 were scored as 2 and only 2 were scored as 3. For the 7 lesson plans submitted at the end of the Teaching Internship seminar (fall 2009, a different cohort) none of them was scored as 1, three were scored as 2 and another three were scored as 3.

The topic of waves, including wave optics, still presents a challenge even after two years in the program, as does quantum optics and modern physics, as very few students design unit and lesson plans for those topics. The biggest difficulties there are the concepts of coherent waves and the dual nature of photons. The reason is that students encounter the major concepts of mechanics and electricity and magnetism at least three times in different courses in the program in different contexts but they only encounter modern physics and optics once or twice.

Another assessment of graduates' content knowledge comes from their student teaching supervisors and cooperating teachers. For the former, we examined the records of student teachers during the past two years. Each preservice teacher was evaluated 14 times during a semester of student teaching. Because 11 students graduated from the program, there were 154 evaluations available. In each evaluation, among other criteria, the student's demonstrated content knowledge was rated on a scale of 0–3, where 0 is not observed, 1 is not meeting expectations, 2 is meeting expectations, and 3 is exceeding expectations. Out of the examined evaluations, the majority of the ratings were in the category of 3 (96) with the rest being in the category of 2. Additional data supporting the hypothesis that content knowledge of the graduates is relatively high comes from the interviews of science supervisors of the graduates who are now teaching. They were asked to rate the content knowledge of those of their teachers who are graduates of the Rutgers program. Out of 9 interviewed supervisors (there are 11 graduates teaching in these districts), 6 rated content knowledge of their teachers (Rutgers graduates) to be 10 on the scale of 0–10 and 3 rated it as 9.

2. Evidence of learning physics processes

Progress in the understanding of the processes of science is achieved similar to the understanding of the content.

Below I describe a part of the study done in the fall of 2003 with the students in the "Development of Ideas in Physical Science." There were ten students in the course working on their MS in Science Education+teacher certification in physics or chemistry. The part of the study described here investigated the following question: Could the students differentiate between different scientific process elements such as observational experiments, explanations, predictions, and testing experiments, and follow the logic of hypotheticodeductive reasoning while reading the book "Physics, the Human Adventure" [49] and reflecting on the classroom experiences?

To answer this question, first submissions of each weekly report were coded with five categories for the instances when students demonstrated: (a) an ability to differentiate between observations and explanations; (b) an ability to differentiate between explanations and predictions; (c) an ability to differentiate between observational and testing experiments; (d) an ability to relate the testing experiment to the prediction; and (e) explicit hypothetical-deductive reasoning (if the hypothesis is correct, and we do such and such, then such and such should happen, but it did not happen therefore we need to revise the hypothesis, examine assumptions, collect more data, etc.). An explanation was a statement related to the patterns in the observed phenomenon, while the prediction involved using an explanation to predict the outcome of a testing experiment. Instances where students confused elements in codes (a)–(d) were coded as well. Examples of the statements coded for understanding or confusion for the above categories are shown in Appendix C.

Two raters discussed the codes, then coded student work for one assignment separately, and then discussed the coding again. When their agreement reached 100% after the discussion, they proceeded scoring the rest of the assignments. The agreement for those without the discussion was around 80%. The results of the coding indicated that, in assignment no. 1, 9 out of 10 students confused observations with explanations; only one did not make this mistake. By assignment no. 8, none of the students made a mistake confusing an observation with an explanation.

Differentiating between explanations and predictions turned out to be a more difficult task. During the first assignment, only two students attempted to write about predictions and both of them confused these with explanations. In the second week, nine students used these elements and three were successful. The trend continued: in assignment no. 6 of the course, every student was writing about explanations and predictions and 8 out of 10 correctly differentiated between them in most cases. Sometimes, on the same assignment, a student would distinguish between explanations and predictions for one idea and then confuse them for another idea.

Relating predictions to testing experiments was another challenge. During the second week, only two students described what predictions scientists made before performing particular testing experiments. This number increased slightly during the semester, fluctuating between 4 and 9. One student in the first submission of the reports never mentioned any predictions before describing testing experiments.

3. Evidence of ability to engage students in active learning of physics

In the past two years we conducted more than 40 classroom observations of the physics lessons taught by the graduates of the program. During the observations, trained observers collected detailed field notes and determined RTOP [58] scores for the lessons (10 lessons were observed by two observers simultaneously to develop the reliability of the scores). The RTOP (Reformed Teaching Observation Protocol) is an instrument that allows a trained observer to produce a score for a lesson that reflects to what extent the lesson is teacher-centered (teaching process is the focus of the lesson) or student-centered (student learning is the focus of thelesson) [42]. The scale of the instrument is 1–100; a score over 50% indicates considerable presence of ‘reformed teaching’ in a lesson. Although it does not directly assess PCK, some RTOP categories reflect it. However for our purpose of assessing the ability to create an interactive-engagement lesson, RTOP is very useful as it allows one to document multiple features of the lesson such as organization of the content, depth of questions, the logic of the lesson, student involvement, teacher attention to students’ comment or questions, patience, etc.

The field notes show that the graduates of the program do indeed engage students in active explorations of physical phenomena (found in more than 70% of the lessons) and group work in which students work together in solving problems and conducting and discussing the experiments (more than 70% of the lessons). The RTOP scores range from 50 to 87 with the average being 75. Interviews with the supervisors provided more information about the climate in the classrooms of the graduates. When asked to assign a score to the classrooms of the graduates based on the statement “students are actively engaged in the construction of their knowledge” (score of 1 means not engaged and 10 means very actively engaged), the supervisor rated the classrooms between 8 and 10 (2 of them provided a score of 8, 4 a score of 9, and 3 a score of 10).

4. Evidence of graduates’ ability to listen to the students and assess their learning in ways that improve learning

To help teacher candidates achieve this goal in the course that accompanies student teaching “Teaching Internship Seminar” they have the following weekly assignment: every day prior to one of the lessons they will teach, they need to answer the following questions: What do I plan to accomplish? How will I know that students are learning? What are the strengths of the students that I plan to build on? What are potential weaknesses? After the lesson they need to reflect on student learning, providing specific examples of what students said (verbatim) during that lesson that showed evidence of understanding. They answer the questions: What did I accomplish? What did student understanding look like? What were their strengths? What were their weaknesses? What would I change in the lesson now?

This assignment is extremely difficult for the students. During the first 6 weeks of student teaching in 2009 only one student teacher (out of 7 doing student teaching that semester) could consistently show examples of student understanding (most left this part of the assignment blank). As time progressed (and the instructor provided feedback and suggestions), all of the preservice teachers were able to give at least one example of a high school student comment that was indicative of understanding. For example one preservice teacher gave the following example of student understanding:

- Me: “How did you find the acceleration of the sled?”
- Student: “Well, he’s pulling the sled at an angle so not all of his force is going into pulling the sled horizontally–so we have to find that portion of the force, which is only this side of the triangle. So we can use the cosine of the angle to find this side, and then use $a = F/m$ to find the acceleration in this direction.”

The evidence of the achievement of this goal in those who are already teaching is difficult to obtain, as it requires multiple observations of the same teacher over multiple years. I do not have this evidence. What I have are the notes from field observations of selected teachers, their postings on the discussion board (see below) and their assessment assignments and assessment strategies, which they send to me voluntarily. From the last two sources of evidence I can say that several of the graduates (about 25%) use student reflective

TABLE VII. Graduation, teaching and retention data.

Year	No. of those who graduated	No. of those who started teaching	No. of those who are still teaching
2003	1 (5-year program)	1	1
2004	5 (1 5-year program, 4 post-bacc.)	5	5
2005	7 (all post-bacc)	6	5
2006	6 (1 5-year program, 5 post-bacc.)	5	5
2007	5 (all post-bacc.)	5	5
2008	6 (4 5-year program; 3 post bacc.)	6	5
2009	7 (3 5-year program; 4 post bacc.)	7	7
2010	6 (2 5-year program; 4 post-bacc.)		

journals similar to those they write themselves in the program [64], and many use the system when their students can improve their work on quizzes and get "recovery points" on the tests (about 50%). A recent development was the invention of one of the teachers (a 2006 graduate) to make students write "a note to yourself going back in time and tell themselves something they would have liked to know at the beginning of the unit." The following is an example of what a high school student wrote after the unit on energy:

> "If I could write down one hint to my past self about the energy unit, i (sic) would tell myself to always draw a picture and an energy bar chart. I would give myself this hint, because with a picture I can understand what to look for and what is going on in that scenario. Then with the picture, i (sic) can then know what I had initially and then what I will have in the final state. After this I can create a bar chart. Then once I have my bar chart I know what equations to use and what variable to solve for. I would also hint to make sure that I'm using the correct units and to make sure that I don't have to convert anything to a certain unit. Finally, i (sic) would write down all the units for each kind of variable I have to solve for. In conclusion, I would remind myself to draw a picture, make a bar chart, solve for unknown variable, and check my units."

In the class of this particular teacher 80% of the students wrote that the note would be either about drawing a bar chart or using a bar chart to set up an equation. The teacher who collected those reflections now used them to help her students prepare for the test. This kind of evidence is not enough to make a claim that all graduates learn how to listen to the students and modify the instruction; much more data are needed here. That is why one of my graduate students is currently working on a dissertation that has a goal of documenting how graduates of the program do this.

5. Evidence of retention in the physics teaching profession

Before the program was reformed, the number of graduating students oscillated around two students per year (zero in 1998, one in 1999, one in 2000, four in 2001, two in 2002) with the retention rate of about 60%.

After the program was reformed, the number of teachers of high school (9–12) physics educated by the program in the past five years and the number of those who remain in the teaching profession oscillates around 6 per year. This is a relatively high number taking into account the very small size of the teacher preparation program at the Rutgers GSE. Table VII shows the number of those who graduated, those who started teaching, and those who remained in teaching.

C. Collaboration with the physics department

There are several programs (for example at the University of Arkansas, Illinois State University, and SUNY-Buffalo State College) preparing physics teachers in the U.S. that have features similar to those of the Rutgers Program (multiple course work that focuses on physics PCK, early physics teaching experiences, etc.). What is unique about the Rutgers Program is that it is an Ed. M. program housed entirely in the Graduate School of Education. Two major reasons for such hosting are the NJ certification requirements and the history of teacher preparation at Rutgers. However, the fact that GSE houses the program does not mean that it is the only participant in the process. In fact, it is the collaboration between the Department of Physics and Astronomy and the Graduate School of Education that makes the program successful. Here are several crucial aspects of this collaboration:

(1) The majority of the students in the program (about 60%) are Rutgers students (in their senior year) or former Rutgers students. These students receive initial advisement from the Undergraduate director in the physics department. When the undergraduate director in the physics department advising undergraduates senses that a particular student has some interest in pursuing a teaching career, he immediately advises this student to contact the program leader in the GSE; additionally, he himself contacts the GSE coordinator to be on the lookout for this student. He also provides initial advising for the potential teacher candidate.

(2) The Department of Physics and Astronomy provides preservice physics teachers with opportunities to teach in the PER-reformed courses giving them priority over its own graduate students.

(3) Faculty and staff in the physics department are willing to spend extra time providing training for the preservice teachers who are course instructors and holding special sessions on how to use equipment and conduct demonstrations and laboratories.

(4) The Department of Physics and Astronomy supports the reforms in the introductory courses. These reforms might have had an effect on four students who were not originally physics majors but, after taking one of the reformed courses, became physics majors and entered the physics teacher preparation program.

All of these connections are informal and are based on the good will and commitment to teacher preparation. However, without them the true integration of physics and pedagogy would not be possible.

D. Creating a professional learning community

Another important feature of the program is the professional learning community [65] that it attempts to create. It has been found through research on teacher retention that the first three years of teaching are the most difficult and this is when teachers quit most often. In addition, it has been found that if the teacher has the support of colleagues, then the probability of quitting decreases [66]. Based on those findings and the personal experience of the coordinator of the program, who has 13 years of high school physics teaching, one of the goals of the program is to create a learning community that will support new teachers through the most difficult years of their teaching career. The building of the community starts when the preservice teachers are in the program: they interact with each other during project preparation in all courses, during preparation for the oral exams, etc. In addition, they build relationships with the graduates of the program who are now teachers by being their students during the student teaching internship. They also build these relationships by attending the meetings twice a month that are held for the graduates in the GSE. In 2004 the cohort that graduated in 2005 created a web-based discussion group and, since then, all new graduates join this group to stay in touch with each other. Since the fall of 2004 there are on average 70 messages per month (from a low of 15 in the summer to a high of 160 in some months; the number is growing steadily every year) on the discussion list, most of them related to the teaching of specific physics topics, student difficulties and ideas, difficult physics questions, new technology, equipment sharing, interactions with students and parents, and planning of the meetings. When a participant posts a question, a response usually comes within 15–30 min from another teacher, and then the strand of the discussion goes on for 5–10 exchanges. The average number of participants in the same discussion is 4 with a low of 2 and a high of 8. The preservice teachers join the group during their student teaching, so that by the time they graduate they are well integrated into the community.

V. HOW TO GET STARTED?

The descriptions we have provided of the extensive course work, the student-student and student-instructor interactions in the program, and the follow-up interactions that occur even after the course of study is completed might seem overwhelming. Multiple courses, connections to other departments, complicated clinical practice—all of these elements make the program such a complicated organism that a person reading about it for the first time might think: “I cannot do it, forget it.” This is not exactly the message I want to send. One does not have to implement all aspects of the program to achieve similar results. In fact, the program described in this manuscript is changing constantly. The latest change was that the course “Research internship in x-ray astrophysics” became an elective instead of a required course in 2009. There were several reasons for this change. The goals of that course when it was designed were to let preservice teachers observe student-centered, inquiry-based teaching in action with high school students, as well as to learn the nature of authentic research and how to bring some sense of that research into to the classroom. But now, with so many graduates of the program teaching in NJ schools, the current preservice teachers can observe student-centered teaching in real settings. Also, with the new research being conducted in the Rutgers PER group, the preservice teachers take part in research from the beginning of the program. In addition, Rutgers now is interested in preservice teachers teaching physics courses for incoming freshman in the summer. Due to all of the above reasons, the research internship course became an elective (although most of the teacher candidates enroll in it). The reason I describe this change is to show that the program is a living organism that changes in response to outside conditions. What is important is that the philosophical aspects stay the same. Several of them can be adopted by a physics department committed to physics teacher preparation and can help students who plan to become physics teachers:

(1) *Learn physics through the pedagogy that preservice teachers need to use when they become teachers.* This can be done in a general physics course reformed according to active-engagement strategies in which students experience learning physics as a process of knowledge construction. The important issue here is the *reflection* on the methods that are used in the course and the discussion of the reasons for using these methods in the context of the most important concepts and relationships learned in the course.

(2) *Learn how the processes of scientific inquiry work and how to use this inquiry in a high school classroom for specific physics topics.* This can be done by engaging students in the learning of physics through experimental explorations, theory building, and testing, and making specific assignments where students need to *reflect* on how their own construction of the concept compares to the historical development of the same physics concept. In addition, preservice physics teachers can engage in undergraduate research experiences with subsequent reflection on how scientists work.

(3) *Learn what students bring into a physics classroom and where their strengths and weaknesses are.* This can be done through *reflection* on the preservice teachers' own learning of specific concepts and mathematical relationships while they themselves are enrolled in a general physics course; they can read and discuss papers on student learning of particular concepts. Later, when they do student teaching, they can focus on analyzing responses given by students who are learning the same concepts.

(4) *Engage in scaffolded teaching in reformed courses before doing student teaching or starting independent teaching.* This can be done through a program similar to ones that

employ Learning Assistants, or by giving seniors an opportunity to teach laboratory and recitation sections with training, feedback, and reflection.

(5) *Learn how to plan and assess instruction.* This can be done through an additional course offered in parallel to the teaching experiences. This course can be team taught by an expert in physics and an expert in education, or by an expert in physics education research and a "teacher-in-residence" (a "teacher-in-residence is an experienced teacher who takes off a year from high school teaching to work at a university science department on course reforms, preservice teacher education, outreach programs, etc.).

(6) *Form a learning community.* This can be done by creating an on-line tool for the students to communicate while they are in the program so they can continue conversations after graduation. A faculty member can contribute to the discussions, but even without these contributions the graduates will be able to support each other.

(7) Be prepared for a long time needed for learning. Just as physicists need multiple courses over an extended time interval to learn physics, our students need multiple courses over an extended time interval to learn how to become physics teachers. Do not expect immediate changes after one activity or one course. My experience is that a great deal of time and effort are needed before you will see changes in your preservice teachers.

VI. SUMMARY

The program described in the paper has been in place for eight years. During this time we observed a growth in the number of teacher graduates, a high level of retention, and an increase in the number of Rutgers physics majors coming into the program. The unique features of the program are the strong and continuous emphasis on physics pedagogical knowledge, ample opportunities for the students to practice newly acquired knowledge, and the presence of a supportive community. Students in the program enroll in six physics-specific teaching methods courses. All of these courses model the instructional practices that 21st century teachers are expected to implement. The assessment of the teaching practices of the graduates shows that they do implement the knowledge and skills acquired in the program. The program attracts students despite the high cost and with no external funding support.

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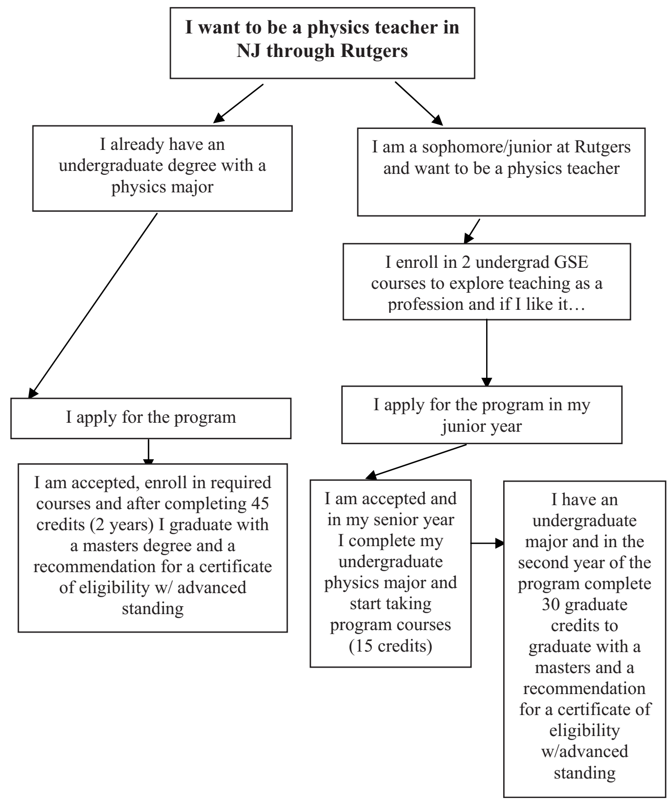
APPENDIX A

Multiple paths that lead to becoming a physics teacher through Rutgers. Diagram 1 shows multiple paths to becoming a teacher.



In the 5-year physics program, students who are undergraduate physics majors begin taking courses in the school of education in their fourth year of undergraduate studies. The courses that they take in the GSE do not apply to their undergraduate major which they complete by the end of their fourth year (independently of being admitted into the GSE program). However, they do apply to the required number of credits needed to earn the bachelor's degree. Then, after they receive their BS or BA degree in physics, they continue the program in the fifth year. In the postbaccalaureate program, students already have undergraduate physics or engineering degrees. The total number of credits (semester hours) that 5-year students take in the GSE is 52 (only 30 credits taken in the fifth year are at the graduate level) and for postbaccalaureate students it is 45.

APPENDIX B

Part 1: Weekly reading assignments for the "Teaching Physical Science" class (in addition to reading a chapter from "5 Easy Lessons" by R. Knight and a chapter from the "Physics Active Learning Guide" by A. Van Heuvelen and E. Etkina)

For class 2

P. Kraus and J. Minstrell, Designing diagnostic assessments, Proceedings of 2002 PERC conference, Franklin, S., Cummings, K. and Marx, J., Eds. PERC Publishing. (2002)

D. Hammer, Two approaches to learning physics, The Physics Teacher, 27, 664 (1989).

A. Elby, Helping physics students learn how to learn, American Journal of Physics, 69, 54 (2001).

N. Nguyen and D. Meltzer, Initial understanding of vector concepts among students in introductory physics courses, American Journal of Physics 71(6), 628–638 (2003).

For class 3

R. J. Beichner, Testing student interpretation of kinematics graphs, American Journal of Physics 62(8), 750–762 (1994).

E. Etkina, A. Van Heuvelen, S. White-Brahmia, D. T. Brookes, M. Gentile, M., S. Murthy, D. Rosengrant, and A. Warren, Scientific abilities and their assessment, Physical Review Special Topics: Physics Education Research. 2, 020103 (2006).

For class 4

D. Hestenes,, M.Wells, and G. Swackhamer, Force concept inventory, The Physics Teacher, 30, 159–166 (1992).

L. McDermott, Research on conceptual understanding in mechanics, Physics Today, 14, 24–30 (1984).

For class 5

J. Minstrell, Explaining "the rest" condition of an object, The Physics Teacher, 1(1), 10–15 (1982).

J. Clement, Using Bridging analogies and Anchoring intuitions to deal with students' preconceptions in physics, Journal of Research in Science Teaching, 30(10), 1241–1257 (1993).

For class 6

A. Van Heuvelen, Learning to think like a physicist: A review of research-based instructional strategies, American Journal of Physics, 59(10), 891–897 (1991).

A. Van Heuvelen and X. Zou, Multiple representations of work-energy processes, American Journal of Physics, 69(2), 184–194 (2001).

For class 8

C.H. Kautz, P. R. L. Heron, M. Loverude, and L. McDermott, Student Understanding of the Ideal Gas Law, Part I: A macroscopic perspective, American Journal of Physics, 73(11), 1055–1063 (2005).

C.H. Kautz, P. R. L. Heron, P.S. Shaffer, and L. McDermott, Student Understanding of the Ideal Gas Law, Part II: A microscopic perspective, American Journal of Physics, 73(11), 1064–1071 (2005).

For class 9

M. Loverude, C.H. Kautz, and P. R. L. Heron, Helping students develop an understanding of Archimedes' Principle. I. Research on student understanding, American Journal of Physics, 71(11), 1178–1187 (2003).

P. R. L. Heron, M. E. Loverude, P.S. Shaffer, and L. McDermott, Helping students develop an understanding of Archimedes' Principle. II. Development of Research-based instructional materials, American Journal of Physics, 71(11), 1187–1195 (2003).

For class 10

D. MacIsaac and K. Falconer, Reforming physics instruction via RTOP, The Physics Teacher, 40, 479–485 (2002).

For class 11

D. Hammer, Two approaches to learning physics, The Physics Teacher, 27, 664–670 (1989).

For class 12

M. Vondracek, Teaching Physics with math to weak math students, The Physics Teacher, 37, 32–33 (1999).

Part 2: Outline for a lesson plan

(1) Title

(2) NJ standards addressed in the lesson.

(3) What students need to know before they start the lesson.

(4) Goals of the lesson, e.g., conceptual (what ideas or concepts will students construct during the lesson), quantitative (what mathematical relationships they will master), procedural (what skills they will learn and practice), and epistemological (what they will learn about the nature of knowledge and the process of its construction).

(5) Most important ideas subject matter ideas relevant to this lesson—describe in detail. Real life connections (make a list).

(6) Student potential difficulties (what might cause trouble) and resources (what you can build on).

(7) Equipment needed, group it into teacher use and student use.

(8) Lesson description: a script of the lesson (What is going to happen, what you will say, what questions you will ask, what students will do, all handouts that you plan to give to the students). Choose activities that are best for the content of the lesson. Make sure you describe how you will start the lesson and how you will end it (to capture students' attention and to have some sort of closure).

(9) Time Table—who is going to be doing what and when during the lesson to make sure that students are actively engaged.

Clock reading during the lesson	"Title of the activity"	Students doing	Me doing
0–6 min	Homework quiz	Writing	Checking up equipment for the first activity

(10) All formative assessments that you plan to use and how you will provide feedback (e.g., if these are problems—include solutions).

(11) Modification for different learners

(a) Compensatory activities for those students who lack prerequisite knowledge.

(b) Describe alternative instructional strategies for diverse learners such as the use of multi-sensory teaching approaches, use of instructional technologies, advance organizers, and cooperative learning activities.

(c) Describe modifications for bilingual students.

(d) List opportunities for students to speculate on stereotypes that exist within the field (in this example—the physical sciences).

(12) Homework—make sure that it addresses two goals: strengthens this lesson and prepares students for the next lesson. Describe the guidance that you will provide to the students.

APPENDIX C

Examples of student writing coded for specific categories

Coding category	Evidence of understanding	Evidence of confusion
(a) an ability to differentiate between observations and explanations	Galileo observed that when objects were dropped from a higher elevation they left a deeper impression in the sand (pile driver).	Galileo observed object falling at constant acceleration
(b) an ability to differentiate between explanations and predictions;	Mayer explained that the difference between C_p and C_v for gases was due to the additional work that needs to be done on the gas when it expands at constant pressure.	Mayer predicted the difference between C_p and C_v because of the work done.
(c) an ability to differentiate between observational and testing experiments;	Joseph Black observed that the heat needed to warm up the same mass by the same number of degrees was much less for quicksilver than for water. He found this surprising as quicksilver was denser than water.	Joseph Black was testing quicksilver and water for the amount of heat they need to change the temperature by 1 degree.
(d) an ability to relate the testing e xperiment to the prediction;	Galileo predicted that the distance that the ball rolling down an inclined plane will increase as 1, 3, 5 units for each successive unit of time. The prediction was based on the idea that objects fall at constant acceleration and the assumption that rolling down the plane is similar to falling.	Galileo predicted that the balls would roll down at the same acceleration.
(e) explicit hypothetico-deductive reasoning (if, and, then, but or and, therefore)	Ampere reasoned that if two currents behave like magnets and he placed them next to each other, then they should repel when the currents are in the opposite direction and attract when are in the same directions.	

APPENDIX D: COURSE WORK

See separate auxiliary material for the course syllabi, examples of class assignments, and student work.

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Combined Physics Course for Future Elementary and Secondary School Teachers*

LILLIAN C. McDERMOTT
Department of Physics
University of Washington
Seattle, Washington 98195
(Received 16 October 1973)

In order to improve the preparation of both future elementary school teachers to teach physical science and secondary school teachers to teach physics, a combined physics course which includes both groups of students has been developed. The course content, which emphasizes depth of understanding, is discussed in some detail. A description is given of the techniques used to encourage the development of the skills and attitudes necessary for teaching the new nationally developed, inquiry-oriented science curricula.

INTRODUCTION

Physicists have become increasingly aware that if the scientific literacy of the general public is to be increased, education at the precollege level must be purposefully directed towards this goal.[1] They have, furthermore, come to realize that physics departments in colleges and universities must share with schools and colleges of education the responsibility for insuring that this task is accomplished effectively. There is a vital need for physicists to take an active role in the training of teachers in physical science not only for secondary schools but for the elementary grades as well.[2,3] With the appearance in the last decade of nationally developed teaching materials of excellent quality for all precollege levels,[4] the possibility exists, as never before, of effecting a marked improvement in the quality of science education in the schools.

A National Science Foundation grant provided support for developing a program which would prepare future elementary school teachers to make effective use of the new elementary science curricula. The program which has evolved rests solidly on a one-year introductory course in physical science (Physics 101–102, 103) intended for general education students as well as for future elementary school teachers.[5] The three-quarter course carries five credits each quarter and is taught in the hands-on, inquiry-oriented manner characteristic of the new curricula. It has been in operation for several years. Beginning in 1971–72, our efforts have been expanded beyond this first-year level to include the development of a continuation course and a closely related practice teaching program for preservice elementary school teachers. At the same time, a special course for future secondary school teachers has also been instituted. Since the two new courses are taught in the same laboratory during the same hours, they comprise what is, in effect, a combined course for future elementary and secondary school teachers.

We believe that the overall program which has emerged is an effective one for the training in science of teachers at all precollege levels. With a few modifications depending upon individual circumstances, it can easily be adapted to the needs of other institutions. Since the introductory course which forms the foundation of the program for the future elementary school teachers has been described by Arnold Arons,[5] this paper is devoted to the combined physics course. The practice teaching program which is directly related to the course will be described in a subsequent paper.

ELEMENTARY SCHOOL LEVEL

The continuation program for the students who plan to be elementary school teachers is centered about a three-quarter series of courses, each carrying five credits—Physics 210, 211, and 212.

These courses are taught in the same hands-on inquiry mode as the introductory sequence but demand steadily increasing degrees of student responsibility and independence. Like the introductory course, the new sequence is not restricted to future teachers but is open to any student who has taken three quarters of work in any introductory physics course other than the one required for physics and engineering majors. In a few cases, such as those of the more capable undergraduates who have participated in our NSF Summer Institute for in-service teachers, admission to the second-level series is possible after only two quarters of work at the introductory level.

For the future elementary school teachers, the Physics 210 sequence of courses has been designed with two major objectives in mind. The first is to enable the students to become acquainted with more of the subject matter encompassed by the new elementary school science curricula than is possible in a two or three-quarter introductory sequence. The second is to help them develop the independence, self confidence, and competence that are necessary to handle materials, the subject matter of which has not been studied in formal courses. This second, and more important, goal is not independent of the first but is harder to achieve. On the basis of our experience thus far, we believe that five or six quarters of study in this program, including work in both the introductory and the continuation courses, are necessary before there is positive evidence that this goal is being realized.

SECONDARY SCHOOL LEVEL

The Physics 210 sequence is taught in the same laboratory during the same hours as another new series of courses (Physics 407, 408, 409) for future high school teachers. The successful completion of Physics 407 and 408 is a requirement for the physics teaching major or minor for secondary certification. A major purpose of the requirement is to acquaint future teachers with the "new" high school curricula—PSSC Physics[6] and Project Physics.[7] It is our intention to further broaden this exposure to the new curricula by including materials from two nationally developed junior high school programs—Introductory Physical Science[8] (already in partial use in the Physics 210 sequence) and the Intermediate Science Curriculum Study.[9]

Gaining familiarity with the materials is not, however, the sole goal. At least as important is the introduction of the preservice high school teachers, all of whom have had two to three years of large lecture and formal laboratory instruction in physics, to the inquiry mode of teaching and learning. The rapid pace at which these students have been exposed to new material has almost precluded their thinking critically about the subject matter. Thus the type of education they have had does not prepare them to recognize either their own learning problems or those of the students they will someday teach. They enter the class almost unaware that their ability to manipulate numbers in memorized formulas has nothing to do with their understanding of physical concepts. They have no idea of what is meant by an operational definition nor have they had any direct experience in the construction of theoretical models induced directly from their own observations. Many of them have not yet learned to distinguish inferences from observations.

Since most people teach as they have been taught, we attempt to teach the inquiry method not by talking about it, but by actively involving the students themselves in direct experiences with the teaching materials. Like the courses for the future elementary school teachers, the Physics 407 sequence requires the active participation of the student in his own learning. It has been our observation that upon entering Physics 407, the students who plan to be high school teachers are no more adept at carrying out a scientific investigation than are the preservice elementary school teachers on entering the introductory course. They are far less capable of proceeding on their own than are their classmates in Physics 210, who have, at this point, had far less physics.

In a large university such as ours, the problems associated with the preparation of high school physics teachers are further exacerbated by the fact that the students involved are often neither the quickest nor the ablest among the undergraduate science majors. Since it is on these students, however, that the profession must rely for secondary school teaching, it is essential that they be given the help they need to raise their

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mastery of elementary physics to a level adequate for their future work.

INTERACTION BETWEEN THE TWO GROUPS

The somewhat unusual class arrangement of Physics 210 and 407 meeting together has a direct bearing on the structure of the course, yielding distinct advantages to both the elementary and secondary preservice teachers. In the process of weaning the future high school teachers from their dependence on memorized formulas, textbooks and lab manuals, the Physics 210 students in the class are a great source of help. After two to three quarters of learning in the inquiry mode in the Physics 101 sequence, these students have acquired the sense of independence and self confidence that enables them to set a good example of inquiry-oriented learning for their Physics 407 classmates. Unlike the latter, the Physics 210 students are a self selected and highly motivated group since their participation in the course is entirely voluntary. The special class arrangement by no means benefits only the future high school teachers. The latter group is, of course, mathematically more sophisticated and has been exposed to many more areas of subject matter than the students in Physics 210. In some parts of the work, they are therefore able to proceed at a more rapid pace. The Physics 210 students, who quickly become aware of their own greater skill in inquiry-oriented learning, are not intimidated by the high school group and quickly get into the habit of consulting them for help in certain areas of the work. They will accept, however, only a certain kind of assistance. Statements such as: "Don't just tell me the answer. I want help in finding out for myself," not only make a point with the high school group but also serve to reinforce the elementary school group's commitment to inquiry-type learning.

Since the Physics 407 group has for the most part no knowledge of the observational astronomy which makes up part of the subject matter of the course, they consult the Physics 210 students, who have already had experience with this material in the introductory course. As they endeavor to help their classmates, the future elementary school teachers get an excellent opportunity to practice the questioning technique so important in inquiry-type teaching. Thus, the constant interaction between the two groups, which is actively encouraged, results in advantages for both.

An additional feature of this model of a combined class for future elementary and secondary school teachers is that it provides for a larger class size than would be possible with either group alone. Although thus far most of the students have been preservice teachers, the emphasis on the development of scientific literacy makes the course equally appropriate for general education students. It would be possible to increase the number of such students without any adverse effect on the teacher-training aspects of the course. The combination class has had an average enrollment of ten students. Since future teachers at both the elementary and secondary school levels will someday have an effect on large numbers of other individuals, the extra cost involved in their education in small classes is likely to be returned to society many times over.

A factor which contributes to the size of the enrollment is that the course is structured in such a way that students can miss a quarter to do their cadet teaching or other required work and be able to rejoin the class. Students returning to college after graduation have also been easily absorbed into the class after more than a quarter's absence. Both self pacing and group pacing play a part in maintaining the necessary flexibility. The students are allowed considerable latitude in setting their own pace but they are not completely free to determine their own rate of progress. Constraints in the form of time limits are imposed for two reasons. One is to protect the student from suffering the full consequences of the tendency to procrastinate that is often evidenced by newcomers to inquiry-oriented learning. The other is to insure an environment in which the students can interact most effectively with one another. There are times during the course when, because of different individual requirements on the part of the students, a variety of topics are being simultaneously explored. The work of the entire group is paced, however, so that the members of the class can work together frequently on material which is appropriate for all.

SELECTION OF SUBJECT MATTER

The subject matter covered in the course is limited to that which can be encompassed under the heading of a few broad unifying themes. *PSSC Physics* and *The Project Physics Course* are the two texts but no attempt is made to cover all the material they contain. Instead it is expected that both texts will be used as references. Some of the experiments performed by the students are suggested in the PSSC lab manual but many more arise naturally in the process of their own investigations. The emphasis is on depth rather than breadth as we attempt to bring about an awareness in the students of what it means to understand a scientific concept as opposed to the rote memorization of statements made by either the instructor or the text. Whatever the subject matter under investigation, the question of how we have obtained our knowledge about it is deliberately raised. The internalization of ideas requires the active involvement of the student in his own learning and can only take place if he is given enough time and the proper atmosphere to ponder and raise questions.

At the beginning of the course, there is a considerable amount of help available from instructor-produced outlines and study guides. Gradually these aids become fewer in number and at times there is no written guidance at all. The instructor is, of course, available at all times to help students develop their own understanding of the subject matter by initiating discussions, making suggestions for further investigations, and guiding the students in answering their own questions through Socratic dialogue.

There is a wide variety of subject matter themes which could provide a satisfactory matrix for the educational process involved. The choice of topics in our case has been affected by a desire to supplement the material covered in the introductory sequence and to give the future elementary school teachers experience with more of the subject matter encompassed by the new curricula than was possible in the introductory course. To indicate the general spirit in which all the subject matter is approached, a part of the course content will be described in some detail. The basic educational considerations that arise, however, could equally well be developed through the choice of a number of other topics. Included in the discussion of the course content are a few examples of how the subject matter selected relates directly to that encompassed by ESS,[10] SAPA[11] and SCIS,[12] as well as to PSSC Physics and Project Physics.

COURSE CONTENT: ELECTRICITY, MAGNETISM AND MECHANICS

The unifying theme for a series of activities extending over a large portion of the year is the pursuit of an operational definition of what we mean by the term "electron." Why do we believe that this tiny constituent of matter, which we cannot see, exists? Our investigation begins with a consideration of what we mean by the word "charge." The students are given some simple electrostatic equipment—pieces of wool and silk, rods made of glass and plastic, etc.—and are asked to arrive at an operational definition of this term and then to define what we mean by the words "like" and "unlike" charge. In spite of two or three years of physics courses at the college level, the future high school teachers have no idea at first of how to proceed. Many have difficulty in engaging in the simple logic that enables us to say that like charges repel, unlike charges attract and that there are only two kinds of charge. It is not even completely clear to them that the term charge does not refer to a material object but to a property of matter. Because they already "know" how like and unlike charges behave, they are in some cases less able to deal with these basic questions than are the future elementary school teachers. Since operational definitions play an important role in SAPA and SCIS, consideration of these same questions by the elementary school teachers serves not only to bring about understanding of the particular material but also to develop a skill they will need in teaching.

Our study of electrical charge also provides an experience in model building. The construction of an abstract model which is capable of being used to account for their observations and to make predictions about new situations is a new experience for the future high school teachers. They have heretofore simply memorized the features of any models they have encountered in their texts or in lectures. For the elementary group, this activity presents another opportunity to develop a facility called for in the handling of the new science curricula, especially SCIS.

Another example of the breadth of learning experiences provided in the course is illustrated by our approach to a Coulomb's law experiment. The experimental arrangement is very simple and can easily be duplicated in the future by the students in their own teaching. The investigation of the force between two light conducting balls which are charged alike and suspended by strings from a common point above the stage of an overhead projector provides a good exercise in the control of variables, a process important in all the elementary, as well as secondary, curricula. It is not obvious to the students in either group that in order to investigate the dependence of the electrostatic force on the magnitude of the charge, the separation between the balls must remain constant while the charge is altered in a systematic way. What does the way in which the force varies while one charge is cut in half and then in half again, while the other is held constant, indicate about the possibility of quantifying charge? This method of looking at the Coulomb experiment has not impressed itself on the students before, even if it has been mentioned in text or lecture.

The description of how we go about doing the Coulomb experiment can also serve as an example of how we attempt to help the students recognize the essential unity of the subject matter of physics. Before they are permitted to do the experiment in which they will investigate how the electrostatic force varies with the separation between the charged balls, they must first perform a similar simple experiment that arises in the study of mechanics. A heavy ball is suspended on a string and the students are directed to measure the force on a spring scale as the ball is pulled out horizontally. They are then asked to express the force as a function of the angle measured from the vertical and to consider what simplification can be introduced for small angles.

Some of the future high school teachers have difficulty in drawing the free-body diagram which allows them to set up the necessary equations. Their troubles involving this simple problem in mechanics clearly demonstrate the futility of expecting them to recognize that for small angles the horizontal displacement of one of the balls from the vertical can be used as a measure of the electrostatic force. To have done the experiment with the use of a formula that had been supplied for the electrostatic case would have contributed nothing of significance to their understanding of physics.

The problems encountered with the hanging ball serve as an incentive to review some of the topics in Newtonian mechanics. It quickly becomes apparent that many of the future high school teachers have difficulty solving the simple problems in mechanics in *PSSC Physics* and *The Project Physics Course*, much less put into their own words explanations of phenomena based on the laws of motion. In spite of several years of physics, they find it extremely difficult to accept the idea that objects are accelerated only by forces originating outside them. No matter how carefully their instructors may have discussed this subject in the past, instruction through lecture has not been successful.

The process of conversion from an Aristotelian to a Newtonian point of view is slow, but it can be achieved through individual dialogue with students and much patience on the part of the instructor. Throughout the entire course, there is a constant spiraling back and connecting to the concepts encountered in mechanics. For example, a fine opportunity for a study of centripetal force is provided by the PSSC experiment to measure e/m later in the course when the electron story is almost complete. Our discussion of this topic is by no means limited to the specific context involving the magnetic force. We look at other examples as well, returning to situations such as the behavior of satellites in orbit. Contrary to what one might expect, it has been our experience that the future elementary school teachers have been as capable as most of the future high school teachers in reaching a sound understanding of these ideas, but neither group has this understanding initially. That a clear comprehension of the Newtonian view of the world is of tremendous aid in developing an elementary school teacher's confidence in teaching SCIS has been demonstrated to us over and over again.

One of the memorable experiences of the course, according to the students, is the performance of the Project Physics version of the Millikan "oil drop" experiment. This experiment, which nails down the discrete nature of electrical charge, makes a strong impression on all the students both for the brilliance of its conception and the diligent efforts required to complete it. For the future elementary school teachers, their ability both to do and to understand the experiment is a source of great personal intellectual satisfaction.

In the process of developing the concept of the electron, it becomes necessary to make use of the electromagnetic force. We begin our investigation of this topic with a study of magnetostatics. This subject is handled in a way designed to give the students practice both in organizing the many experiences and ideas that are involved in inquiry-oriented learning and also in model building. Starting with bar magnets and then proceeding to make use of other very simple equipment, each student is expected to conduct an independent investigation of simple magnetic phenomena. He must write a carefully organized, logically constructed report based on his own experiences which could be used as a guide to lead children through inquiry to the development of a model that can explain and predict these phenomena.

The task of putting together the paper inevitably exposes the students to the sense of frustration that so frequently accompanies an attempt of the mind to impose order on what seem at first to be completely unrelated phenomena. Although the issue has been raised previously on a number of occasions, most of the students still have not fully realized that it is the human intellect and not nature that has organized our knowledge of the physical world in ways that are mentally satisfying as well as useful. The amount of creativity involved in the inductive process comes as a surprise to them since, in spite of being told otherwise, they tend to consider science as a purely deductive activity. This view of science as art cannot be taught by lecture; it must be experienced to be understood.

The construction of a model to account for magnetostatic phenomena, coupled with the experiences encountered in developing a current model for electricity in the introductory course, serves as excellent preparation for the preservice elementary school teachers for teaching the sixth grade SCIS unit on model building in electricity and magnetism. In the process of their investigations they have also acquired all the background needed to teach the SAPA units involving the same subjects. They have no trouble predicting the polarity of the electromagnets they make by following the directions in the ESS unit "Batteries and Bulbs."

Our investigation of the electromagnetic force leads to a much-needed review for the future high school teachers of simple electromagnetic phenomena. For the preservice elementary school teachers, there is an opportunity to become aware through direct experience of the force on a current-carrying wire in a magnetic field and of the force between two current-carrying wires. They study the effects of moving a conductor through a magnetic field and gain a rudimentary understanding of the operation of a simple generator. They are delighted when, after they have constructed the simple home-made motors described in "Batteries and Bulbs," they can successfully predict in which direction their motors will begin to turn.

COURSE CONTENT: OPTICS AND WAVES

A study of geometrical and physical optics based on the PSSC format takes up about one quarter's work. Through direct experience with simple equipment, the students address the question of whether, and under what circumstances, a wave or particle description of light is the more appropriate. Their work in optics starts with an investigation of reflection from plane mirrors. They develop procedures for the location of images by ray-tracing which they later apply to refraction experiments as well. This work with geometrical optics serves to prepare the future elementary school teachers to handle the optics units in ESS and SAPA with a well-founded sense of confidence that merely following the activities in the teacher's guide does not generate. At the same time, all the students become aware of the successes and failures of a corpuscular model of light in accounting for what happens in reflection and refraction. A fairly thorough investigation of waves in a ripple tank leads to insights on the interference and diffraction of light. From the interference pattern produced by two coherent point sources, the students find the wavelength of the water waves by direct measurement between the crests of two successive waves as well as from the geometric relationship between the source separation and spacing of the interference maxima. When they are later handed a mercury discharge source, a couple of meter sticks and a diffraction grating, they have virtually no problem in devising and performing an experiment to measure the wavelength of light. They find it easy to transfer from the relatively concrete model of the water waves to the more abstract situation with light.

TRANSITION TO FORMAL OPERATIONAL THINKING

From their own experiences such as the one just described, the future high school teachers gain an appreciation of the value of proceeding from a concrete example to an abstract one in their own teaching. The assumption that most students in the last two years of high school, when they ordinarily take physics, are already formally operational and thus do not need concrete experiences to help them learn, has been shown to be unwarranted on the basis of recent studies on freshmen in a large state university.[13] It is extremely important for those who will be teaching physics to students in secondary school to be aware of this fact and its implications for them as teachers. Our regular observation of the students in the Physics 210–407 class has shown that, over the period of a year, a steady growth takes place in their ability to think logically. By the end of the course, there is a noticeable improvement in the "If..., then...; therefore..." type reasoning, which according to Piaget is associated with the attainment of formal operations.

DEVELOPMENT OF MATHEMATICAL SKILLS

The examples cited above are only a few of the many instances where the subject matter and the way in which it is approached in the course find direct application in the implementation of the new science curricula at both the elementary and secondary levels. In the case of those who plan to teach in elementary school, an indirect but equally important contribution to their overall development as teachers is the gradual but continuous progress towards a greater degree of mathematical competence. Proceeding from the computational skills involved in simple arithmetical reasoning, on which so much emphasis has been placed in the Physics 101 sequence, the students in the Physics 210 series gradually become interested in geometry, trigonometry, and vector algebra as they recognize a need for them in their work. When, at their own request, they are given just enough help so that they themselves can arrive at quantitative solutions to some of the questions which arise, their insecurity in dealing with mathematics gives way to a sense of satisfaction in overcoming a challenge. The positive attitudes towards mathematics that are developed through their work in physics also result in a heightened interest in the teaching of arithmetic. They become eager to teach a subject most of them have avoided as much as possible in the past.

EXAMINATIONS AND EVALUATION

Since students interpret the kinds of questions asked on examinations as an indication of what is really important in a course, the tests are carefully designed to reflect the emphasis placed on understanding. The questions posed are intended to provide an opportunity for synthesizing the course material. Nothing is asked that depends on memorization or sophisticated mathematical facility. An effort is made to generate transfer-type problems with enough guidance given towards a solution so that learning can take place during the examination. Because there is a great deal of interaction throughout the course between the students and the instructor, the tests do not provide the sole, nor even the most important, criteria for the evaluation of the students' understanding of the subject matter. The atmosphere in which the examinations are administered is therefore relatively relaxed, and a number of students have commented that they have actually enjoyed and learned from the experience.

The evaluation of a student's performance in the course does not depend only upon an assessment of his mastery of the subject matter. In the case of future teachers, a growth in their ability to help others learn is one of the main objectives of the course. Although one cannot predict with certainty who will become a successful teacher, it is not difficult to make a judgment of whether or not a student has developed certain attributes known to contribute to effective teaching. Among the indications that such a development is taking place are: A continuing effort to explore the subject matter beyond the minimum required level, an increased capacity for independent work, a greater facility in the organization of ideas and in logical reasoning, and a demonstrated interest in both teaching and learning from fellow students through dialogue and discussion. Although a good understanding of the course content is essential for a superior grade, it is not sufficient.

Evaluation of the course on the part of the students has been very favorable as indicated by both their oral and written comments. The small class size and large amount of personal contact between the instructor and students are naturally conducive to such a reaction. A much more significant indication of whether the course has been effective can be obtained by a study of the teaching performance of the students. Our observation of a number of the students in classroom situations has provided evidence that in at least several cases there have been definite positive effects.

SUMMARY

In conclusion, a few general remarks should be made which are specific to each of the two groups of students who make up the combination class. The course content which has been described may, at a glance, appear to be of relatively low level for secondary teaching majors and minors who have spent two or three years in a college sequence for physics majors and engineers. However, the logical and phenomenological questions raised throughout the course are of considerable depth and sophistication. It quickly becomes very clear that it has never occurred to these students to examine the origin of the scientific concepts and theories upon which our explanation of the physical world rests.

Those who have made the necessary effort to look at the situation closely are aware of the enormous gaps in understanding on the part of these students.[14] Because of the rapid pace at which it has been presented, they have had no chance to assimilate the enormous volume of material to which they have been exposed. In most cases, the combination of large lecture and formal laboratory instruction has not been successful in developing the degree of mastery of the subject matter necessary to teach high school physics effectively. The Physics 407 sequence of courses provides us with a final opportunity to help these students remedy some of the deficiencies in their background. Breadth of subject matter coverage has been consciously sacrificed in favor of providing the time needed to achieve a genuine understanding of a relatively few important topics. In addition to acquainting the students with PSSC Physics and Project Physics, the course serves an equally important function as an introduction to inquiry-oriented learning. We hope that the manner in which the subject matter is approached will serve as a model to the students for their own teaching later.

The future elementary school teachers who make up part of the combination class are admittedly a select group. They constitute only a small fraction of the preservice elementary school teachers who have taken the introductory course. A need exists, however, at the elementary level for teachers who have sufficient grasp of the subject matter to exercise leadership in implementing the new science curricula. The combined class arrangement has provided a stimulating learning environment for the preservice elementary school teachers. Through the program in practice teaching, which will be discussed in a subsequent paper, we have had the opportunity to observe these students from the Physics 210 sequence at work in the classroom on many different occasions. Their performance has constituted an impressive demonstration of just how effective science instruction in the elementary schools can be when

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the teacher has a sound command of the subject matter.

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A perspective on teacher preparation in physics and other sciences: The need for special science courses for teachers

Lillian C. McDermott
Department of Physics FM-15, University of Washington, Seattle, Washington 98195

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This article proceeds from the premise that one of the major reasons for the perceived crisis in science education is the failure of our colleges and universities to provide the type of preparation that precollege teachers need to teach science effectively. The perspective taken is based on many years of teaching physics and physical science to prospective and practicing teachers at all grade levels. The inadequacy of the present system of preparing teachers is examined and an argument is presented for offering special physics courses for teachers. Experience at the University of Washington provides the basis for a discussion of the type of intellectual objectives and instructional methods that should characterize such courses.

I. INTRODUCTION

It is generally accepted that science education in the United States is in serious difficulty. Between the seventh and twelfth grades, the number of students taking science drops by more than 50%.[1] With less than 2 years of science required for graduation by the majority of states,[2] most graduates of American high schools have taken considerably less science than their counterparts in other countries. When achievement is compared, American students do not perform as well as others.[3] If present trends continue, the number of students entering college with both the interest and the preparation to pursue a scientific or technical profession will not be sufficient to meet our national needs.

This article addresses one aspect of the current crisis: the failure of our colleges and universities to provide the type of preparation that precollege teachers need to teach science effectively. The discussion is in terms of physics, but the situation in other sciences is similar.

A. The problem

Over the last 2 decades, the percentage of first-year graduate students in physics who have been educated in this country has been dwindling with respect to the foreign enrollment.[4] This situation is only one consequence of a process that has critical impact beyond the profession: the continual narrowing of the pipeline in physics throughout the period of formal education.[5]

The greatest constriction occurs during the precollege years and is demonstrated by the fact that only about 20% of the students in American high schools study physics.[6,7] Reasons for the steady attrition are complex. Political, social, economic, and intellectual factors all play a role, and it is difficult to separate cause from effect.[8] However, although it cannot be proved, it seems reasonable to assume that one of the most important factors affecting enrollment and retention of students is the shortage of teachers adequately prepared to teach physics.[6,7] According to a recent survey by the American Institute of Physics, about one-third of the teachers with physics assignments have neither majored in the subject nor taught it on a regular basis.[6,7]

The problem of inadequate teacher preparation is not limited to high school, but extends down into middle and elementary school. There, lacking the proper background to teach with enthusiasm and confidence, teachers often transmit to students a dislike of science, especially physical science. With a negative attitude often firmly established by the ninth grade, most students do not voluntarily take physics in high school. Failure to do so decreases the likelihood that students will complete a college course in the subject. However, taking physics in high school does not necessarily ensure adequate preparation for later study. Incompetent teaching may leave students with serious deficiencies that may make physics difficult for them in college. Poor performance in the introductory college sequence not only closes the gateway to a career in physics, but to participation in other science-related professions.

The chain of events described above has other serious ramifications. One is the early limitation of opportunity for students who do not take physics in high school or who take courses from underprepared teachers. A disproportionately large number of these students belong to groups underrepresented in the physical sciences and engineering: women and minorities. The result is unequal opportunity for a large segment of our population and a waste of talent that might increase the pool of American students pursuing advanced degrees in science and engineering.

The low level of scientific literacy produced by our educational system has another serious consequence. In a democracy, the formulation of national and local policy is highly susceptible to public opinion. Therefore, uninformed judgments on important technological issues may have an effect that extends beyond the physics community to our entire society.

B. The perspective

The perspective taken in this article reflects the cumulative experience of the Physics Education Group at the University of Washington where teacher preparation has been an integral part of a comprehensive program in research, curriculum development, and instruction for many years. Our research focuses on investigations of student understanding in physics.[9] The results are used to guide the design of instructional strategies to address specific conceptual and reasoning difficulties encountered in the study of physics.[10] Curriculum development takes place in our instructional program, which includes special physics courses for prospective and practicing teachers at all grade levels. Support from the National Science Foundation has made it possible to devote a major effort to the production of instructional materials to prepare precollege teachers to teach physics and physical science.[11]

II. SUGGESTIONS FOR SOLVING THE PROBLEM

To help define our point of view, it may be useful first to examine some popular proposals for improving the quality of science instruction in the schools. The most frequently suggested remedy involves financial incentives for teachers. Many physicists and other concerned citizens believe that the shortage of physics teachers would disappear if salaries were increased. There is no doubt that a low pay scale makes teaching a less desirable option than industry for many recipients of a Bachelor's degree in physics. Preferential salary increases could help address this problem.

The situation, however, is far too complicated for this solution to be as effective as its proponents imagine. Many individuals, willing to make financial sacrifices in order to teach, cannot find positions as physics teachers. A consequence of the low enrollments in physics is that few high schools can offer a full-time teaching position in the subject. Most physics teachers must also teach general science, chemistry, or mathematics. Since these courses are in greater demand, prospective physics teachers need to be able and willing to teach these subjects. Also, the use of seniority as a basis for making teaching assignments may mean that a senior teacher with very little background will be given a physics assignment in preference to hiring a new teacher whose qualifications may be much stronger. Sometimes willingness to serve as a coach for sports may be a more important factor in hiring a teacher than competence in teaching physics. Thus, although there may be a shortage of physics teachers, there can also be a shortage of positions.

A popular recommendation among physicists for increasing the number of qualified teachers is to relax the requirements in education for certification. Such a change would allow individuals with a strong background in physics to teach. Many physicists assume that students who have majored in physics in college are adequately prepared to teach the subject. This assumption will be examined later in the article.

Another proposal involves the entry into the classroom of technically trained professionals as teachers. A small but significant number of scientists and engineers are opting for midcareer and late-career shifts into teaching. It is taken for granted that the technical competence of these individuals ensures that they have the necessary command of the subject to be effective teachers. However, working in industry does little to develop the requisite depth of understanding, either of the subject matter or of the learning process. Practical experience is usually sufficient for carrying out day-to-day duties. Furthermore, during the years of industrial employment, the scientist or engineer has been away from the school environment and is likely to be less aware than a classroom teacher of the special difficulties physics presents to students.

Volunteer teaching in the classroom by scientists and engineers has been suggested as another way to improve the quality of precollege science education. Such efforts can be highly motivational to young students in the short term, but occasional or intermittent visits are unlikely to result in sustained long-term learning. Experience has also shown that volunteers seldom succeed in leaving the teacher better able to teach science independently. Indeed, very often the result of having a visitor in the classroom is to provide relief for the teacher, who turns attention to other matters.

The measures discussed above are simple in concept and could be implemented relatively quickly, provided financial and political complications could be resolved. Such remedies are temporary at best, however, and cannot be applied on a large scale. Plans to improve science education over the long term and on a national level must address the fundamental issue of competent teaching in the schools. It is essential that teacher preparation be a major focus in any effort at reform.

An effective teacher education program must take into account the needs of two different populations: (1) prospective (or preservice) teachers who are not yet certified and (2) practicing (or in-service) teachers who are already in the classroom. Preservice teachers can usually enroll in regular undergraduate science courses. However, in-service teachers have less flexibility and may be unable or unwilling to participate in a standard instructional program unless special arrangements are made.

The emphasis in this article is on the subject matter preparation of both preservice and in-service teachers. Throughout the discussion, the word "teachers" refers to both prospective and practicing teachers; the modifiers "preservice" and "in-service" are reserved for cases in which a distinction needs to be made. The only aspects of in-service teacher education that are considered are those that can be addressed through the regular departmental structure of a college or university. No attempt is made to give an overview of the variety of in-service programs.

III. TRADITIONAL APPROACH TO TEACHER PREPARATION

Precollege teachers in the United States are educated in the same colleges and universities as the general population. Prospective teachers must complete a Bachelor's degree and also obtain state certification. In most institutions, two independent administrative divisions are involved in the process of producing teachers: a college or school of education, and a college of arts and sciences (or equivalent). Faculty in education offer courses on methodology and on the psychological, social, and cultural aspects of teaching. Faculty in arts and sciences offer courses in the subject matter.

A. Requirements for professional certification

A major responsibility of schools and departments of education is the coordination and implementation of state standards for certification. The minimum requirements vary from state to state.[12] Often a two-stage process is involved. Initial, or provisional certification is granted for a specified period, at the end of which a teacher must meet additional requirements for permanent, or continuing certification. To receive initial certification, a prospective teacher must take certain education courses and must usually also have an undergraduate major outside of education. However, it is not necessary to major in a subject in order to be officially approved to teach it. An endorsement to teach a subject other than the major may often be obtained on the basis of courses solely at the introductory level. Furthermore, to receive permanent certification an in-service teacher usually does not have to take additional courses in any subject matter department. Even when a Master's degree is required for permanent certification, state standards can be met almost entirely with education courses. Once initial certification is obtained, there may be little incentive for teachers to continue studying science.

B. Preparation in academic subjects

Almost all subject matter preparation for teaching science takes place within academic departments. Prospective science teachers generally take standard departmental courses. Aside from teaching these courses, faculty in the sciences usually have no involvement in teacher preparation except for determining which courses should be required for certification to teach at the high-school level. Some departments offer courses for nonscience majors that may be taken by prospective elementary and middle-school teachers. Usually no special attempt is made to take into account the needs of these future teachers. Whereas the education of preservice teachers may be central to schools of education, such a function is often considered peripheral to the mission of a science department. Most take the point of view that teacher preparation is the responsibility of schools or departments of education.

Universities offer few opportunities to in-service teachers to strengthen their backgrounds in science. Usually, course credit in an introductory or lower division course does not help teachers move up on the salary scale, nor does such credit count toward a Master's degree. In order to be acceptable as advanced study by a school district, state, or university, the credits earned must be in upper division or graduate courses. The situation is particularly difficult in physics. The vertical structure of the subject matter requires that students progress in a prescribed sequence. There may be no courses beyond the first year for which high-school teachers are likely to have the proper prerequisites. Most elementary and middle-school teachers do not have the mathematical facility that is needed for the usual introductory physics course. Quite apart from matters of scheduling, it is unlikely that many in-service teachers at any level will enroll in a standard physics course. Not only is such coursework unnecessary for permanent certification, but it may also be quite impractical unless a teacher already has a relatively strong background in physics.

The National Science Foundation and other federal and state agencies have sponsored programs for in-service teachers. However, for the most part, the courses provided through these programs have not been institutionalized, and their existence has depended solely on the willingness of individual faculty to take the initiative in writing proposals that may or may not get funded. The lack of long-term stability in financial support and teaching staff make development of a strong academic in-service program very difficult.

IV. INADEQUACY OF TRADITIONAL APPROACH IN PHYSICS DEPARTMENTS

Many science faculty seem to believe that the effectiveness of a precollege teacher will be determined by the number and rigor of courses taken in the discipline. This attitude seems to prevail in most physics departments. Accordingly, the usual practice is to offer the same courses to future teachers as to students who expect to work in industry or to enter graduate school. However, traditional physics courses generally do not provide the type of preparation that teachers should have.

The content of the typical high-school course is closely matched to that of the first-year college course, but study of the same material in college is not adequate preparation for teaching it in high school The breadth of topics covered in the typical introductory college course allows little time for acquiring a sound grasp of the underlying concepts. Ordinarily, no special effort is made to address the common conceptual difficulties that prospective teachers, like other students, encounter. The lecture format encourages passive learning. Students become accustomed to receiving knowledge rather than helping to generate it. The routine problem solving that characterizes most introductory courses does not help teachers develop the reasoning ability necessary for handling the unanticipated questions that are likely to arise in a classroom situation.

The laboratory sequence that accompanies the introductory course also does not address the needs of teachers. Often the equipment used is not available in the teachers' schools, and no provision is made for showing them how to plan laboratory experiences that utilize simple apparatus. A more serious shortcoming is that experiments are mostly limited to the verification of known principles. Students have little opportunity to make observations and perform the reasoning involved in formulating these principles. As a result, it is possible to complete the laboratory course without confronting conceptual issues or understanding the scientific process.

A year of introductory college physics is admittedly insufficient for teaching a high-school course. However, it does not follow that advanced physics courses provide useful preparation for teaching, either. The abstract formalism that characterizes upper division courses in physics is not of immediate use in the precollege classroom; neither are the complicated experiments and sophisticated equipment of advanced laboratory courses. Although work beyond the introductory level may help teachers deepen their understanding of physics, no guidance is provided about how to make appropriate use of this knowledge in teaching younger students.

Physics faculty sometimes teach special in-service courses. Often these have some of the same disadvantages for teachers as undergraduate courses. To help fill the gaps in background, the instructor often attempts within a short period of time to present a large portion of the content covered in a traditional physics course. There seems to be a tacit assumption that if the material is well organized and clearly presented, teachers will be able to absorb the information quickly and be able to disseminate it to their own students. However, the amount of material and the rate of presentation may be so overwhelming that learning is impossible at any but the most superficial level. Sometimes in the belief that teachers need to update their knowledge, a university instructor may give a lecture course on contemporary physics. Such courses are of limited utility. The information may be motivational but does not help teachers recognize the distinction between a memorized description and substantive understanding of a topic.

The total separation of instruction in methodology from instruction in content decreases the value of both for teachers. Effective use of a particular instructional strategy is often content specific. If teaching methods are not studied in the context in which they are to be implemented, teachers may be unable to identify the elements that are critical. Thus they may not be able to adapt an instructional strategy that has been presented in general terms to specific subject matter or to new situations. The consequences of underestimating the amount of teacher preparation needed for implementation of a new science curriculum was demonstrated in the case of the NSF-sponsored school projects. A major reason that ESS, SCIS, and other fine elementary school programs did not prosper was that they were not as "teacher-proof" as developers had hoped.[13] Inadequate teacher preparation was also a contributing factor to the failure of middle- and high-school programs, such as IPS, PSSC, and Project Physics,[14] to achieve sustained, widespread adoption. Even detailed directions cannot prevent the misuse of excellent instructional materials when teachers do not understand either the content or the intended method of presentation.

The traditional approach to teacher preparation in physics departments has another major shortcoming. Teachers tend to teach in the same way as they have been taught. If they learned through lecture, they will lecture to their own students, even if this type of instruction may be inappropriate. Many teachers cannot, on their own, separate the physics they have learned from the way in which it was presented to them. It is especially unrealistic to expect large adjustments in mode of presentation if teachers must teach material soon after having learned it themselves. Even very able teachers, who eventually might be able to adapt content learned through lecture to activity-based instruction, cannot be expected to do so quickly.

V. DEVELOPMENT OF SPECIAL PHYSICS COURSES FOR TEACHERS

A well-prepared teacher of physics or physical science should have, in addition to a strong command of the subject matter, knowledge of the difficulties it presents to students. To counter the public perception that physics is extremely hard, the teacher must be able to teach in a way that allows students to achieve adequate mastery of the topics studied and confidence in their ability to understand and apply what they are learning in their daily life. Since neither traditional physics courses nor professional education courses can provide the appropriate kind of preparation for precollege teachers, there is a need for special physics courses.[15]

An effort to meet this need at the University of Washington led to the establishment of the teacher education program in the Physics Department.[16] Development of the program began in 1968, when A. B. Arons introduced a course for elementary school teachers.[17,18] Shortly after, special courses for middle-school and high-school teachers were added.[19] Modified versions of the original courses constitute the core of the present program, which includes preservice and in-service teachers at all grade levels. The program has also included other projects.[20]

The special physics courses for teachers have provided an environment in which we could identify their academic needs. We have used the insights gained to define important objectives for such courses.[21,22] In addition to the instructional function, the courses have provided a context for research on the learning and teaching of physics and a setting for the development of curriculum.[9–11]

The program has been in continuous operation for 20 years. The following commentary is a distillation of what we have learned and have tried to incorporate in *Physics by Inquiry*.[11] The discussion below is not an exhaustive summary of all that should be done to prepare teachers. Practical matters, such as laboratory logistics and classroom management are not addressed. The focus is on intellectual aspects.

A. Intellectual objectives

Special courses for teachers should emphasize the content that the teachers are expected to teach. A primary intellectual objective should be a sound understanding of important concepts and their formal representations. Equally critical is the ability to perform the reasoning that underlies the development and application of both concepts and representations. Conceptual understanding and capability in scientific reasoning provide a firmer foundation for effective teaching than superficial learning of more advanced material. Teachers should be given the opportunity to study introductory physics in depth, beyond what is possible in the typical introductory sequence. They need to examine the nature of the subject matter, to understand not only what we know, but on what evidence and through what lines of reasoning we have come to this knowledge.[22]

Teachers should develop proficiency in both quantitative and qualitative reasoning. It has been demonstrated that university students enrolled in the standard courses often lack certain basic skills, such as the ability to reason with ratios and proportions.[22] Courses for teachers should cultivate these skills, which tend to be overlooked in traditional instruction. Also important is the development of facility in the use and interpretation of scientific representations, such as graphs, diagrams, and equations. If they are to make the formalism of physics meaningful to students, teachers must be adept at relating different representations to one another, to physical concepts, and to objects and events in the real world.

Teachers must be able to solve the types of problems that are included in the typical introductory physics text. However, the main emphasis in a course for teachers should not be on acquiring facility with mathematical manipulation. As necessary as quantitative skills are, ability in qualitative reasoning is even more crucial. For example, teachers should be able to distinguish observations from inferences and to do the reasoning necessary to proceed from observations and assumptions to logically valid conclusions. They need to recognize what is considered evidence in physics and what is meant by an explanation. They must recognize the difference between naming and explaining. Problems in which the use of mathematical formalism alone suffices for a solution are not effective measures of conceptual understanding. Thus, instead of concentrating on the type of algorithmic problem solving that characterizes most physics courses, the instructor should assign problems that require careful reasoning and should insist that an explanation of the reasoning be part of the solution.

An understanding of the scientific process should be an important objective in a course for teachers. The scientific process can only be taught through direct experience. An effective way of providing such experience is to give teachers the opportunity to construct a scientific model from their own observations. Teachers should go through the step-by-step process of making observations, drawing inferences, identifying assumptions, formulating, testing, and modifying hypotheses. The intellectual challenge of applying a model that they themselves have built (albeit with guidance) to predict and explain progressively more complex phenomena can help teachers deepen their own understanding of the evolving nature, use, and limitations of a scientific model. Furthermore, we have found that successfully constructing a model through their own efforts helps convince teachers (and other university students) that reasoning based on a coherent, consistent model is a far more powerful approach to problem solving than rote substitution of numbers in memorized formulas.

In addition to the instructional objectives discussed above, which in principle are equally appropriate for the general student population, teachers have other requirements that special physics courses should address. For example, it is particularly important that teachers learn to express their thoughts clearly. The indiscriminate use of words that have both technical and common meanings hinders development of conceptual clarity. Teachers need practice in formulating and using operational definitions. To be able to help students distinguish between related but different concepts (e.g., velocity and acceleration), they must be able to identify in words precisely and unambiguously what the significant differences are.

Teachers must also be able to anticipate common conceptual difficulties that students are likely to encounter in the study of a topic in physics or physical science. Such information may come from the teachers' own experience in learning the material or, if they have avoided the usual pitfalls, through knowledge of results from research in physics education. To help students overcome specific difficulties, teachers need to be familiar with instructional strategies that have proved successful and that are likely to be effective with precollege students. Again, direct experience is one way of gaining such knowledge; another is through awareness of research.

Courses for teachers should also help develop the critical judgment necessary for making sound choices on issues that can indirectly affect the quality of instruction. For example, teachers must learn to discriminate between learning objectives that are meaningful and those that are trivial. When instruction is driven by a list of objectives that are easy to achieve and measure, there is danger that only shallow learning will take place. Memorization of factual information often falls in this category.

Teachers need a framework for evaluating instructional materials, such as textbooks, laboratory equipment, and computer software. They should become familiar not only with the most popular texts, but also with others that the instructor considers exemplary. They should recognize the strengths and weaknesses of using the computer in various ways (e.g., simulations, microcomputer-based laboratories, interactive tutorials).[23] Aggressive advertising and an attractive presentation often interfere with objective appraisal of intellectual content. We have observed teachers react with enthusiasm to an appealing format, while they ignore serious flaws, such as a lack of accuracy in physics.[24]

The ability to make wise decisions on matters such as the foregoing is important since, through service on district committees, individual teachers can often have an impact that extends beyond their own classrooms. A poor curriculum decision can easily deplete the small budget most school districts have for science without resulting in an improvement in instruction.

B. Instructional methods

Teachers should be prepared to teach in a manner that is appropriate for the precollege level. Science instruction for young students is known to be more effective when concrete experience establishes the basis for the construction of scientific concepts.[25] We have found, as have others, that "hands-on" laboratory investigations guided by appropriate questions also help foster concept formation at the college level. Therefore, in addition to learning how to teach their own students most effectively, teachers benefit directly from instruction that is centered in the laboratory.

The curriculum used in physics courses for teachers should be in accord with the instructional objectives. If the capacity to teach "hands-on" science is a goal of instruction, then teachers need to work through a substantial amount of content in a way that reflects this spirit. However, there is another compelling reason why the choice of curriculum is critical. We have found that teachers often try to implement instructional materials in their classrooms that are very similar to those which they have used in their college courses. Even though it has not been our intent to have young students work directly with the materials that we have developed for teachers, the curriculum has been used in this way.

Whether intended or not, teaching methods are learned by example. The common tendency to teach physics from the top down, and to teach by telling, runs counter to the way precollege students (and many university students) learn best. The instructor in a course for teachers should not transmit information by lecturing. However, neither should the instructor take a passive role, but instead should assume responsibility for student learning at a level that exceeds delivery of content and evaluation of performance. Active leadership is essential, but in ways that differ markedly from the traditional mode.

The instructor's role is characterized below by a few examples that are described in general terms. Instructional strategies in the context of specific subject matter are illustrated, either explicitly or implicitly, in several of the references that are cited in the article.[26]

The study of a new topic should begin with an opportunity for open-ended investigation in the laboratory in which teachers can become familiar with the phenomena to be studied. Instead of introducing new concepts or principles in the customary manner by definitions and assertions, the instructor should set up situations that suggest the need for new concepts or the utility of new principles. By providing such motivation, the instructor can begin to demonstrate that concept formation is a process in which the student must be actively engaged. Generalization and abstraction should follow, not precede, specific instances in which the concept or principle may apply. Once a concept has been developed, the instructor should present the teachers with new situations in which the concept is applicable. This process of gradually refining a concept can help develop an appreciation of the successive stages that individuals must go through in developing a sound conceptual understanding.

As the teachers work through the curriculum, the instructor should pose questions designed to help them to think critically about the subject matter and to ask questions on their own. The appropriate response of the instructor to most questions is not a direct answer, but another question that can help guide the teachers through the reasoning necessary to arrive at their own answers. Questions and comments by the instructor should be followed by long pauses in which the temptation for additional remarks is consciously resisted. Findings from research indicate that the quality of student response to questions increases significantly with an increase in "wait time," the time the instructor waits without comment after asking a question.[27]

A course for teachers should develop an awareness of the conceptual and reasoning difficulties likely to be encountered by students. For example, research has helped identify numerous common misconceptions, ideas in conflict with the formal concepts of physics.[28] Some of these ideas result from a misinterpretation of daily experience,[29] others from a misunderstanding of formal instruction.[30] Regardless of origin, certain misconceptions are at such a fundamental level that, unless they are effectively addressed, meaningful learning of the relevant content is not possible. Teachers should learn to recognize such difficulties. However, mere discussion of research findings is not sufficient for this purpose. Teachers need to work through the material and have the opportunity to make their own mistakes. When student difficulties are described in words, teachers may perceive them as trivial. Yet from experience we know that often these same teachers, when confronted with unanticipated situations, will make the same errors as students.

Exposure to findings of research should also include critical examination of instructional strategies designed to address specific difficulties. The instructor should illustrate these strategies as the opportunity arises during the course. If possible, the discussion of a specific strategy should be postponed until after it has been used in response to an error that has actually occurred. Teachers are much more likely to appreciate important nuances through an actual example than through a hypothetical discussion. Without specific illustrations in the context of subject matter with which they are thoroughly familiar, it is difficult for teachers to envision how to translate a general pedagogical approach into a specific strategy that they can use in the classroom.

It is not only poorly prepared teachers who can profit from the type of instruction described above. Those with a strong background can also benefit. The experience of working through the material can help all teachers identify the difficulties their students may have. Those who understand both the subject matter and the difficulties it poses for students are likely to be more effective than those who know only the content. Moreover, unless teachers have experience with learning physics through active inquiry, they are unlikely to foster this behavior in students.

C. Illustrative course structure

The brief description below of the teacher education program at the University of Washington shows how we have addressed some common administrative problems, such as course enrollments, prerequisites, credits, and grading standards. Although special courses for teachers can be organized in a variety of ways, the example illustrates an arrangement that has worked well within a physics department that is part of a large, research-oriented university. The specific details are not essential for implementing the intellectual objectives and instructional methods discussed above.

As mentioned previously, the program has both preservice and in-service components. Preservice teachers take special courses during the academic year, while in-service teachers participate in intensive summer sessions and in a continuation class during the academic year.

1. Preservice program

At present, three year-long preservice courses have been developed to accommodate students with a wide range of previous preparation. Each course meets for 6 h a week in a laboratory setting. One of the courses is designed for future elementary and middle-school teachers, as well as high-school biology teachers who have had little or no experience with physics. There are no prerequisites other than moderate facility with arithmetic and algebra. The other two courses are for high-school teachers and for middle-school teachers who have an adequate background in mathematics and physical science. Taught in the same room at the same time, the two courses essentially constitute a single combined course in which the two parts differ in prerequisites and in the amount of formal mathematics required.

The course for high-school teachers contains very few physics majors. At the University of Washington, as elsewhere, students who have majored in physics seldom elect to pursue a teaching career at the precollege level. Most of the students are mathematics, chemistry, or biology majors who are working on an endorsement in physics as a secondary teaching field. In addition to undergraduates, the class typically includes a few students who already have undergraduate degrees and are returning to the university to obtain certification to teach physics. A year of introductory physics and a year of calculus are minimum requirements for the course. The intellectual content and the work required are sufficiently demanding for course credit at the senior level. The department has established a quality standard for certification to teach physics in high school by requiring that prospective teachers take the course for at least two quarters and earn a grade of B or better.

The concurrent course for middle-school teachers requires less mathematics. A prior year of physics is a prerequisite, either the course for elementary school teachers or any of the department's standard courses. The course for middle-school teachers also includes prospective high-school biology teachers seeking an endorsement in physical science. The emphasis on qualitative reasoning also makes this course, which is offered for credit at the sophomore level, suitable for students who are not planning to be teachers but who wish to take a second year of physics.

The organizational structure of the combined course makes it possible to have an enrollment that varies between 15 and 25. In addition to providing an enrollment that justifies offering the class, the combined course has other advantages. Interaction among the different kinds of preservice teachers enriches the experience of all. Those majoring in physics, chemistry, and mathematics are used to memorizing and manipulating formulas and often cannot recognize the difference between stating the name of a concept or principle and being able to do the reasoning involved in its construction or application. In contrast, prospective teachers majoring in the life sciences and those who are not science majors have generally not had much mathematics and are thus less likely to accept explanations that consist solely of mathematical formalism. As a consequence, the more mathematically oriented students gradually change their approach and begin to emulate the instructor as they try to use Socratic dialogue to respond to questions by their less well-prepared classmates.

2. *In-service program*

Efforts that concentrate on the preparation of preservice teachers probably offer the most promise for bringing about improvement in science education in the long term. For the near future, the most efficient means of effecting change is to try to strengthen the background of in-service teachers. Modified versions of the preservice courses form the core of our intensive summer program for in-service teachers. During the academic year, a continuation course meets weekly after school. In this class, the teachers continue to improve their subject matter knowledge and also consult with the university staff and with one another as they apply what they have learned to their own teaching.

The awarding of senior level credit and the teachers' perception that the program will be useful provide an incentive for participation. In recent years a stipend has also been given, but this has not always been the case. A significant number of the in-service teachers in our program have used their course credits for a Master's degree in education. A few have applied these credits toward a Master's degree in physics.

VI. CONCLUSION

The present difficulties in physics education can have serious consequences for the future of the profession and the nation. The effect on the greatest number of students is during the precollege years. The point of view taken in this article is that improvement can take place only when the underlying problem of inadequate teacher preparation is successfully addressed. The type of instruction that can meet the needs of teachers is not available in the standard courses offered in most physics departments. However, neither can a college of education provide adequate instruction in physics. It is unlikely that study of the subject matter at a depth necessary for a teacher can take place anywhere but in a university or college physics department. The situation in other sciences seems to be very much the same. Thus it must be the responsibility of science departments to provide appropriate instruction for teachers. An effective mechanism for accomplishing this task is through special courses in the disciplines.

The argument presented above has an important implication for university and college science departments. It is unrealistic to expect faculty to dedicate a significant amount of effort to an activity not recognized by the academic reward structure.[31] The general perception in some science departments is that such efforts may even be penalized. If active and creative individuals are to be encouraged to devote their talents to problems in science education, then regular tenure-track positons should be allocated or created within the subject matter departments. These positions should not be limited to teacher preparation alone, but should include responsibility for addressing other problems in science education that require creative, scholarly attention. For example, there is a need to identify and analyze the conceptual and reasoning difficulties students encounter in the study of all the sciences. To be useful for the design of instruction, such research must be content specific and thus be conducted by individuals with a deep understanding of the subject matter. The development of effective instructional strategies to address specific difficulties requires experience in teaching the material at a level that cannot usually be found outside of science departments.

Faculty positions of the type described have been recommended previously. The following statement is from a report issued by the Association of American Colleges: "If departments, particularly research departments, allocated one or two regular faculty positions to research on learning their discipline, they could produce results which would improve their own teaching effectiveness and would have visibility and impact beyond the walls of their own institutions. They would influence instructional materials at the secondary as well as the college level."[32] The criteria for faculty performance in these positions should be parallel and equivalent to those that exist for traditional research and teaching. To be effective, the leadership required for significant change in science education must be based on positions that have strength and stability within the university structure.

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[12]See "Teacher certification requirements," in *Indicators of Precollege Education in Science and Mathematics*, edited by S. A. Raizen and L. V. Jones (National Academy, Washington, DC, 1985), pp. 62–63.

[13]*Elementary Science Study* (Education Development Center, Newton, MA); *Science Curriculum Improvement Study* (University of California, Berkeley, CA).

[14]U. Haber-Schaim, J. B. Cross, G. L. Abegg, J. H. Dodge, and J. A. Walter, *Introductory Physical Science* (Prentice-Hall, Englewood Cliffs, NJ, 1972). U. Haber-Schaim, J. B. Cross, J. H. Dodge, and J. A. Walter, *PSSC Physics* (Heath, Lexington, MA, 1971). F. J. Rutherford, G. Holton, and F. G. Watson, *The Project Physics Course* (Holt, Rinehart and Winston, New York, 1970.)

[15]The need for special physics instruction for teachers has been recognized in countries in which the subject matter background of teachers is generally at a higher level than the U.S. (e.g., Germany). See, for example, D. Nachtigall, "What is wrong with physics teachers' education?" Eur. J. Phys. (January 1990).

[16]L. C. McDermott, "An example of a teacher education program in a physics department," in the proceedings from the *Conference on Physics Teacher Institutes and Workshops*, edited by P. Lindenfeld and J. M. Wilson, AAPT Topical Conference Series (American Association of Physics Teachers, College Park, MD, 1985).

[17]A. B. Arons, "Anatomy of a physical science course for non-science students," J. Coll. Sci. Teach. **1**, 30–34 (April 1972).

[18]A. B. Arons, *The Various Language* (Oxford U. P., New York, 1977). This book was developed for the original verison of the course for elementary school teachers.

[19]L. C. McDermott, "Combined physics course for future elementary and secondary school teachers," Am. J. Phys. **42**, 668–676 (1974).

[20]See, for example, L. C. McDermott, "Teacher education and the implementation of elementary science curricula," Am. J. Phys. **44**, 434–441 (1976); "Practice-teaching program in physics for future elementary school teachers," Am. J. Phys. **42**, 737–742 (1974).

[21]L. C. McDermott, "Improving high school physics teacher preparation," Phys. Teach. **13**, 523–529 (1975).

[22]A. B. Arons, *A Guide to Introductory Physics Teaching* (Wiley, New York, 1990). A significant portion of this book is directly relevant to the discussion in this paper. In addition to providing guidance for teaching specific topics, Arons identifies important intellectual objectives for introductory physics courses and describes instructional strategies he has found effective. There is also a brief discussion of special problems that need to be addressed in teacher education. The reader is referred to the bibliography at the back of the book for a list of his many articles on physics education and teacher preparation.

[23]For an overview of the use of computers in physics instruction, see *Proceedings of the Conference on Computers in Physics Instruction*, North Carolina State University, Raleigh, NC, August 1988, edited by J. Risley and E. Redish (Addison-Wesley, New York, 1989).

[24]*Physics*, Sensei Software for Learning (Broderbund Software, San Rafael, CA, 1987) is an example. This widely distributed, visually appealing program contains several conceptual errors. The teachers in our inservice program were so impressed with the visual presentation of the program that they failed to recognize that it could introduce or reinforce serious misconceptions in their students. For example, in the only screen display devoted to Newton's third law, two spheres representing the Earth and the Moon are shown with force vectors of unequal length. This diagram appears immediately under a correct verbal statement of the third law.

[25]See, for example, Refs. 10, 11, and 13–22.

[26]J. Griffith and P. Morrison, "Reflections on a decade of grade-school science," Phys. Today **25** (6), 29–35 (1972); R. Karplus, "Physics for beginners," Phys. Today **25** (6), 36–47 (1972).

[27]M. B. Rowe, "Wait-time and rewards as instructional variables, their influence on language, logic, and fate control: Part one—wait time," J. Res. Sci. Teach. **11**, 81–94 (1974).

[28]References 9, 29, and 30 are examples of research on student understanding in physics conducted by the Physics Education Group. For a review on research in mechanics that includes the work of other investigators, see L. C. McDermott, "Research on conceptual understanding in mechanics," Phys. Today **37** (7), 24–32 (1984). For a review on computers and research in physics education, see L. C. McDermott, "Computers and research in physics education," in *Proceedings of the Conference on Computers in Physics Instruction* (see Ref. 23). Space limitations preclude a comprehensive listing of the large body of research reports that have been produced in the last decade.

[29]See, for example, F. M. Goldberg and L. C. McDermott, "Student difficulties in understanding image formation by a plane mirror," Phys. Teach. **24**, 472–480 (1986). This article contains examples of precon-

ceptions that seem to be the result of previous experience in observing images in plane mirrors. Two of the most common are that the position of an image in a plane mirror depends on the position of the observer and that the size of the mirror needed to view an object varies with the distance of the object from the mirror.

[30]See, for example, 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). This article contains an example of a misconception that results from a misunderstanding of instruction rather than prior experience: the belief that the principal rays in a ray diagram are necessary rather than merely sufficient to form an image with a converging lens.

[31]*An Exploration of the Nature and Quality of Undergraduate Education in Science, Mathematics and Engineering*, a report of the National Advisory Group of Sigma Xi, The Scientific Research Society (Sigma Xi, The Scientific Research Society, New Haven, CT, 1990), p. 7.

[32]*Integrity in the College Curriculum: A Report to the Academic Community*, M. H. Curtis, Chairman (Association of American Colleges, Washington, DC, 1985), p. 12.

Improving the preparation of K-12 teachers through physics education research

Lillian C. McDermott, Paula R. L. Heron, Peter S. Shaffer, and MacKenzie R. Stetzer
Department of Physics, University of Washington, Seattle, Washington 98195-1560

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Physics education research can contribute to efforts by college and university faculty to improve the preparation of K-12 teachers to teach physics and physical science. Examples from topics included in precollege and university curricula are used to demonstrate the need to help K-12 teachers deepen their understanding of basic physics, to illustrate how research-based instructional materials can assist in this process, and to examine the impact on student learning in K-12 classrooms.

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I. INTRODUCTION

Noting that "teachers are the key to improving student performance," several recent reports have called for greatly increasing the number of teachers able to teach science.[1] Producing well-qualified teachers is a complex task that involves college and university faculty, experienced teachers, and school administrators. Ideally, K-12 certification is based on a sound undergraduate education that is supplemented by specialized courses. The process of becoming an effective teacher continues through early mentoring and ongoing professional development. This paper focuses on an aspect of the process that requires direct involvement by physics faculty.[2] We illustrate how research conducted in physics departments can help identify and address the intellectual problems that teachers (and students) encounter with the concepts, reasoning, and formal representations of physics.

The Physics Education Group at the University of Washington (UW) has been engaged in preparing K-12 teachers to teach physics and physical science by inquiry for more than 30 years.[3] The environment in which our interactions with teachers take place has provided an ongoing opportunity to examine how prospective and practicing teachers think about physics and to develop curriculum based on this research. The work described here involved prospective and practicing K-12 teachers, introductory students in calculus-based physics, and physics graduate students. The preservice high school teachers were enrolled in a special physics course that consists of students with a major or minor in physics, mathematics, or other sciences. The inservice teachers were participants in an intensive six-week NSF Summer Institute, for which admission is nationally competitive. The undergraduate and graduate students were enrolled at UW and at other universities.

Several of the examples given here have been discussed in papers in which the emphasis was on undergraduate education.[4–8] However, most of the data related to K-12 teachers have not been published and are presented as evidence of the need for, and utility, of providing special preparation in physics and physical science for teachers.[9]

II. EVIDENCE OF A MISMATCH BETWEEN STANDARD CURRICULUM AND TEACHERS

The only university instruction that most teachers receive on topics in K-12 physics and physical science occurs in physics departments. However, there is ample evidence from research that a large gap often exists between what is taught and what is learned in physics courses at all levels of instruction.[10] The situation is of special concern in the standard courses taken by future high school teachers as well as in the descriptive courses that may be taken by prospective elementary and middle school teachers.

The three examples that follow are from investigations by our group. In each, the context is a qualitative question on a topic common to precollege and university curricula.

A. Mismatch for K-5 teachers: Example in the context of balancing

Elementary school curricula often include a unit on balancing.[11] A question based on the diagram in Fig. 1 was used to probe understanding of this concept in two different populations.[4] Students were told that a baseball bat of uniform mass density is balanced on a finger and were asked to compare the total mass to the left and right of the balance point. This question was administered to about 675 students in introductory calculus-based physics and about 50 inservice K-5 teachers. The introductory students had completed their study of the relevant topics. Many of the elementary school teachers had previously taught units on balancing. Only about 20% of the introductory physics students and about 15% of the K-5 teachers responded correctly. Nearly everyone who gave an incorrect answer claimed there must be equal mass on both sides.

Along with a description of suggested activities, the teacher's guide accompanying one of the units includes the following statement: "Every object (or system of connected objects) has a point around which the mass of the system is evenly distributed. This point is the center of gravity."[12] There seems to be a tacit assumption that the teacher already understands the material or can quickly learn by reading. However, the results from the question on the baseball bat suggest that the term "evenly distributed" may inadvertently reinforce an incorrect belief that is common among teachers and students.

B. Mismatch for 9-12 teachers: Example from kinematics

Concepts from kinematics are taught in several K-12 grades, beginning in elementary school. Students encounter the concept of acceleration in high school physics and sometimes in middle school physical science courses, often in connection with objects that are falling freely or rolling down an incline.

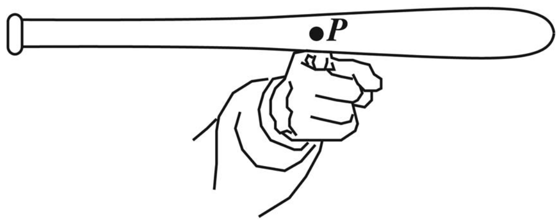

Fig. 1. Question about balancing. Students are told that the bat, which has uniform density, remains at rest when placed on a finger as shown. They are asked whether the mass to the left of the balance point P is greater than, less than, or equal to the mass to the right of the balance point.

In an investigation that extended over several years and included several colleges and universities, we examined student understanding of kinematical concepts in one and two dimensions.[5] In one problem used in this study, students were shown a strobe diagram of a ball rolling up and down an inclined ramp and were asked to draw acceleration vectors at various points along the trajectory (see Fig. 2). We examined the responses from about 15,000 students in introductory physics, 180 preservice and inservice teachers (primarily grades 9-12), and 300 physics graduate students who were teaching assistants in the introductory course. The most common incorrect answers were that the acceleration would be zero at the turnaround point, or that it would be directed vertically downward at all points. Only about 50% of the teachers and 20% of the introductory students drew correct sketches with acceleration vectors of constant magnitude always directed down the ramp. About 75% of the graduate students gave correct responses.

C. Mismatch for K-12 teachers: Example from electric circuits

The topic of electric circuits is part of many precollege curricula, often in the context of batteries and bulbs. In our research on student understanding of this material, we have administered a wide variety of questions. One, which is based on Fig. 3, has been given to several different populations, including introductory physics students and preservice and inservice teachers of all grade levels.[6] The question asks for a ranking of the brightness of the identical bulbs in the three circuits, which have identical, ideal batteries. Explanations are required. The correct ranking is A=D=E>B=C.

The results from introductory students and K-12 teachers have been approximately the same. Only about 15% in each group have given a correct ranking. The preservice and inservice teachers performed similarly, even though many of

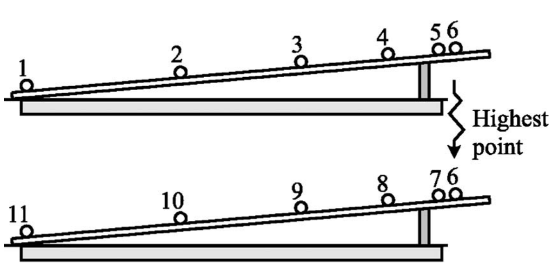

Fig. 2. Question about acceleration. Students are shown the diagram of a ball rolling first up and then down the ramp. They are asked to draw vectors for the velocity and the acceleration at each of the marked points.

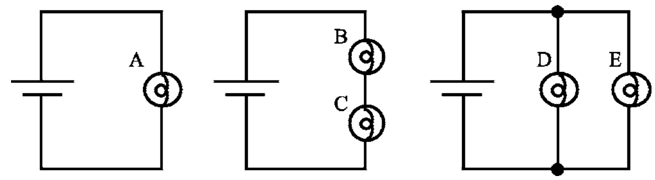

Fig. 3. Question about electric circuits. Students are told the bulbs are identical and the batteries are identical and ideal. They are asked to rank the bulbs from brightest to dimmest.

the latter had previously taught this topic. Analysis of the explanations by all the populations, including high school physics teachers, revealed the widespread presence of two apparent beliefs: the battery is a constant current source and current is "used up" in a circuit.

The results from this question and from the one on balancing discussed earlier illustrate a general finding. Teaching a topic does not necessarily deepen one's own conceptual understanding. The following event, which occurred during a professional development workshop, is illustrative. A high school teacher with 12 years of classroom experience had just completed experiments and exercises intended to help students associate bulb brightness with current. When asked to compare the brightness of a single bulb across a battery with that of two bulbs in parallel across a second battery, she observed that all three were equally bright. Surprised, she exclaimed, "That would mean that the amount of current from the battery is different in different cases, and that doesn't make any sense!" She suddenly realized that her assumption that the current through a battery is always the same was incorrect. Although she was likely adept at solving textbook circuit problems, her understanding of the material was far short of what it should have been.

III. DEVELOPMENT AND ASSESSMENT OF CURRICULUM

These examples illustrate some specific difficulties that teachers often share with many university students. Because of their responsibility to help their students learn, the situation for teachers is more serious and needs more attention. They must know and be able to do more than is expected of their students. We should therefore ask what we want young students to know and be able to do and prepare teachers accordingly. These questions have led to the development of *Physics by Inquiry (PbI)*, a laboratory-based curriculum primarily intended for the preparation of preservice and inservice teachers but also suitable for other populations.[13,14]

We begin instruction on all topics by drawing on research that identifies where students are intellectually. We use this information to design, test, and revise curriculum on the basis of experience in classes at UW and at pilot sites. Teaching is by asking questions to help students construct a coherent conceptual framework, rather than by telling. The emphasis is not on solving standard problems, but on developing the reasoning ability needed to apply relevant concepts to situations that have not been memorized. The curriculum explicitly addresses specific difficulties that research has shown may preclude a functional understanding. Even when teachers do not have these difficulties themselves, it is likely that their students will. *PbI* helps teachers develop the type of knowledge necessary to be able to teach a given topic effectively (pedagogical content knowledge).[15] Ongoing assessment that includes pretests and post-tests is an integral part of the iterative process involved in our ongoing curriculum development. We illustrate our design and assessment of curriculum in the context of dynamics.

Design of curriculum. Student understanding of dynamics has been the focus of much research by our group and others.[7,10] The results have guided the development of *Dynamics*. This module builds directly on *Kinematics*, in which the concepts of velocity and acceleration are developed from their operational definitions. *Dynamics* begins with the concept of force as a push or a pull. As in all of *PbI*, the equipment is simple and inexpensive so that it is readily accessible to teachers. Measurement procedures are as straightforward as possible with no black boxes. We start with simple "pull meters" made of rubber bands and meter sticks, rather than with spring scales or force probes. Students build and calibrate the pull meters and explore how multiple pulls affect the motion of a wheeled cart. They find that a cart subject to a constant pull undergoes constant acceleration.

Experiments with wooden blocks on rough surfaces and pieces of dry ice on level slate surfaces lead students to recognize that an interaction between surfaces can be thought of in terms of a force. These experiments help students distinguish between a single applied force, for example, exerted by a pull meter or a hand, and the net force that an object experiences. The students build on their previous experience with kinematics and explore cases in which the net force is exerted in the direction of motion and in the opposite direction. They conclude that an object accelerates in the direction of the net force. The well-known tendency to associate force and velocity is explicitly addressed. For example, the students consider hypothetical dialogues in which fictional students express common incorrect ideas.

The students use spring scales (calibrated in newtons) to conduct experiments on carts to which varying numbers of identical objects have been added. They find that the net force required to produce a given acceleration increases as the number of objects increases. They are then led to develop the concept of inertial mass and arrive at an algebraic expression of Newton's second law. Subsequently, the students explore gravitational and frictional forces in more detail. They also develop skill in drawing free-body diagrams. Newton's third law is introduced by experiments in which students find that two magnets exert forces of equal magnitude and opposite direction on each other, regardless of which magnet is stronger. Subsequent experiments and exercises provide students with experience in applying Newton's laws to systems of increasing complexity.

There is an emphasis on the development of scientific reasoning skills throughout *Dynamics*. The module stresses graphing, proportional reasoning, and vectors. Ideas introduced in the *Kinematics* module, for example, the interpretation of the slopes and the areas under the curves for graphs of position, velocity, and acceleration as functions of time, are reinforced. Thus, mathematics and physics teachers are given concrete ways to help students relate differentiation and integration to real-world phenomena.

The process of scientific model building is made explicit. In particular, the difference between observation and inference is stressed repeatedly. For example, students are expected to recognize that the extension of a spring scale from which an object is hanging is not a direct measurement of the gravitational force exerted on the object; rather, it can be used in conjunction with Newton's second law to deduce the magnitude of the force.

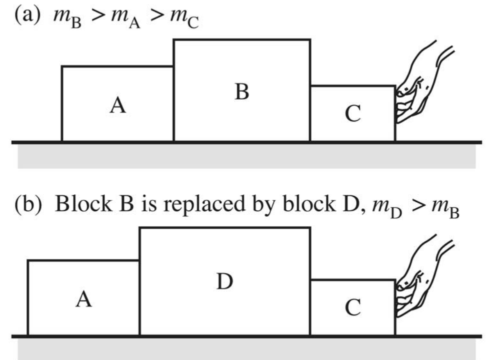

Fig. 4. Question about Newton's second law. (a) Students are shown a figure in which three incompressible blocks are pushed across a frictionless table by a hand. (b) They are then told that block B is replaced by a block of greater mass. The question asks how, if at all, the acceleration of block A and the net force on block A change if the hand exerts the same horizontal force in both cases.

Assessment of student learning. We have assessed student learning by comparing results from pretests and post-tests. The following post-test question, which requires multistep reasoning, is an example.

A system of three incompressible blocks is pushed across a frictionless table by a hand that exerts a constant horizontal force (see Fig. 4).[16] Students are asked how, if at all, the acceleration of block A and the net force on block A changes if block B is replaced by a block of greater mass while the hand continues to exert the same constant force. To answer correctly, students must recognize that the inertial mass of the system has increased while the net force on the system (due to the hand) remains unchanged. Newton's second law may be applied to determine that the acceleration of the entire system and thus that of block A has decreased. Using similar reasoning, the students can then infer that the net force on block A has also decreased.

When this question was administered in introductory physics courses after standard instruction, fewer than 20% of the students ($N > 100$) answered correctly.[7] About 90% of the teachers ($N = 45$) who worked through the *Dynamics* module gave a correct response. We have also given this question to introductory students after they had worked through *Tutorials in Introductory Physics*.[17] (This curriculum addresses the intellectual issues discussed previously, but in a form adapted to a large introductory course.) About 55% of the students ($N \sim 720$) answered correctly. Although this result represents a sizable gain over that obtained with standard instruction, it is not good enough for prospective teachers. Even when an introductory physics course is supplemented with research-based materials, students are unlikely to develop the depth of understanding that is possible with the type of instruction provided by *PbI*. There is evidence from other topics that not only is the resultant gain in conceptual understanding greater, it is also persistent.[18]

Commentary. To illustrate our instructional approach in preparing teachers, we have used an example from dynamics. A topic from earlier grades would have served equally well. Elementary and middle school teachers need the same type

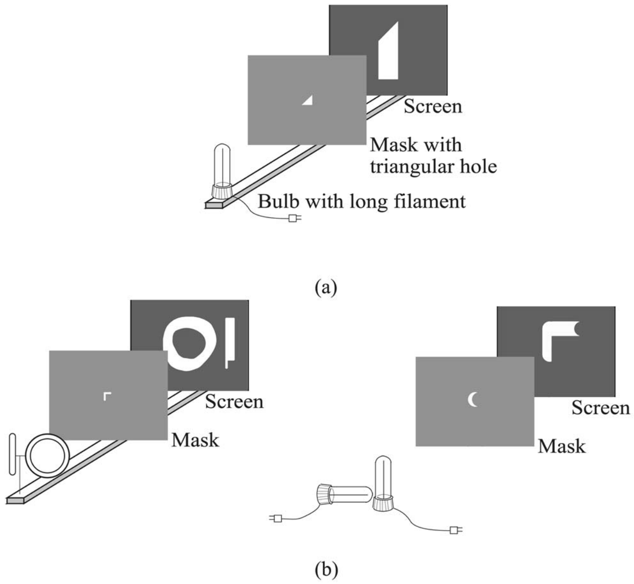

Fig. 5. (a) Pretest and (b) post-test questions on light and apertures. Students are asked to predict what they would see on a screen when assorted apertures are placed between various extended light source and the screen.

of preparation. Although the topics that they are expected to teach may appear simple to a physicist, it takes a significant amount of time and effort to develop the depth of understanding needed to teach this material in a coherent manner, rather than as a set of separate activities.

IV. RELATION BETWEEN TEACHER PREPARATION AND STUDENT LEARNING

The assessment of the effectiveness of a physics program for the preparation of teachers should focus on how well they understand the content and process of physics. A major incentive for conducting such a program is to improve student learning in K-12 classrooms. Therefore, it is also important to assess the effect of the type of preparation that teachers have received on the intellectual development of their students. Making such judgments in a K-12 classroom is challenging, partly because access is difficult. Nevertheless, we have been able to conduct some limited assessments.

To help teachers in our preservice course develop pedagogical content knowledge, we have them teach in a precollege classroom a topic that they themselves have studied. In the following example, preservice teachers designed and taught lessons on the straight-line propagation of light to ninth-grade students and then assessed the results.[19]

A. Preparation of K-12 teachers

The preservice teachers began their study of this topic with a pretest that has been given to more than 2000 students from the introductory to the graduate level, and to many K-12 teachers.[8] The part of the pretest in Fig. 5(a) asks what would be seen on a screen when a mask with a triangular hole is placed between a long-filament bulb and the screen.

As Table I indicates, preservice teachers and introductory students performed at about the same level (20%) on the pretest. About 65% of the graduate students responded correctly. In all three populations, many students could not apply the basic ideas that light travels in a straight line and that every point on an object acts as a source of an infinite number of rays emitted in all directions.

After working through the relevant sections of *Light and Color* in *PbI*, the preservice high school teachers developed a ray model for light that they could apply to predict and explain the patterns formed on a screen by light sources and apertures of various shapes.[20] Two of the many post-tests that we have administered are in Fig. 5(b). As Table I shows, the preservice teachers did better after *PbI* instruction (85%) than physics graduate students did on the simpler pretest.

B. Effect on K-12 students

After they had acquired the background discussed in Sec. IV A, the preservice teachers modified the relevant sections of *PbI* and used these sections in a ninth-grade classroom. They then assessed the performance of their students with one of the post-tests in Fig. 5(b). About 45% of the ninth-grade students gave a correct response (see Table I). If these students had learned from teachers with only a typical background, they would have likely done no better than their teachers or university undergraduates (20%). Table I also contains results (85%) from other ninth-grade students taught by an experienced teacher who was thoroughly familiar with both the content and instructional approach in *PbI*. Not sur-

Table I. Percentage of correct responses on pretest and post-test questions on light and apertures. Pretest results are from a question about a long-filament bulb and a triangular aperture [see Fig. 5(a)]. Post-test results are from questions about various light sources and apertures [see Fig. 5(b)]. The preservice teachers had worked through the relevant sections of *PbI* before modifying the curriculum. The experienced inservice teacher was thoroughly familiar with the content and with the *PbI* approach.

Pretest		Post-test		
Undergraduates and preservice teachers (9-12)	Graduate TAs	Preservice teachers (9-12)	Ninth-grade students	
after standard instruction	after standard instruction	after *PbI*	*after PbI* (modified by well-prepared preservice teachers)	*after PbI* (modified by very well-prepared inservice teacher)
$N > 2000$	$N \sim 110$	$N \sim 60$	$N \sim 55$	$N \sim 55$
20%	65%	85%	45%	85%

prisingly, when experienced teachers have intensive preparation in the physics involved, the quality of student learning is even better.

V. CONCLUSION

In this paper, we have illustrated how *Physics by Inquiry*, a research-based curriculum developed by our group, can help preservice and inservice teachers deepen their understanding of the topics that they are expected to teach.[21,22] Evidence has also been presented of a significant increase in learning by ninth-grade students who were taught by teachers who had worked through this curriculum.

Because of their influence on large numbers of students, K-12 teachers should have a strong command of basic physics and physical science. Results from research conducted among physics majors and graduate students, all of whom have taken courses on more advanced material, indicate that these courses often do not help them deepen their understanding of some important concepts taught in high school.[23] Descriptive survey courses are inadequate preparation for teaching physical science in elementary and middle school. Moreover, as has been illustrated, experience in teaching a topic does not necessarily lead to the development of a functional understanding. There is therefore a need for special physics courses for elementary, middle, and high school teachers. Some important features of these courses have been illustrated in this paper and are also discussed in the Guest Editorial in this issue.[1]

ACKNOWLEDGMENTS

The research and curriculum development described in this paper were a collaborative effort by many past and present members of the Physics Education Group at the University of Washington. Donna Messina, a former high school teacher, led the preservice teaching project. Karen Wosilait collected and analyzed data from her ninth-grade class. Support from NSF for our annual Summer Institutes for Inservice Teachers and for the development of *Physics by Inquiry* made these related projects possible.

[1]For specific references and additional discussion, see L. C. McDermott, “Preparing K-12 teachers in physics: Insights from history, experience, and research,” Am. J. Phys. **74**, 758–762 (2006).

[2]Other important aspects include classroom management, social and cultural problems, psychological concerns, epistemological beliefs, and theories of learning.

[3]L. C. McDermott, “A perspective on teacher preparation in physics and other sciences: The need for special courses for teachers,” Am. J. Phys. **58**, 734–742 (1990); “Teacher education and the implementation of elementary science curricula,” *ibid.* **44**, 434–441 (1976); “Improving high school physics teacher preparation,” Phys. Teach. **13**, 523–529 (1974); “Combined physics course for future elementary and secondary school teachers,” Am. J. Phys. **42**, 668–676 (1974).

[4]L. G. Ortiz, P. R. L. Heron, and P. S. Shaffer, “Student understanding of static equilibrium: Predicting and accounting for balancing,” Am. J. Phys. **73**, 545–553 (2005).

[5]P. S. Shaffer and L. C. McDermott, “A research-based approach to improving student understanding of the vector nature of kinematical concepts,” Am. J. Phys. **73**, 921–931 (2005).

[6]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); *ibid.* **61**, 81(E) (1993); 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,” *ibid.* **60**, 1003–1013 (1992).

[7]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).

[8]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 (1999); P. R. L. Heron and L. C. McDermott, “Bridging the gap between teaching and learning in geometrical optics: The role of research,” Opt. Photonics News **9**(9), 30–36 (1998).

[9]The results support the views expressed in Ref. 1.

[10]L. C. McDermott and E. F. Redish, “Resource letter: PER-1: Physics education research,” Am. J. Phys. **67**, 755–767 (1999).

[11]See, for example, “Balance and motion,” in *Full Option Science System* (Lawrence Hall of Science, Berkeley, CA, 1995).

[12]See “Background for the teacher,” p. 2 of “Balance” in “Teacher Guide: Balance and motion,” in *Full Option Science System* (Lawrence Hall of Science, Berkeley, CA, 1995).

[13]L. C. McDermott and the Physics Education Group at the University of Washington, *Physics by Inquiry* (Wiley, NY, 1996).

[14]*PbI* has been used in courses for nonscience majors, as well as in preparatory courses for students aspiring to science-related careers but who are underprepared in science and mathematics. Two examples are R. E. Scherr, “An implementation of *Physics by Inquiry* in a large-enrollment class,” Phys. Teach. **41**(2), 113–118 (2003)and L. C. McDermott, L. K. Piternick, and M. L. Rosenquist, “Helping minority students succeed in science, Part I. Development of a curriculum in physics and biology,” J. Coll. Sci. Teach. **9**, 136–140 (1980).

[15]The term “pedagogical content knowledge” was introduced by L. S. Shulman, to characterize what a teacher needs to know beyond the content and pedagogy in order to help students learn. See, for example, L. S. Shulman, “Those who understand: Knowledge growth in teaching,” Educational Researcher **15**(2), 4–14 (1986).

[16]This question is discussed in greater detail in Ref. 7.

[17]L. C. McDermott, P. S. Shaffer, and the Physics Education Group at the University of Washington, *Tutorials in Introductory Physics* (Prentice Hall, Upper Saddle River, NJ, 2002).

[18]See, for example, the discussion of research in the context of electric circuits described 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).

[19]For a more detailed description of the teaching experience, see D. L. Messina, L. S. DeWater, and M. R. Stetzer, “Helping preservice teachers implement and assess research-based instruction in K-12 classrooms,” AIP Conf. Proc. edited by J. Marx, P. Heron, and S. Franklin (AIP, Melville, New York, 2005), p. 97.

[20]See Secs. 1 and 2 of the module *Light and Color* in *Physics by Inquiry* (Ref. 13).

[21]In addition to the examples from dynamics and geometrical optics discussed in this paper, see also the second paper in Refs. 6 and 18.

[22]For additional assessments of teacher understanding in courses based on *Physics by Inquiry* that were reported by faculty at other institutions, see, for example, R. E. Scherr, “An implementation of *Physics by Inquiry* in a large-enrollment class,” Phys. Teach. **41**(2), 113–118 (2003); K. C. Trundle, R. K. Atwood, and J. E. Christopher, “Preservice elementary teachers’ conceptions of moon phases before and after instruction,” J. Res. Sci. Teach. **39**(7), 633–658 (2002); J. A. Marshall and J. T. Dorward, “Inquiry experiences as a lecture supplement for preservice elementary teachers and general education students,” Am. J. Phys. **68**(7), S27–S36 (2000); B. Thacker, E. Kim, K. Trefz, and S. M. Lea, “Comparing problem solving performance of physics students in inquiry-based and traditional introductory physics courses,” Am. J. Phys. **62**(7), 627–633 (1994); and S. M. Lea, “Adapting a research-based curriculum to disparate teaching environments,” J. Coll. Sci. Teach. **22**(4), 242–244 (1993).

[23]See, for example, Refs. 4–6 and 8.

Inquiry experiences as a lecture supplement for preservice elementary teachers and general education students

Jill A. Marshall[a] and James T. Dorward
Utah State University, Logan, Utah 84322-4415

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The study reported here was designed to substantiate the findings of previous research on the use of inquiry-based laboratory activities in introductory college physics courses. The authors sought to determine whether limited use of inquiry activities as a supplement to a traditional lecture and demonstration curriculum would improve student achievement in introductory classes for preservice teachers and general education students. Achievement was measured by responses to problems designed to test conceptual understanding as well as overall course grades. We analyzed the effect on selected student outcome measures in a preliminary study in which some students engaged in inquiry activities and others did not, and interviewed students about their perceptions of the inquiry activities. In the preliminary study, preservice elementary teachers and female students showed significantly higher achievement after engaging such activities, but only on exam questions relating directly to the material covered in the exercises. In a second study we used a common exam problem to compare the performance of students who had engaged in a revised version of the inquiry activities with the performance of students in algebra and calculus-based classes. The students who had engaged in inquiry investigations significantly outperformed the other students.

I. INTRODUCTION

In recent years a substantial and growing body of research has demonstrated that interactive engagement (IE) allows students to construct and implement appropriate mental models of physical phenomena better than the traditional passive lecture (or lecture with prescriptive laboratory) approach to physics education. McDermott and Redish[1] have compiled an exhaustive overview. Basic precepts of cognitive science suggest the importance of IE for all physics students,[2] but the need is particularly acute in the case of preservice elementary teachers, especially given the expectation that these students will go on to teach science in the same way that they have been taught.

Logically, one might expect a hands-on approach to be better for science education in the primary grades. Elementary students are not likely to be engaged by a lecture or demonstration in which they do not participate. Research supports this assertion. Students who regularly engage in hands-on activities have been shown to outperform students who do not.[3] Further, students who engaged in inquiry activities (hands-on activities oriented toward discovery learning) outperformed students in programs that used laboratory activities only as verification exercises.[4] Perhaps equally important, fourth and fifth graders' enjoyment of science has been shown to increase after inquiry exercises.[5] This was particularly true for female students, supporting a widespread contention[6] that hands-on experiences are key to retaining girls' interest in science. Lack of teacher preparation, however, has been a major stumbling block in the implementation of inquiry-based curricula.

Studies have shown that a lack of content knowledge will prevent teachers from using the inquiry approach with their primary school students, but even solid content knowledge has been shown to be insufficient to guarantee that teachers will adopt this approach.[7–9] McDermott has made a convincing case that physics classes for preservice teachers should be taught by physics department faculty using an inquiry approach.[10] She describes a 20-year development effort for such a course, beginning with the work of Arnold Arons in *The Various Language*[11] and culminating in the published version of *Physics by Inquiry*.[12]

Physics by Inquiry has been shown to be a highly effective approach to science learning for both preservice and in-service teachers.[10] Thacker *et al.* report that elementary education majors at Ohio State who were taught using *Physics by Inquiry* significantly outperformed other students, including those in a calculus-based course and an honors course, on common quantitative and conceptual exam problems.[13] Lea reports that elementary education majors in that same *Physics by Inquiry* class at Ohio State developed more positive attitudes toward teaching physics and intended to use inquiry activities when they went on to teach.[14]

The *Physics by Inquiry* approach enables students to develop a more robust conceptual framework, but it requires a commensurately higher commitment of resources on the part of the teaching institution and of students. The *Physics by Inquiry* course for preservice teachers as taught at the University of Washington and Ohio State consists of six hours a week[10] and three hours twice a week,[14] respectively, in a laboratory setting, over the course of two (presumably ten-week) quarter terms. The method requires both a low student-to-instructor ratio and a laboratory setting, resulting in limited class sizes. Physics departments that typically teach large numbers of elementary education majors (greater than 200, for example) each year would be hard pressed to commit these necessary resources.

Students are also required to commit two three-hour blocks per week for two (ten-week) terms to complete the *Physics by Inquiry* curriculum, whereas most traditional lecture courses for elementary education majors (or general education students) provide a survey of physics in only one quarter or one semester. Upper division female students, in particular, have expressed concern over the time commitment for some inquiry-based programs. These students expressed frustration with a method that was at variance with their expectations of learning as straightforward fact gathering or memorization.[15] Some researchers have argued that ''constructivist'' curricula such as these may in fact fail to meet student needs because they do not take into account student expectations and goals.[16]

A strict inquiry approach will also result in coverage of fewer curriculum topics in the same amount of time. Students discussed in Ref. 13 covered only electrical circuits and light and optics in their one-quarter course. Many proponents of science education reform are calling for just such a trade-off of ''mile-wide, inch deep'' coverage for a more narrowly focused, in depth curriculum, particularly in light of the recent TIMSS results.[17] Yet, the fact remains that the elementary science curriculum in many states requires teachers to teach many topics within science. McDermott reports that for preservice teachers in a small practice teaching program at the University of Washington about five (presumably ten-week) quarters of work in (physics) courses are required before the students can prepare and teach material that has not been previously studied, and that the situation is similar for inservice teachers, although the time required does not appear to be quite so long.[9]

Given these constraints (laboratory setting, low student-to-instructor ratio, reduced coverage of topics) on a course taught exclusively by the inquiry method, some physics educators have instituted a compromise approach, supplementing a traditional lecture with limited exposure to IE. There is evidence that such a combined approach yields improvements over traditional instruction alone. In Hake's comprehensive survey of IE and traditional introductory physics courses,[18,19] some university courses that employed peer instruction and concept tests[20] during lectures achieved Hake factors nearly double that of any class with traditional instruction alone. The Hake factor is the normalized gain (ratio of actual gain to possible gain) between pre- and postcourse scores on the Force Concept Inventory (FCI),[21] and is a widely used figure of merit for the effectiveness of instruction in introductory mechanics courses.

Traditional university physics lecture courses supplemented with inquiry activities outside of lecture have also been shown to yield higher Hake factors than courses with no inquiry activities. Two examples are *Tutorials in Introductory Physics*[22,23] and *Group Problem Solving*.[24] These curricula were both developed in an iterative cycle of research, curriculum development, and instruction. The *Tutorials* approach augments a traditional lecture with one hour per week in which small groups of students work on research-based worksheets, replacing the traditional recitation or ''problem session'' in which teaching assistants model problem solving skills and students usually do not actively participate. *Group Problem Solving* replaces a traditional recitation session with one hour per week of IE through problem solving in small groups.

Both these methods have been shown to be effective. Redish and Steinberg recently reported a systematic study (with matched pairs) of more than 2000 university physics students at eight institutions.[25] These students were enrolled either in traditional lecture courses (no inquiry), lecture courses supplemented with *Tutorials*, or *Workshop Physics*. *Workshop Physics* replaces lecture, recitation, and laboratory with two three-hour sessions per week of research-based, hands-on activities and discussion, and is considered a full exposure to the inquiry method. A report by Saul[26] extended the comparison to courses using *Group Problem Solving*.[27] These studies again reported normalized percentage gains from pre- to postcourse administration of the FCI, i.e., Hake factors. *Workshop Physics*, which uses the inquiry approach exclusively for six hours each week, yielded the highest Hake factor, 0.41 ± 0.02. The two limited approaches, however, also achieved significantly higher Hake factors (0.35 ± 0.03 and 0.34 ± 0.01) with only one hour of inquiry per week, as compared with traditional, non-inquiry courses (0.16 ± 0.03).

At the time of the study reported here, we knew of no matched-pair study comparing a limited inquiry approach to a traditional approach for elementary education majors or students in non-algebra-, non-calculus-based courses designed to fulfill general education requirements. In this context, limited inquiry is an average of one hour per week or less of inquiry-based, hands-on activities as a supplement to a regular lecture curriculum.

To determine the effectiveness of limited exposure to inquiry activities for elementary education majors and other students in introductory (non-algebra, non-calculus) courses, we implemented a preliminary study of the effectiveness of (1) two-hour inquiry sessions six times during ten weeks for elementary education majors and (2) one-hour inquiry sessions six times during ten weeks for general education students. Following the preliminary study and revision of the inquiry activities based on formative assessment, limited inquiry activities were implemented for both groups of students during a third ten-week term.

We give details of the implementation and a description of the inquiry exercises in Sec. II. In Sec. III we describe the various formative and summative assessments used. In Sec. IV, we present detailed results, and, in Sec. V, we present our discussion and conclusions.

II. EXPERIMENTAL DESIGN

In order to determine the extent to which limited exposure to inquiry activities affects student mastery of concepts for elementary education majors and others in introductory (non-algebra, non-calculus) courses, we incorporated selected inquiry activities into the curriculum of a large (140 students) lecture class at a large land grant institution. During two consecutive ten-week terms (winter and spring quarters, 1996) we performed a preliminary study of the inquiry activities. The activities were then revised and institutionalized into our curriculum. During a third ten-week term (winter quarter, 1997), we performed a comparison study, involving a common exam problem, with algebra- and calculus-based classes at the same institution.

During each term, the class comprised two groups of students: (1) those who were taking the course to satisfy general education science requirement and (2) those who were taking the course to satisfy a laboratory science requirement (primarily elementary education majors). There were no prerequisites for the introductory course in our study. Many of the general education students had never had an algebra course and had only rudimentary mathematics skills. Elementary education majors were required to maintain a minimum grade point average prior to their acceptance into that program and to take a college algebra course (although not necessarily prior to taking the physics survey course).

All students attended the same 50-minute lectures (nominally five times a week). Students in the second category also attended six two-hour laboratory sessions with mandatory attendance. All students, both with and without a laboratory session, took the same exams during the lecture period.

A. Preliminary study

The existence of two student populations allowed for a simple division of the class into students who would be assigned to participate in inquiry activities and those who would not (the ''inquiry'' and ''non-inquiry'' groups). During the first term, students who did not register for the laboratory performed inquiry exercises and those registered for labs did not. In the second term this assignment was reversed, so that students with labs performed inquiry exercises and the students without labs did not.

The inquiry group clearly constitutes a convenience sample under this procedure, but resources did not permit subdivision of the two populations by inquiry and non-inquiry within each term to create a truly random sampling. Such convenience samples have been widely used in physics education research. For example, Hake[18] and Redish and Steinberg[25] both compared IE versus traditional methods using data entirely obtained by convenience samples, that is, the teaching method varied on a class-by-class basis and students were not randomly assigned to one method or the other.

We sought to mitigate the shortcoming of a convenience sample by carefully comparing students in the two terms on all measures available to us (grade point average prior to taking the class, gender, and major). We found no significant term-to-term variation in either subgroup. Further, students did not know whether they would be assigned to inquiry activities when they registered for the course, eliminating the possibility of self-selection on the part of the students.

During the first term, students who were registered for a lab ($N=47$) attended lectures five days a week and completed six traditional physics labs outside of lecture hours. These laboratory exercises were prescriptive in nature, listing a series of experimental steps to be performed and calling for a well-described data analysis procedure (for example, measure this, graph this, etc.). The labs were intended for practice in measurement skills rather than concept development and were not designed with a constructivist approach in mind. Students did not have to make any predictions, draw any qualitative conclusions, or explain their thinking. A portion of each student's final grade was based on laboratory performance as recorded in a laboratory notebook.

During the first term students who were not registered for a lab performed selected inquiry exercises (described in detail below) during six one-hour lecture periods. Students worked in self-selected groups of four to six. The laboratory students were excused from attendance during these six class periods. Students performed the activities either in their seats or on the floor in the lecture auditorium or in nearby halls or outdoors. The instructor and an undergraduate assistant who had taken the class before circulated among the groups providing guidance in the form of suggestive questions and approving students' work at designated check points in the worksheets. A portion of the final grades for students who did not attend laboratory (corresponding to the laboratory grade for the students with labs) was based on worksheets completed during these ''hands-on'' periods.

During the second ten-week term, the situation was reversed. Students who registered for labs performed the inquiry exercises during their assigned two-hour laboratory periods in place of the prescriptive, measurement-oriented labs. A portion of their final grade was based on their performance of these exercises. During this term, students who did not register for a lab did not participate in inquiry exercises. Instead, they were required to complete extra homework problems each week. Scores on homework comprised 35% of their final grade as compared to 25% for the students with labs. The extra homework problems were both conceptual and quantitative, and were representative of problems on exams.

Table I. Summary of the treatment of students during the preliminary study.

Student population	Term 1 (winter 1996) preliminary study	Term 2 (spring 1996) preliminary study
Registered for lab (primarily elementary education)	Prescriptive labs **(non-inquiry)**	Six two-hour **inquiry** exercises during lab period
Not registered for lab (general education)	Six one-hour **inquiry** exercises during lecture period	Extra homework problems **(non-inquiry)**

In the second term, there were no lecture periods set aside for inquiry activities, resulting in five extra lecture periods. (Spring term is one day shorter than winter term.) This time was used to cover selected topics in subatomic physics. These topics were not covered in our inquiry activities during the preliminary study and were addressed only in the final exam. Coverage of all other topics was approximately equal, in terms of lectures, during the two quarters. Table I summarizes the treatment of the two groups of students during the two terms of the preliminary study.

B. Comparison study

Following the preliminary study, the inquiry activities were revised based on students' comments on class evaluations, problems reported by teaching assistants, and evidence of persisting misconceptions in student work. During a third ten-week term (winter 1997) the revised exercises were implemented into the curriculum for all students in our introductory class. Students with a lab assignment (primarily elementary education majors) completed the inquiry exercises during six two-hour laboratory sessions. Students without a lab assignment completed a shorter version of the exercises during six one-hour lecture periods; students with labs were excused from class during these periods. One problem on the final exam was based on Fig. 3 from Ref. 28, shown here as Fig. 1.

A version of this problem was also administered to a calculus-based physics class as part of a final exam, and to an algebra-based physics class as an ungraded quiz during the last week of the term. Both were classes at the same univer-

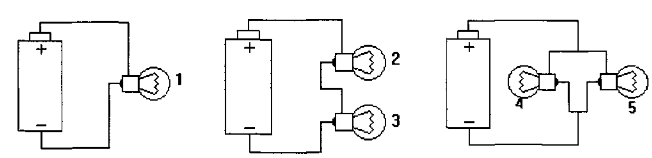

Fig. 1. Students were asked to rank the five bulbs in the circuits shown here by brightness, assuming that all bulbs are identical and all batteries are identical and ideal (after Fig. 3 in Ref. 28).

Table II. Summary of the laboratory experiences of the four groups of students during the comparison study.

Our students registered for lab (primarily elementary education) ($N=70$)	Our students not registered for lab (General Education) ($N=46$)	Students in traditional algebra-based course ($N=59$)	Students in calculus based course ($N=150$)
Six two-hour **inquiry** exercises during lab period	Six one-hour **inquiry** exercises during lecture period	Six nominally three-hour prescriptive labs	Six nominally three-hour computer-based labs

sity, and both were part of a year-long series of three ten-week terms. The common question was administered at the end of the second term, during which electric circuits were covered in lecture and laboratory sessions. At the request of the instructor of the calculus-based class, we changed the problem to read ''Rank the five resistors in terms of power dissipation'' instead of ''Rank the five bulbs in order of brightness,'' and redrew the diagram to show resistor symbols rather than light bulbs. The algebra- and calculus-based students had studied the behavior of generic resistors (rather than actual light bulbs) in their laboratories and the instructor was concerned that students might not be able to express their knowledge of currents in terms of light bulb brightness. The issue of power dissipation had been discussed in both classes.

A shortcoming of our design is that we did not include a common quantitative problem for comparison, as per Ref. 13. As our final exams are comprehensive, covering many additional topics, we felt that two problems addressing resistive circuits would be excessive. We had given a quantitative version of this problem to students in our preliminary study and found that both those who had experienced the inquiry exercises, and those who had not, had higher mean scores on the quantitative version than on the qualitative version shown in Fig. 1.

Table II summarizes the various laboratory experiences of all students in the comparison study.

C. The inquiry exercises

Each exercise was designed to address certain misconceptions in a particular subject area. These misconceptions had been identified, partly from experiences (informal discussions and test questions responses) with previous groups of students, but also from the literature.[28,29] The ''elicit, confront, resolve'' educational paradigm[30,31] was used. This strategy first requires that students make predictions or provide explanations about a physical system to be studied. Students then investigate the system using a simple physical model. They follow a set of guideline questions and activities designed to expose misconceptions and develop an appropriate conceptual model that the students can then use to predict the results of changes to the system and the behavior of similar systems. Finally, students are asked to describe or explain the behavior of the system in their words, that is, to explicitly express their mental model.

In this study, the elicit phase of the program did not include a formal pretest. Rather, students were asked questions, either in the introductory part of the exercises or as part of the lecture portion of the class. For example, students were asked to predict the motion of a ball leaving a circular channel prior to the activities on circular motion (question 6 from the Force Concept Inventory[21]). Students then collected the necessary equipment and worked through a short worksheet in self-selected groups of two to six people. The exercises covered eight topics: constant velocity and accelerated motion in one dimension, circular motion, conservation of energy, heat transfer, density and the buoyant force, light (reflection), standing waves, and resistive circuits.

For some topics, namely resistive circuits and one-dimensional motion, the activities were shortened versions of the *Physics by Inquiry* activities developed for elementary education majors by McDermott *et al.*[12] The circuit activities followed the outline of McDermott, but time constraints did not allow for the entire McDermott ''Batteries and Bulbs'' unit to be implemented. Students performed the well-known exercise of lighting a small bulb with a battery and one piece of wire and then progressed to comparing the brightness of bulbs and the effect of removing or adding bulbs to series and parallel resistive circuits. The concepts of conductors and insulators and current flow had been previously introduced in lecture and were not developed in inquiry exercises. Students did not investigate more complicated circuits such as resistors in series with parallel elements or the use of voltmeters and ammeters. Similarly, the activities on one-dimensional motion were abbreviated versions of those in *Physics by Inquiry*.

Other activities (conservation of energy and circular motion) had been developed as part of a workshop on Amusement Park Physics.[32] The conservation of energy activities used a low-friction model roller coaster, made of BBs and plastic tubing. Students investigated the concepts of a change in gravitational potential energy versus an absolute value of gravitational potential energy. McDermott and Shaffer had identified failure to distinguish between potential and potential difference as a difficulty commonly experienced by students in introductory electricity,[28] and we had observed that our students experienced similar difficulties with gravitational potential. Students also investigated the lack of dependence on intermediate path of energy conservation from final to initial state. The circular motion activities investigated the idea of a centrifugal versus centripetal force and the relation between velocity and centripetal force using simple models of the channel described in question 6 from the FCI[21] and another rotating system.

Finally, some activities (reflection, heat transfer, and standing waves) were developed especially for these classes, but were based in part on suggestions by Arons.[33]

The students in this study were not given formal posttests, but were instructed to consult with instructors at specific points in the exercises. Instructors reviewed the students work and posed additional questions. Conceptual and quantitative questions on the material covered in the exercises were included on exams.

In every case, an attempt was made to cast the activities in terms of an interesting theme. For example, the activities on one-dimensional motion were *Marble Races*, conservation of energy was *BB Roller Coasters*, and heat transfer was *Ice Cream Sundaes*. This was done partly to remove the stigma of a formal physics laboratory experiment as being perhaps boring, difficult to understand, and unlikely to produce the expected result.

We also hoped that the preservice teachers among our students would view these activities in the light of preparation for activities with which they might engage their own students in the future. While these activities are not appropriate for young children as they stand, many actually have their roots in activities specifically developed for primary students. For example, our units on density and the buoyant force and resistive circuits correspond to *Clay Boats* and *Batteries and Bulbs*, respectively, from Elementary Science Study (ESS).[34] ESS was developed under the sponsorship of the National Science Foundation as a model inquiry curriculum for elementary school. Our conservation of energy activity (*BB Coasters*) has been used in a modified form at the middle school level. Inquiry activities, although of a less guided nature, have been generally shown to be appropriate for elementary audiences.[5]

D. Constraints and limitations

Constraints to our research design limit the generalizability of our results. Our use of a convenience sample (i.e., without random sampling) raises the distinct possibility that inquiry- and non-inquiry-based groups were not representative of their respective populations. We mitigated this limitation to some degree by randomly assigning each class to follow an inquiry-based curriculum or a traditional curriculum. With random assignment, a test of statistical significance can address whether groups under analysis can be regarded as samples from the same population.[35] When we investigated the effect of the inquiry exercises on subgroups, such as female students or elementary education majors, our sample sizes became fairly small. For this reason, we report effect size metrics to assess practical significance.

III. ASSESSMENT

We used multiple methods to assess the effectiveness of the two limited inquiry approaches in our experiment. Reference 36 suggests that interpretations from triangulation of information collected using multiple methods on different samples at different times can be more credible than conclusions based upon one-dimensional data collection techniques. In the preliminary study, a number of student outcomes were compared for students who experienced inquiry activities and those who did not.

The outcome measures we selected for analysis included final exam grades, course grades, and scores on midterm exam questions related to topics covered in the inquiry exercises. We chose these outcomes measures, as opposed to standardized tests of conceptual understanding such as the FCI, first because widely accepted standardized questions are not available for all the topics we covered in the course. Second, we believe that these measures are of primary value to our students. Unfortunately, course grades may be more important to our students in their careers than a more robust understanding of physics.

Table III. Multivariate analysis of variance summary for majors by instruction method (inquiry versus non-inquiry).

Multivariate ANOVA		Univariate ANOVA			Questions on topics covered in inquiry exercises
Source	F		Final exam	Course grade	
Student major	25.68[a]	F	0.05	0.27	0.62
Instruction method	47.11[a]	F	0.28	1.78	7.75[a]
Student major by instruction method	9.57[a]	F	0.08	1.18	6.16[a]

[a] $p<0.05$.

That being said, with proper assessment instruments, exam and course grades should reflect student understanding. We chose to look at both comprehensive measures, such as final exam and course grades, as well as scores on problems directly related to the topics we were able to cover in the inquiry activities. This allowed us to investigate the possibility of a secondary effect, in which student performance on topics not covered in the inquiry activities might somehow be affected, possibly through heightened interest in or commitment to the course.

All exams consisted of both qualitative and quantitative problems in a variety of formats. Students were required to set up and solve numerical problems, write out explanations and predictions, and select from multiple choice responses. Some of the problems used on exams were taken directly from the physics education research literature (for example, problems cited in Ref. 13 and problems from the FCI) as well as problems of one of the author's (JAM) invention. While the tests were not identical from term to term, problems were comparable from one term to the next. For example, one problem presented a graph of an object's velocity versus time and asked students to identify when the object was stopped, when and how much it was accelerating, how much distance it covered in the time period, etc. A second part of the problem asked students to choose a description of a motion that might correspond to the one shown in the graph. The problem was the same in both terms except that the details of the graph were changed.

The final exam was cumulative. Course grades were based on homework and exam scores, and either inquiry worksheets, lab reports from prescriptive labs, or extra homework depending on the class as discussed earlier. Roughly one-third of the material covered on exams had been the subject of an inquiry exercise. The rest had been covered in lecture only. A separate tally was kept of scores on the midterm exam questions that related directly to the inquiry exercises. Because of time constraints in returning exams, we did not evaluate final exam questions on topics covered in the inquiry exercises separately.

At the beginning and end of courses in the preliminary study we conducted one-hour focus group interviews of volunteer students, both those who were registered for labs and those who were not. These interviews were designed to elicit student attitudes toward the inquiry activities and toward science and scientists in general.

Table IV. T-test comparisons of percent correct on exam questions on inquiry exercise topics for elementary education majors experiencing inquiry and non-inquiry activities. $t=-3.51$, $p=0.001$, $ES=0.68$.

Variable	No. of cases	Mean percent	s.d.	SE of mean
Inquiry	33	91.24	7.54	1.31
Non-inquiry	47	84.23	10.30	1.50

In the comparison study, the performance of students who participated in limited inquiry activities (of both one- and two-hour duration) was compared with that of students in traditional algebra- and calculus-based lecture courses with prescriptive labs.

IV. RESULTS

A. Preliminary study

To determine the effect of the inquiry exercises in the preliminary study, we performed a multivariate analysis of variance, MANOVA, on outcome measures from all four classes combined (171 students).[37] This technique allows for controlling for grade point average and gender. Table III presents the results of the MANOVA for three outcome measures (final exam score, course grade, and scores on exam questions related to topics covered in the inquiry exercises) as a function of student major, instruction method (inquiry versus non-inquiry), and a combination of the two.

The MANOVA results in an F statistic (somewhat analogous to the more familiar chi-square statistic which is used when data are in the form of frequency counts). A significant F statistic indicates that the means of the three (or more) samples in the MANOVA are significantly different (see p. 355 of Ref. 37 for further details). The F statistics shown here suggest that there are differences in outcomes between students who are elementary education majors and those who are general education majors, and also between those who experienced inquiry activities and those who did not. In both cases, differences were significant only on exam questions related to material directly investigated in the inquiry exercises.

In order to determine which factors were responsible for these differences, we performed a series of T-tests (the statistical test of choice when small samples are studied[37]). Table IV shows the results of a T-test comparing the scores (mean percent correct) on exam questions related to topics covered in the inquiry exercises for elementary education majors who participated in inquiry investigations and those who experienced a prescriptive lab. The inquiry students outscored those doing prescriptive labs by seven percentage points.

Table V. T-test comparisons of percent correct on exam questions on inquiry exercise topics for general education majors experiencing inquiry and non-inquiry activities. $t=-0.25$, $p=0.804$, $ES=0.055$.

Variable	No. of cases	Mean percent	s.d.	SE of mean
Inquiry	48	88.96	9.74	1.41
Non-inquiry	42	88.46	9.12	1.41

Table VI. T-test comparisons of percent correct on exam questions on inquiry exercise topics for education and general education majors experiencing inquiry-based activities. $t=-1.19$, $p=0.238$, $ES=0.23$.

Variable	No. of cases	Mean percent	s.d.	SE of mean
General Education	48	88.96	9.74	1.41
Education Majors	33	91.24	7.54	1.31

The relatively high effect size, a metric measuring the magnitude of results that is independent of sample size and scale of measurement,[35] suggests this result has practical, as well as statistical, significance.

In contrast, there was no observed difference in the performance of general education majors who experienced one hour each week of inquiry-based laboratory exercises and general education majors who experienced extra homework problems on this same outcome measure (see Table V).

Student's performance on exam questions dealing with topics investigated in our inquiry activities did not seem to be determined by their majors. A T-test comparing this outcome measure by major bore out this result (see Table VI). There was a difference in the amount of time that elementary education majors and other students in our study spent engaging in inquiry activities, two hours every other week for elementary education majors compared with one hour for the others. Therefore, these results also indicate that the amount of time spent in the inquiry activities was not the predominant factor in whether these activities effected a change.

This led us to suspect that gender, which is related to major in that elementary education majors in this study were more than 90% female, might have played a major role. As mentioned earlier, prior research has suggested that younger female students may benefit from inquiry-based laboratory strategies.[5] Our study provided support for the conjecture that women at the college level have higher achievement on some measures when they participate in inquiry exercises. Table VII reports the results of a MANOVA for female students by major (elementary education and others), instruction method (inquiry and non-inquiry), and a combination of the two.

Analysis of data from female students revealed that those who experienced the inquiry-based laboratory exercises also had higher achievement on exam questions on inquiry topics when compared with women experiencing the non-inquiry laboratory exercises (see Table VIII). In comparison, differences between means on all dependent measures for the corresponding two groups of male students were not significant.

Table VII. Multivariate analysis of variance summary for females by student major and instruction method ($n=104$).

Multivariate ANOVA		Univariate ANOVA			Questions on topics covered in inquiry exercises
Source	F		Final exam	Cumulative grade	
Student major	31.36^a	F	0.01	0.73	0.99
Instruction method	53.10^a	F	0.40	1.61	1.36
Student major by instruction method	13.31^a	F	0.04	0.54	6.92^a

$^a p<0.05$.

Table VIII. *T*-test comparisons of percent correct on exam questions on inquiry exercise topics for female students in inquiry-based and non-inquiry-based classes. $t = -2.61$, $p = 0.01$, $ES = 0.45$.

Variable	No. of cases	Mean percent	s.d.	SE of mean
Non-inquiry	56	84.90	11.13	1.49
Inquiry	58	89.93	8.93	1.17

When a *T*-test of the same outcome measure was performed for female students by major (elementary education or general education), there was not a statistically significant difference (see Table IX). This again confirms that gender may play a more important role than a student's chosen major in whether that student will benefit from inquiry exercises.

B. Comparison study

Following Ref. 13, we administered a common problem to all students in our class, as well as those in the algebra- and calculus-based classes at Utah State. The problem, shown here as Fig. 1 and taken from Fig. 3 in Ref. 28, asks students to rank the order of brightness of bulbs in three different circuits. All bulbs are identical and all batteries are ideal. One circuit has a single bulb, one has two bulbs in series, and one has two bulbs in parallel. As a correct answer, we expected students to state that $1 = 4 = 5 > 2 = 3$.

We expected a complete explanation to indicate (1) that the current through (and therefore the brightness of) any bulb is independent of the existence of parallel branches in the circuit so that bulb 1 is in an identical situation to bulbs 4 and 5 and therefore would be equally bright. (2) Students needed to mention that the same current that flows through bulb 2 must flow on through 3; therefore these bulbs must be equally bright. (3) Students were required to state that the current through 2 and 3 would see higher resistance than the current through 1, 4, or 5, and therefore the current through 2 and 3 would be less, and bulbs 2 and 3 would be dimmer than the others.

Comparisons of responses from our students, who experienced inquiry-based activities, and from the students in the algebra- and calculus-based classes, who did not, are shown in Table X. Only 9% of the non-inquiry students (3% of the algebra students and 11% of the calculus students) gave a correct answer with an adequate explanation. Reference 28 reports that typically 15% of students in a standard calculus-based course are able to produce a completely correct response to this question. Our algebra-based students may have produced a particularly low number of correct responses as the question was given to them as a nongraded quiz. It is possible that some students who might have been able to provide an explanation simply did not take the time to do so.

Of our ''inquiry'' students, 26% were able to give a completely correct response to the question with an adequate explanation. Reference 23 reports that students who had experienced *Physics by Inquiry* tutorials were able to give completely correct responses 45% of the time to a similar problem. This difference may be due to a difference in time spent on the subject of resistive circuits. Our students typically spent only one hour on this specific topic. Students who performed the exercises during a two-hour lab period also investigated batteries and Ohm's law during the same session. In the *Physics by Inquiry* approach resistive circuits are part of a much more comprehensive and carefully orchestrated series of steps toward building a mental model of electric circuit, and therefore it is reasonable to expect that approach to yield a better result. Our result could in fact be a continuation of a trend toward better results from more extensive IE hinted at in Refs. 25 and 26.

Table IX. Comparisons of percent correct on exam questions on inquiry exercise topics for female education and general education majors experiencing inquiry-based activities. $t = -1.86$, $p = 0.069$, $ES = 0.42$.

Variable	No. of cases	Mean percent	s.d.	SE of mean
General education	29	87.7	10.02	1.86
Elementary education	29	91.96	7.24	1.35

Table X. Chi-square test comparison between groups on resistive circuit question. Chi-square $= 59.36$, $p < 0.05$.

Variable	No. of cases	Percent with completely correct response
Non-inquiry	209	9.1
Inquiry based	116	25.9

We saw many of the same misconceptions in the explanations given for wrong answers that were reported in Ref. 28. In particular many students indicated that the current in bulb 3 would be less than the current in bulb 2 because bulb 2 would have ''used up some of the current.'' Likewise, many students indicated that the current through bulbs 4 and 5 (while equal to each other) would be less than the current through bulb 1, indicating a belief that the battery is a fixed current source. These responses were much more common among the non-inquiry students (algebra- and calculus-based classes) than among our students who had experienced inquiry exercises with batteries and bulbs.

Among the students who had experienced the inquiry exercises there was no evidence of confusion between total (equivalent) resistance of the entire circuit and the resistance of individual bulbs. Reference 28 had reported that some students expect bulbs 4 and 5 to be brighter than bulb 1 because ''a parallel circuit has lower resistance.'' Our students were taught to find the total current in a circuit by adding the currents through individual branches and then to find an ''equivalent resistance'' using Ohm's law. They were not taught a formula for the equivalent resistance of resistive elements in parallel. Some students in the algebra- and calculus-based classes used such a formula as justification that bulbs 4 and 5 would be brighter.

A small but disturbing number of our students did state that bulbs 2 and 3 differed in brightness or that bulbs 4 and 5 were dimmer than bulb 1 because they ''saw it that way in the lab.'' It is possible that they did see it that way during the inquiry exercises. Irregularities in bulbs sometimes result in differing brightness for bulbs in series. An inadequately charged nonideal battery can exceed its maximum current limit when attached to two bulbs in parallel, and therefore the two bulbs in parallel may also be dimmer than the one bulb by itself in an actual demonstration.

Shaffer and McDermott argue that these variations from the ideal situation ''can be exploited to help deepen conceptual understanding.''[23] This is true in theory. Our teaching assistants should have been able to catch the problem at the point where students were required to have their work checked and suggest ways in which students might investigate the true cause of the variations in brightness. The persistence of these misconceptions could have one of two explanations. Either our assistants were less than completely diligent in checking students' work (which may well have been true in the general education class where the student to instructor ratio was particularly high), or these misconceptions were so strongly rooted that students misremembered what they had seen during the exercises. To avoid this problem, we now require our TAs to check the bulbs systematically for irregularities and the batteries for proper voltage immediately before each implementation of the batteries and bulbs activities.

C. Interviews

Quantitative assessment data suggested that limited inquiry approach did contribute to an increase in student understanding of the topics covered in the inquiry activities, at least for some students. Improved performance on several outcome measures was particularly evident among female students and elementary education majors. Anecdotal comments from the focus-group interviews provided additional insights on these findings.

Students who volunteered to participate in the focus-group interviews agreed to attend a pre- and postcourse session in place of one homework assignment. All 22 interview participants experienced inquiry-based activities. Questions asked by an external evaluator during the four pre- and four post-treatment interviews were designed to assist interpretation and validation of quantitative data.[38,39] Responses from the interviews were analyzed and codified.

An emergent theme from discussions about the hands-on component of the introductory physics class was value associated with concept confirmation. Concrete activities, regardless of whether they were laboratory experiences or classroom demonstrations, were perceived as beneficial.

''I love to actually be able to work with the material and actually see how it comes out. Also I think it's not just working with it, it's also the examples she gives, like seeing is believing.'' (female general education student)

Some students indicated that the inquiry activities were more beneficial when the concepts under investigation were directly linked to previous lecture topics. A previous study also found that open-ended inquiry sessions were most beneficial when they followed combined lecture and demonstration sessions.[40]

''I felt sorry for those people that had hands-on or their laboratory at the beginning of the week when we didn't cover the material in class until later...I have to see it on paper and see it in the laboratory. It's a reinforcing experience for me.'' (male general education major)

There was some indication from the interviews that students in classes experiencing the longer inquiry-based exercises in the laboratory valued those experiences more than students who participated in abbreviated activities during the lecture hour. However, findings from the interviews suggested that this value was attributed more to ''increased time'' and ''being in a lab setting'' than a fundamental difference in instructional strategies.

''I think if I would have been in the lab environment (rather than the classroom or hallway), it would have been a lot easier. Because when you're in a lab setting you're always constantly doing experiments.'' (female general education major, inquiry-based exercises in the lecture room)

A second emergent theme from interview and observation information was the value associated with inquiry-based strategies of concept acquisition. Students approached the introductory physics classes with common expectations of what goes on in a science classroom. These perceptions were illustrated when students were asked to describe differences between scientists and science teachers:

''The scientist is actually involved. They have a lot more knowledge of the deeper stuff, the more scientific things that you wouldn't explain to a student. A science teacher has to cover a lot of material in a short period of time, so I would think that they would have more of a basic knowledge. One knows a lot about a little and the other knows a little about a lot.'' (female general education student, precourse)

''Science teachers want students to measure something that is going to be a certain weight...a scientist working in a lab can try and discover new things.'' (male general education major, precourse)

While students at the beginning of each quarter were very clear that science teaching consisted of transmission of known facts and prescriptive laboratory exercises, comments at end of the quarters were less definitive. This narrowing of a perceived gap between doing science and learning about science was attributed to several variables.

''In an idealistic sense, I think of myself as more of a scientist in her class. I think her being a woman teacher affected me a lot; and because it (the lab) was more realistic.'' (female education major)

It was evident that some students participating in the inquiry-based exercises had begun to challenge their earlier perceptions about the nature of science teaching and learning. The more realistic nature of inquiry-based approaches and use of a variety of instructional mediums to complement the inquiry-based exercises may have contributed to these changes.

The value students placed on concept discovery appears to have influenced their acquisition of the concepts covered in the inquiry exercises. Some students who experienced the inquiry-based exercises were reluctant to challenge their perceptions of a distinction between learning science and doing science. One noticeable characteristic of inquiry-based exercises that reinforced this distinction was the absence of time devoted to detailed outline of procedure. For several students with strong prescriptive expectations of science labs, a perceived lack of direction resulted in frustration and withdrawal, rather than challenge and active involvement in problem solving.

On the other hand, students who valued the concept discovery aspect appeared to appreciate the exercises more. Comments within this theme were characterized by such words as ''dynamic,'' ''exciting,'' and ''alive,'' and lab groups were typically actively working and communicating.

''You could see the field and how it's progressing. It gets you excited. It makes the field come alive. Whereas my chemistry class is just the same old, same old. It's like a drill.'' (female, education major)

Student comments about the inquiry exercises on course evaluations were very nearly universally positive, providing anecdotal evidence that these activities improved student attitudes toward the course. There were infrequent comments indicating that students preferred to have lecture coverage of a topic prior to their inquiry investigations. Course evaluation scores and instructor evaluation scores were both higher during quarters when inquiry exercises were included in the curriculum.

One interpretation of comments related to the value of concept discovery is that these students view the content as more dynamic and themselves as more active participants in the learning process. In this scenario, concept discovery is closely linked to responsibility for learning. For students involved in this project, the aspect of discovery in the inquiry-based exercises was one motivating factor that contributed to acceptance of responsibility in the learning process.

V. CONCLUSIONS AND IMPLICATIONS

Results from this study indicate that implementation of limited (one or two hour every other week for a ten-week term) inquiry-based laboratory exercises increases understanding of concepts treated in the exercises for some students. In particular, female students and female preservice teachers in an introductory class for elementary education majors and general education students showed increased understanding compared with their peers who had received no inquiry training. Possible reasons for these observed differences include the validation or confirmation value of hands-on activities, and value associated with alternative ways of acquiring knowledge in science, particularly discovery.

It should be noted, however, that differences in the inquiry and non-inquiry groups were significant only on assessment measures that dealt directly with concepts investigated in the inquiry exercises. We saw no ''cascading effect'' through which student performance on topics not directly covered in the inquiry exercises was enhanced. This result suggests that, for optimum preparation, preservice teachers should be exposed to inquiry activities on as many topics as possible, especially on topics which they will be required to teach as part of a state elementary science curriculum. This need must, of course, be balanced by the need for in-depth and possibly repeated exposure.

Our study was not able to distinguish between students experiencing one hour of inquiry exercises as a replacement for a lecture and extra homework once every two weeks and students experiencing two hours of inquiry activities as a replacement for traditional prescriptive laboratory activities once every two weeks. Student comments did provide some anecdotal evidence that students perceived the longer exposure to be more beneficial. Further study of the effectiveness of inquiry activities versus the length of exposure time is needed.

Gender differences also appeared to play a role in our study. In general, the physics education research literature has not addressed gender as a variable. There are some notable exceptions. As mentioned earlier, Laws has reported that some female students may be particularly resentful of the time commitment required for an inquiry approach. Brown *et al.* found gender differences in student response to a task with batteries and bulbs.[41] We found the effect of our inquiry activities to be statistically significant on female students but not on male students. In contrast, one study of high school students in the Netherlands found that girls did not perform as well as boys under the active inquiry approach but did under vicarious inquiry.[42] Clearly, this issue merits additional study.

Recognizing risks inherent in interpretation of findings from education research, we suggest that physics educators who teach introductory classes for preservice elementary teachers consider the importance of including inquiry-based exercises into their courses, even if it is only possible to do so on a limited basis. Activities such as those described earlier may be of particular value to the largely female population of prospective elementary teachers. Efforts to increase future teachers' conceptual understanding and attitudes toward science are of particular importance in that they may result in improved elementary science instruction, thus affecting large numbers of future science learners.

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[a]Electronic mail: marshall@cc.usu.edu

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A modeling method for high school physics instruction

Malcolm Wells and David Hestenes
Department of Physics and Astronomy, Box 871504, Arizona State University, Tempe, Arizona 85287-1504

Gregg Swackhamer
Glenbrook North High School, 2300 Shermar Road, Northbrook, Illinois 60062

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The design and development of a new method for high school physics instruction is described. Students are actively engaged in understanding the physical world by *constructing and using scientific models* to describe, explain, predict, and to control physical phenomena. Course content is organized around a small set of basic models. Instruction is organized into *modeling cycles* which move students systematically through all phases of model development, evaluation, and application in concrete situations—thus developing skill and insight in the procedural aspects of scientific knowledge. Objective evidence shows that the *modeling method* can produce much larger gains in student understanding than alternative methods of instruction. This reveals limitations of the popular "cooperative inquiry" and "learning cycle" methods. It is concluded that the effectiveness of physics instruction depends heavily on the pedagogical expertise of the teacher. The problem of cultivating such expertise among high school teachers is discussed at length, with specific recommendations for action within the physics community. *© 1995 American Association of Physics Teachers.*

I. INTRODUCTION

Malcolm Wells is the primary author of this paper, because it is about his contribution to physics teaching. Malcolm has intended to publish an account of his work since his doctoral dissertation was completed in 1987. But the writing was delayed, first because he gave himself to conducting workshops for the benefit of other teachers, and then, in the last few years, because Lou Gehrig's disease has consumed his energy in implacable decline. So it has fallen on his coworkers, D.H. and G.S., to speak for and about Malcolm Wells. We do this gladly to celebrate the life of a truly great teacher, but more—because Malcolm has elevated the craft of teaching, and we believe that his unique contributions can help others surpass themselves and perhaps even Malcolm.

II. MALCOLM'S EDUCATIONAL RESEARCH

The story of Malcolm's research is told by D.H., who directed Malcolm's doctoral work and continued to collaborate with him thereafter. The story has an *unambiguous moral*: to upgrade high school physics, *partnerships* are needed between experienced teachers and physicists involved in educational research.

By any conventional measure, Malcolm was a superior teacher before his partnership with me. Yet his doctoral thesis documents a *large* improvement in the outcomes of his teaching, and it clearly identifies the contribution of educational research to the change. I have been active in theoretical physics research for the duration of our partnership. Though my physics research has deeply influenced my educational research, only the latter has been of direct benefit to Malcolm. Here is the story.

When Malcolm approached me about doctoral research, he was nearly 50, with a long career in high school physics and chemistry teaching behind him. His career began with a powerful boost from PSSC and Harvard Project Physics teacher workshops in the heyday of Sputnik space-race fever. The influence was indelible. He has been a "hands-on" teacher ever since, always eager to build his own apparatus, and always looking for simple demonstrations of deep physics. He also retained a "spirit of adventure" in the physics classroom and a "spirit of kinship" with other physics teachers. This "spiritual imprint" of the PSSC workshops seems to have marked many of Malcolm's generation and sustained them through long careers as physics teachers. The lack of such spirit may contribute to the disturbing dropout rate among the younger teachers in recent years. Malcolm has always been sensitive to this problem. When he got the chance to conduct his own workshops later on, he spared no effort to nourish *camaraderie* among the teachers—even to the extent of rising early every day to purchase fresh donuts, out of his own pocket. He had the teachers bubbling at the coffee breaks in animated discussions about the details of their craft. He had them grappling with practical problems in the workshop sessions. *True camaraderie* comes from collaborative efforts on common problems; it is the strongest kind of professional glue—a source of professional pride and satisfaction. Physics teachers need it to cope with the professional *isolation* most of them face in their schools. They need it as a stimulus to improve; they need it for a sense of belonging. The sporadic successes of teacher workshops in meeting this need demonstrates the importance of permanent institutional mechanisms to support teacher interaction and professional development. Malcolm's work will lead us back to this issue later on.

Since Malcolm's high school is close to Arizona State University, over the years he was able to take every university course in science and education that was relevant to his teaching. When he excelled in physics and chemistry courses, his professors presumed that he would "leave teaching for a more challenging career"—a sad testament to the vision of professors. To understand the depth and richness of the teaching challenge, college professors should spend some time in classrooms or workshops run by superior teachers like Malcolm. With Malcolm's extensive academic background, he could have dashed off a thesis and obtained his doctorate from the college of education in a few months.

Instead, he came to me looking for a doctoral research project that would count as a genuine contribution to physics education. We discussed a variety of possibilities over several years before settling on one that satisfied us both. During this period he became familiar with the details of my educational research program, and I learned about his ceaseless efforts to improve his teaching.

Malcolm was among the first to use computers in high school physics. He did not wait for someone else to tell him how to do it. As soon as the Apple computer was available, he was writing his own programs and designing activities for his students to use on it. He had enough of this for a complete high school physics course when he came to me, so it was a natural subject for his dissertation. The main issue in our discussions was how to prove the pedagogical value of his activities and, more generally, how to establish sound principles for using computers in the physics classroom. Malcolm was hard pressed to come up with a suitable plan for his research until he was shocked by a sudden revelation about his own teaching in 1983.

At that time Ibrahim Halloun was compiling the statistics from our *Mechanics Diagnostic* test as part of his doctoral research. This test measures the difference between Newtonian concepts and the students' personal beliefs about the physical world. The published results[1] show that this difference is large, and conventional introductory physics courses are not effective at reducing the gap. Further, the results are independent of the instructor's qualifications and teaching style. These conclusions have been supported by many other studies since. When examining the *Mechanics Diagnostic* for the first time, most physics teachers think that the questions are too obvious to be informative; then they are shocked by the post-instruction scores of their own students. Malcolm was no exception. In fact, he was the first high school teacher to be confronted by such evidence.

Like many physics teachers, Malcolm is strict about maintaining high academic standards, and he is hard-nosed about requiring students to assume responsibility for their own knowledge. When confronted by an irate parent who demanded to know why his son had received an "*F*," Malcolm replied, "Because there is no lower grade!" Even so, Malcolm is realistic about student capabilities, and he assumes full responsibility for his own role in what they learn. When confronted by the dismal scores of his students on the *Diagnostic*, he soon concluded that the fault was in his teaching and set about doing better. Thus, he was finally launched on his doctoral research.

In his own teaching, Malcolm had already abandoned the traditional lecture-demonstration method in favor of a student-centered inquiry approach based on the *learning cycle* popularized by Robert Karplus.[2] He was thoroughly schooled in all aspects of the learning cycle from a course in "methods of science teaching" by Anton Lawson, who employed it extensively in his research and teaching.[3] Despite all this, the performance of Malcolm's students on the Mechanics Diagnostic was poor. In fact, later data show that it was no better than the typical result from traditional instruction. Malcolm did not try to rationalize this failure by pointing out that his method has many other advantages which are obvious to anyone observing his classes—that the students are captivated by the classroom activities and their capacity for independent investigation improves markedly over the course. Instead, Malcolm confirmed the results of the Diagnostic by interviewing the students himself. He concluded that his instructional method was missing something essential.

Malcolm soon saw how to improve his instruction by following the modeling approach under development at ASU. At that time in 1983, I had just drafted a long paper proposing a theory of physics instruction with modeling as the central theme.[4] Physics professors have told me that the paper is difficult to read, but in my extensive discussions with Malcolm I found that he had mastered every detail relevant to his teaching. His real genius, though, appeared when he implemented the theory. That will be discussed in a later section. Here we review the underlying ideas.

There are several reasons for adopting a modeling approach to physics instruction: First, because it brings instruction closer to emulating scientific practice. Second, because it addresses serious weaknesses in traditional instruction. Finally, as documented below, Malcolm's research gives it strong empirical support. The first two reasons have been discussed at length elsewhere,[4,5] but a brief review is in order here to explain Malcolm's motivation.

The crucial role of *mathematical models* in physics research and applications is common knowledge to practicing physicists. It should be surprising, therefore, that the general concept of a scientific *model* is scarcely recognized in physics textbooks, though their pages are chock-full of specific examples. Change is in the winds, however. In recent blue-ribbon proposals for wholesale reform of the K–12 science and math curriculum, *modeling* has been explicitly identified as a major theme.[6,7] It will be no easy task to implement this theme, but Malcolm Wells has taken the lead.

From the pedagogical perspective, a major reason for adopting the modeling approach is to help students develop a more coherent, flexible, and systematic understanding of physics. The knowledge that students acquire from traditional instruction tends to be fragmented and diffuse. To most students the physics course appears to be "one damn thing after another," so they are forced into rote methods to learn it. Soon they are overwhelmed by the accumulation of rote fragments, with disaffection as an inevitable consequence.

The modeling approach organizes the course content around a small number of *basic models*, such as the "harmonic oscillator" and the "particle subject to a constant force." These models describe *basic patterns* which appear ubiquitously in physical phenomena. Students become familiar with the structure and versatility of the models by employing them in a variety of situations. This includes applications to explain or predict physical phenomena as well as to design and interpret experiments. It also includes the construction of more complex models by modification of the basic models. Explicit emphasis on basic models focuses student attention on the *structure* of scientific knowledge as the basis for scientific understanding. Reduction of the essential course content to a small number of models greatly reduces the apparent complexity of the subject.

Besides a general plan for organizing course content, modeling theory supplied Malcolm with many other ingredients for instructional design. Without going into details given elsewhere,[4] three ingredients are worth mentioning here.

First, an analysis and explicit definition of *model*. The models in physics are conceptual representations of physical systems and processes. Specifications for defining a complete model are outlined in Box 1

Box 1: Model specification

Object / system	Model	
I. Organization	**System Schema**	
• composition	• (internal) constituents	
• environment	• (external) agents	
• connectivity	• connections	
II. Basic Properties	**Descriptors**	(*Examples*)
• intrinsic	• object variables	m, q, I
	• state variables	$\mathbf{x}, \mathbf{v}$
• interactive	• interaction variables	$\mathbf{F}, \mathbf{T}$
III. Structure (internal/external)	**Laws of interaction**	$F = GmM/r^2$
IV. Behavior (temporal structure)	**Laws of change**	$m\dot{\mathbf{v}} = \mathbf{F}, \quad \dot{\mathbf{L}} = \mathbf{T}$

(details in Ref. 4). This includes an *interpretation* of the model, specifying how the structure of the model relates to the structure of the object or system it represents. Accordingly, a mathematical model is not fully specified until it has been supplied with an interpretation.

Second, an extensive discussion of qualitative reasoning and *representational tools*, especially *force diagrams and motion maps*. The main point being that such tools are essential for competent modeling and problem solving. The failure of students to learn this from conventional instruction has been established.

Third, a detailed analysis of the procedural knowledge involved in constructing and deploying scientific models, including a characterization of specific *modeling* stages. This provided Malcolm with the key to his chief instructional innovation, the *modeling cycle*. It enabled him to identify clearly what the learning cycle was missing, namely, detailed specification of the modeling processes and techniques involved. The modeling cycle is discussed in Sec. IV.

While Malcolm was getting started on his dissertation in 1983, Halloun and I were conducting a pedagogical experiment in the University Physics course at ASU. Although a detailed account of the experiment has been published,[8] reiteration of the main idea will put Malcolm's work in a broader context.

A primary objective of University Physics is to develop student problem-solving skills. The bane of traditional instruction is that most students cling to a "plug-and-chug" problem-solving strategy that severely limits their skill development. "Well-grounded" teachers are keenly aware that the key to effective problem solving is in the initial *qualitative analysis* of the problem, including the construction and use of suitable diagrams. Employing the traditional didactic approach, they demonstrate good technique in solving many problems, and they can explain their reasoning clearly when necessary. In my experience, such teachers are often nonplused or even angered by evidence suggesting that their approach is ineffective for the vast majority of students—insisting that their presentations are clear and thorough, so any failure reflects on the intelligence, attitude, or preparation of the students.

A different conclusion comes from considering the student viewpoint. The student sees that the "answer" to a problem invariably comes from plugging numbers into equations and chugging a little arithmetic. All that fluff about diagrams and "physical intuition" can be ignored. The key to problem solving is finding the "right equation" in which to plug the "given numbers." If the teacher is "fair" and the course is "well-organized," the right equation is easily extracted from a short list of equations for the "current topic." Exam preparation is reduced to memorizing the list for each topic to be covered. The effectiveness of this strategy is abundantly confirmed by good grades on homework and exams. It fails only when the teacher gets tricky. Tricky teachers are a pain!

Tricky teachers try to tell students that there is a better way than plug-and-chug. But what is it, exactly? They do not even have a name for it!

Modeling theory enables us to do better. My pedagogical experiment with Halloun instructed students in a sharp alternative to plug-and-chug called the *modeling method*. We take the position that the *complete solution* to every physics problem is actually a *model*, not, as often supposed, a mere number, the *answer* to some question posed in the problem. The model supplies the context which makes the answer meaningful. Without the model the significance of the answer (its numerical value, for instance) cannot be evaluated—which explains why plug-and-chuggers seldom question their unreasonable answers. We maintain that expert physicists always presume some model in their answer to a physics problem, though they may be unaware of that fact and seldom explicate the model fully. This suggests that problem-solving performance can be improved by instruction which insists on making the model in every problem explicit.

With the modeling method, every physics problem is solved by creating a model or, more often, adapting a known model to the specifications of the problem. Most problems in introductory physics are solved by deploying a small number of *basic models*. For example, all the standard projectile problems are solved by deploying a single *kinematic model*: the *particle with constant acceleration*. Students are thrilled when they realize this and thrilled again when they understand how all the models in mechanics can be generated by a single theory.

Our modeling method for problem solving is accompanied by a modeling method for teaching it. Implementation of the method in our pedagogical experiment[8] was constrained by the large course, lecture-recitation format at the university. My lectures deviated considerably from standard practice by expounding the modeling perspective exclusively, concentrating on thorough analysis of a small number of exemplary models and illustrating their deployment to solve problems. More subtle aspects of the method were implemented by Halloun in an experimental recitation section. He engaged students in group problem solving with the instructor as mediator. The critical role of the instructor in this process need not be described here, because it is so similar to Malcolm's approach. Results of our experiment will be compared with Malcolm's in Sec. II.

We think that the emphasis on solving textbook problems in physics courses is often excessive and misguided. It may even promote a distorted view of physics, because textbook problems are so artificial. In the modeling approach to instruction, *problem solving is secondary to modeling*. The modeling of physical systems raises all sorts of problems—problems which are more meaningful in the context of modeling than when they have been extracted and presented as textbook exercises—and problems which do not appear in textbooks at all. The modeling method may facilitate the solution of textbook problems by providing deeper physical insight. But it also supports a de-emphasis on textbook problems.

Malcolm developed a quite different or, rather, a complementary version of the modeling method—one which is laboratory based and adapted to scientific inquiry. It emphasizes the use of models to describe and explain physical phenomena rather than solve problems. It aims to teach modeling skills as the essential foundation for scientific inquiry. To accomplish this in a systematic fashion, Malcolm developed the *modeling cycle*, to be described in Sec. III.

In the implementations by both Halloun and Wells, the modeling method has a *student-centered* instructional design. This is believed to be critical to its success, because students must be *actively engaged* in the right kinds of activities to develop modeling skills. In both problem-solving and laboratory activities, students are required to articulate their plans and assumptions, explain their procedures, and justify their conclusions. The modeling method is unique in requiring the students to present and defend an *explicit model* as justification for their conclusions in every case. The instructor must be well prepared to consistently guide this process to a timely and satisfying closure. Specifically, the instructor must be (1) fully conversant with all aspects of the relevant models and (2) acutely aware of likely student misconceptions or knowledge deficiencies.

At last we are prepared to understand how Malcolm corrected the deficiency in his instructional method which was exposed by the Mechanics Diagnostic. As students are led to articulate their reasoning in the course of solving a problem or analyzing an experiment, their naive beliefs about the physical world surface naturally. Rather than dismiss these beliefs as incorrect, Malcolm learned to encourage students to elaborate them and evaluate their relevance to the issue at hand in collaborative discourse with other students. *In the context of modeling activities students have a framework for testing and correcting their own ideas*, especially in regard to relevance and coherence with other ideas.

To sharpen his skills for dealing with student misconceptions, Malcolm mastered the *taxonomy* developed by Halloun and Hestenes,[9] a systematic classification of naive beliefs about mechanics. He used the taxonomy for planning, to ensure that class activities would provide repeated opportunities for confronting all the serious misconceptions. He prepared an agenda of misconceptions to be addressed in connection with each activity. This preparation sensitized him to opportunities for addressing misconceptions in the course of student presentations and discussions.

Halloun made a similar use of the taxonomy in the limited domain of problem solving, but Malcolm had much more freedom to extend the modeling method in his high school course. He concentrated on developing techniques for improving the *quality of student discourse* about scientific subjects. Modeling theory supplied a clear goal: *scientific discourse* featuring the formulation, elaboration, evaluation, and application of well-defined models; discourse exhibiting a suitable mixture of qualitative and quantitative elements. In pursuit of this goal, Malcolm expanded the class time allotted to oral presentations by students. The time for *student postmortems* of laboratory activities was increased to a third of the total activity. The postmortem is devoted to analyzing and consolidating what the students have learned from the experiment. It seems likely that the most significant learning occurs in this period—at least, when the activity is guided with the skill of a teacher like Malcolm Wells.

To facilitate postmortems and other student presentations, Malcolm experimented with a variety of techniques. For example, he tried having students outline their presentations on "butcher paper" to be hung up for other students to see, but that proved to be awkward. Finally, he hit on a brilliant idea. He equipped student groups with "whiteboards." A *whiteboard* is a 24 in.×32 in. section of "kitchen and bath" paneling. It is easy to write and draw on it with colored dry markers, and it is easily erased. The whiteboard soon became an integral part of Malcolm's method.

Teaching students how to use the whiteboard effectively became an important subgoal. For Malcolm the whiteboard is an instrument for improving the quality of student discourse. In preparation for a presentation, student groups are encouraged to outline their model and supporting argument on the whiteboard. Evaluation of the presentation then includes an evaluation of the whiteboard display.

Besides the design and implementation of the instructional innovations already mentioned, Malcolm's research included a careful evaluation of actual results in the classroom. To that we turn next.

III. EVIDENCE FOR EFFECTIVENESS OF THE MODELING METHOD

In creating his version of the modeling method, Malcolm incorporated every good idea he could find—some from his own long experience, some from educational research. When evaluating educational innovation it is important to ascertain what the various factors contribute to improvements. This is difficult, not only because there are so many variables and practical constraints severely limit the possibilities for controlling them independently, but because a significant effect may come from combining separate factors which do not

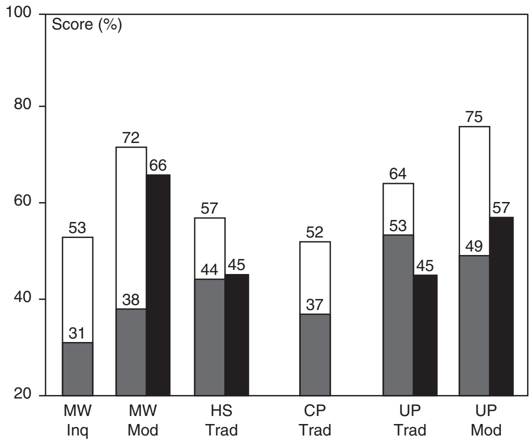

Fig. 1. Mean scores on the *Mechanics Diagnostic* for three high school classes (on the left) and three university classes (on the right). The bar chart shows the pretest score (at the beginning of the course) below the post-test score (at the end of the course). The dark bars are mean class scores on problem solving tests. See the text for explanation.

appear to contribute much alone. Fortunately, the unusual circumstances of Malcolm's doctoral research made it possible to achieve an exceptionally clean separation of the major factors contributing to his instructional results.

Figure 1 shows the impact of Malcolm's teaching in comparison with that of other teachers as measured by the Mechanics Diagnostic. Data on the high school courses come from Malcolm's thesis. The remaining data come from Refs. 1 and 8, which also provide an extensive analysis of the validity and implications of Diagnostic data. To interpret the data in Fig. 1, distinguishing features of the various instructional approaches must be identified. The three high school courses employed distinctly different approaches, which we describe by the terms "cooperative inquiry," "modeling method," and "traditional." We discuss each in turn and then compare their results.

Cooperative Inquiry has become increasingly popular in recent efforts to reform K–12 science education, and it is strongly advocated by educational researchers. The term is generally applied to any method of instruction with the following characteristics: It is student centered, activity oriented, and often laboratory based; students are actively engaged in investigating real phenomena in collaboration with their peers and under guidance by the instructor. Investigations are frequently organized into learning cycles by the teacher. All this fairly describes Malcolm's method in 1982–83—He was ahead of his time in this.

To be more specific about the content of Malcolm's inquiry course: 70% of class time was devoted to lab activities, which were either developed by Malcolm or modified from the Harvard Project Physics handbook. The lab activities targeted concepts involved in Newton's laws. Thirty percent of class time was devoted to in-class study groups utilizing the PSSC fourth-edition textbook. Problems for class and homework were selected from the textbook or designed by Malcolm to reinforce and expand on concepts developed in the lab activities.

Modeling Method. Malcolm's method at the close of his doctoral work (1986–87) can be described as *cooperative inquiry with modeling* structure and emphasis. He retained the general features of his original cooperative inquiry approach, including all the lab activities, to which he still devoted 70% of class time. The instructional difference resided in the systematic emphasis on models and modeling. The learning cycle was elaborated into a modeling cycle. Though it remained unobtrusive, teacher guidance was strengthened by focusing on a modeling agenda informed by the "misconceptions taxonomy." Consequently, student investigations and presentations were more coherently structured. The net result was an increase in the *coherence* of the whole course and its subject.

Traditional Method. The high school teacher who agreed to using his 1986–87 honors physics course as a control for comparison with Malcolm's course was well matched to Malcolm in regard to age, experience, training and dedication. He used a standard textbook [A. W. Smith and J. N. Cooper, *Elements of Physics*, (McGraw-Hill, New York, 1979) 9th ed.]. His course consisted of lectures and demonstrations (80% of class time), with homework questions and problems selected to reinforce important concepts from lecture and to provide practice in problem solving. There was a heavy emphasis on problem solving, with many examples worked out in lecture. Lab activities (20% of class time) were designed and/or selected to emphasize important concepts from lectures and/or to develop laboratory skills. In short, the course was quite traditional.

Comparisons. All three high school courses (inquiry, modeling, traditional) were honors courses with about 24 students in each. By prior agreement between the teachers, all three covered the same topics in mechanics on nearly the same time line (from early September until mid-March), so the total instructional time was the same.

The data in Fig. 1 strongly support the conclusions that Malcolm's modeling method is a considerable improvement over his cooperative inquiry method and clearly superior to the traditional method. In Diagnostic post-test score, the modeling class (MW Mod) surpasses the inquiry class (MW Inq) by 19% and the traditional class (HS Trad) by 15%. This is a large effect, because the standard deviation of student scores does not exceed 16% for any of the classes in Fig. 1. The inquiry class pretest score is exceptionally low for an honors physics class. However, it may be doubted that this accounts for any difference in the post-test scores. The pretest scores for both classes are so low (20% is a random score) that the difference cannot be attributed to more than superficial knowledge. For the same reason, the data do not show much difference between the inquiry and traditional methods, although inquiry produced a 9% greater gain.

These results should serve as a *warning* that the general approach of cooperative learning is not likely to improve student learning by itself. Improvement depends critically on the structure of the activities and the guidance by the teacher, so much so that, even for a superior teacher like Malcolm, results can be greatly improved by careful instructional design.

For comparison with Malcolm's score, Fig. 1 gives Diagnostic scores for traditional (algebra-based) College Physics (CP) and (calculus-based) University Physics (UP) courses. These courses were taught by the traditional lecture-demonstration method to classes with hundreds of students. One of the instructors has many awards for superior teaching. Nevertheless, as measured by the pre–post Diagnostic gains, neither course is more effective than the traditional high school course and both are far less effective than Malcolm's modeling course. Even on the final post-test Malcolm's high school students perform much better than the university students. Only Halloun's experimental modeling class (UP Mod) achieves a comparable result—which should not be surprising.

Problem solving. The modeling course was also compared to the traditional course with respect to student competency in traditional-type problem solving. For this purpose, a test was constructed consisting of 24 mechanics questions and problems from the 1983 NSTA–AAPT standardized examination, and 16 questions from PSSC and Harvard Project Physics tests. The problems were carefully selected to require some reasoning and some understanding of physics concepts, as opposed to being solvable by blind substitution into a formula. In this respect, it could be regarded as a "hard test." Otherwise, physics teachers would regard the test as fairly ordinary.

Since the traditional class had far more conventional problem solving practice, it might be expected to do better on the test. However, as Fig. 1 shows, Malcolm's modeling class outperformed the traditional class by 21%. How could this happen?

We have a definite answer which we can assert with much more confidence than Malcolm could in his thesis, because the result has been replicated many times since and detected with the more refined instruments described below.

The lower post-test score on the Mechanics Diagnostic (Fig. 1) means that the traditional class has a much weaker grasp of basic Newtonian concepts than the modeling class. In fact, at least half the class can be classified as pre-Newtonian (see discussion of Fig. 3). This means that those students are seriously deficient in basic concepts required for effective problem solving. Without those concepts, the students are forced to fall back on rote learning and plug-and-chug problem solving. Therefore, most of their problem-solving practice is a waste of time. Malcolm's approach concentrates on a thorough grounding in basic concepts first. Thereafter problem-solving skill develops more easily and surely. More evidence for this below.

Halloun's results in Fig. 1 support our conclusions about Malcolm's results. Although he was teaching problem solving directly, Halloun concentrated on identifying and correcting weaknesses in student grasp of basic concepts. Halloun's (UP Mod) class surpassed the traditional (UP Trad) class by 12% on a common problem-solving final exam (scores represented by dark bars in Fig. 1). More noteworthy is Halloun's success with underprepared students:[8] All such students in his recitation section passed the course with grade C or better, while 80% of the underprepared students in the traditional class failed to achieve at least a C grade, though there was a common grading system for both. This is comparable to Malcolm's achievement with high school students. It strongly supports the conclusion that traditional instruction fails miserably with underprepared students, though much better results are possible.

D.H. was so impressed with the results of Malcolm's thesis that he collaborated with Malcolm on a NSF grant to continue improving the method and develop workshops to pass it on to other teachers. The high school teacher who had acted as Malcolm's control was equally impressed and eagerly signed up for the first workshop. The experience revolutionized and rejuvenated his teaching, so he postponed his retirement.

The first task on the NSF grant was to improve the evaluation instruments. For this task Malcolm's intensive experience examining and applying the Mechanics Diagnostic and

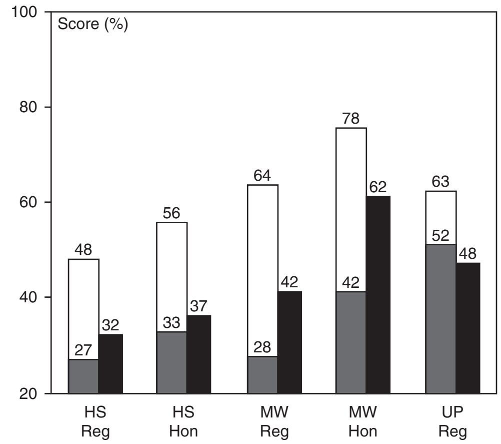

Fig. 2. Mean scores on the *Force Concept Inventory* and the *Mechanics Baseline* test. Pretest scores are displayed below the posttest scores for the *Inventory*. The dark bars represent *Baseline* scores.

the misconceptions taxonomy was invaluable. The first result was the *Force Concept Inventory*,[10] which can be regarded as an improved version of the Mechanics Diagnostic. The second result was the *Mechanics Baseline* test,[11] which can be regarded as a greatly improved version of the problem-solving test that Malcolm used in his thesis. Details about the tests are given in the references. Here we are only interested in using test results for further documentation of Malcolm's achievements as a teacher.

The Inventory and Baseline tests provide a thorough and systematic evaluation of *basic conceptual understanding and problem-solving competence in mechanics.* They were published along with extensive data that have made it possible to compare the mechanics competence of physics students at every level from high school into graduate school. An enormous and rich body of data has accumulated since, and efforts are underway to analyze and organize it for informative publication.[12] It can be asserted, however, that the new data are generally consistent with the original data and so support the original conclusions.

Figure 2 is constructed from data in the original Inventory and Baseline papers. The scores for the traditional high school regular and honors physics courses are averages for more than 700 students and 17 different teachers. The dispersion of scores among the teachers is negligible, because it is much smaller than the dispersion among students in a single class. Unpublished data from other teachers give about the same result. We are quite confident in asserting that the scores in Fig. 2 *are typical for traditional* physics courses throughout the nation. Moreover, the small dispersion of scores for different teachers leads to the surprising conclusion that these typical scores are essentially *independent of the teacher's experience and academic background.* Data on university physics lead to much the same conclusion.[1,10] The scores for University Physics in Fig. 2 are for a single course. Again, consistent with our broader knowledge of the data, we regard these scores as typical for traditional University Physics courses at *large state universities.*

To summarize, the scores for traditional classes in Fig. 2 are typical and firm. Moreover, large variations in teacher expertise produce insignificant variations in student performance on the Inventory and Baseline tests. *Results of traditional instruction are uniformly poor for all teachers.* This suggests that instructional methodology is a more serious

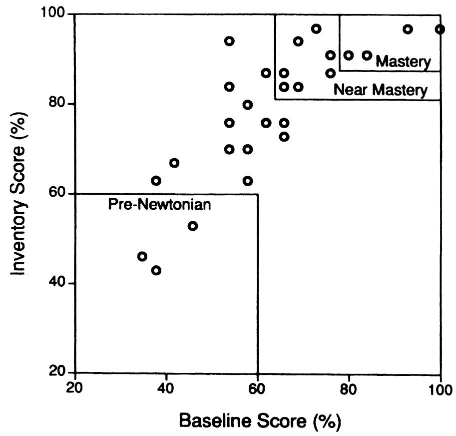

Fig. 3. Student competence after instruction in Malcolm's honors physics course. Post-test *Inventory* score is plotted against *Baseline* score for each of the 27 students.

problem than teacher competence. The good news is that the firm numbers in Fig. 2 provide a reliable baseline from which to measure the success of instructional innovation.

It should now be obvious that the scores in Fig. 2 document a remarkable achievement by Malcolm Wells, fully confirming the results of his thesis. Malcolm's superiority on this measure is so decisive that there is no need to describe the many other virtues of his method to be sure of its overall superiority. Malcolm's scores in Fig. 2 are for a single year, but unpublished data show that he achieved similar scores consistently year after year—with one exception. The scores fell one year when he was spending a lot of time on an experimental course at ASU. On seeing the results, he lamented "I wasn't minding the store!" This is indicative of his intense personal commitment to teaching.

Though Malcolm contributed heavily to the construction of the Inventory and Baseline tests, he scrupulously avoided teaching to the tests in his own courses. His scores were about the same, whether the tests were given immediately after the mechanics portion of the course or at the end of the spring semester. Thus, the retention of his students is strong.

Figure 3 gives the distribution of scores for students in Malcolm's honors course. A comparable figure for the University Physics course at Harvard is published in Ref. 10. Remarkably, the distributions for the two courses are very similar, though the Harvard course has four times as many students. Their mean scores on both tests are also about the same. Even for a group of first year physics graduate students at ASU, the mean scores are about the same as Malcolm's. Malcolm is in very good company indeed! He has given us an existence proof that high school physics students just about anywhere can be competitive with Harvard! There is no reason to believe that Malcolm had a special breed of student in his classes.

The details of Fig. 3 tell us more about Malcolm's impact. First note that all the data points lie above the diagonal. The reason for this is that the basic physics concepts (measured by the Inventory) are necessary but not sufficient for problem solving (measured by the Baseline). We refer to scores below 60% on the Inventory as *Pre-Newtonian*, because they indicate serious conceptual deficiencies, such as inability to discriminate reliably between velocity and acceleration. As data on Fig. 3 suggest, Pre-Newtonians are unable to score better than 60% on the Baseline. Scores in the box at the upper right-hand corner indicate genuine *mastery* of basic Newtonian mechanics. The "mastery box" is contained in a slightly larger *near mastery* box. Near mastery students are likely to be top physics students at any university they attend. More than a quarter of Malcolm's students fall within the near mastery box. Remarkably, this is more than the number of near mastery students from *all* 700 students in the traditional high school physics classes contributing to the data in Fig. 2. Malcolm's regular physics class also has several students in the near mastery box, though the full data will not be presented here. Malcolm's regular physics class differs from his honors class mainly in having a larger number of students stuck in the Pre-Newtonian box.

We have discussed Malcolm's case in such detail because there is a dearth of objective evidence for truly exceptional teaching and a lot of doubters that any such evidence exists. To our knowledge Malcolm's combined Inventory–Baseline scores have never been surpassed by any other high school teacher. But others are getting closer, and a few college teachers have surpassed him in absolute score, though not in fractional gain. Malcolm's mark is worth shooting at. We are sure that no one would be happier than Malcolm to see himself surpassed!!

IV. MALCOLM'S CLASSROOM

G.S. had the unique privilege of observing Malcolm's classroom in action over many months. G.S. had become intrigued with the possibilities of "modeling instruction" from published articles by D.H., so he arranged to spend sabbatical leave from his own high school physics teaching, with D.H. at ASU. He arrived just when Malcolm and D.H. had completed a preliminary version of the *Force Concept Inventory*, whereupon he was invited to join them in completing the job. His main task was to investigate the validity of the test through extensive interviews of high school students. This brought him to Malcolm's classroom for many hours, and he remained there for many more out of fascination. Here are his recollections of Malcolm's classroom, admittedly transmogrified by subsequent reflection and experience.

It was a November morning when I first visited Malcolm Well's classroom. The class was discussing a problem about the motion of an object subject to several forces. One student was holding up a whiteboard with a solution sketched on it. The board displayed clearly drawn diagrams with a few algebraic equations and some numbers. The class was gathered round as he explained his solution. An occasional question from another student was answered crisply. Relations between the diagrams and the algebraic statements were explained clearly. Substitution of the numbers into the algebraic statements was explicit. But Malcolm challenged the student further.

"Why did you do that?"

The student replied that he had identified and added all the forces along one dimension.

"Why did you do that?"

"So I could find the net force."

"Why did you do that?"

"Because $a=F/m$."

"How do you know that?"

"Because that's Newton's Second Law."

It was the first time that I had heard a student account for *everything* he had done in solving a problem, explaining why he had done it, and ultimately appealing to theory developed on the basis of experiments that had been done by the students. These students were explicit in their understanding. Malcolm did not take correct statements for granted. He always pressed for explicit articulation of understanding.

The students in Malcolm's class explained their solutions to problems publicly, and he made sure that they could justify them. He was uncanny in his ability to expose deficiencies in student explanations with questions. Many times I would have joyfully accepted a student's correct answer as sufficient. But Malcolm would again ask one more question, and, much to my surprise, the student would falter. This ability, as I gradually came to understand it, arose from his mastery of modeling in Newtonian physics. His understanding extended beyond the content of Newton's Laws to an acute awareness of the techniques for applying the laws in practice.

Malcolm was alerted when a student failed to mention the procedures required to be faithful to Newtonian physics. He would ask for elaboration at the very point where I was satisfied that the student had achieved the desired result. His deep understanding of scientific explanation and justification enabled Malcolm to be a remarkable Socratic guide. He had clear knowledge of what students had to make explicit to be assured that their understanding is adequate. His line of questioning was unfailingly purposeful. Students were required to present an explicit model to account for the physical situation in question and explain how the model had been obtained from overarching theory and/or experimental data. His students became accustomed to supplying not just answers and clear explanations of how they got them, but also full justification for their approach. The students' solutions to physics problems were superior.

The students were busy in Malcolm's classes. Working in groups of three they performed experiments, solved problems, explored activities. Regularly, Malcolm would assemble them to present accounts of their work orally with the aid of whiteboards or join in questioning the presenters. Whiteboards were new to me. Student groups prepared them with care and pride. With colorful dry markers they dressed the whiteboard with diagrammatic, graphical, and mathematical representations of physical situations from problems or lab activities. By the time I visited the class, students were consistently referring to these representations as *models*. They were using these models to solve problems or interpret experiments, and they could explain how the various representations cohere in their interpretations. The dialog during oral presentations was potent, whether the presentation was consistent with Newtonian physics or not. Students found holes in their understanding and honed their arguments, both by questioning one another and providing answers. Malcolm served as Socratic guide to keep the dialog moving in a profitable direction.

Another feature of Malcolm's teaching that was new for me was the solid experimental underpinning for all theoretical constructions that followed. Malcolm had adapted and designed experiments which were conceptually clean, with equipment enabling students to generate good data reliably. The students were given no instructions for doing these experiments. Rather, Malcolm would introduce the class to the physical system to be investigated and engage the students in describing the system until a consensus was achieved. Malcolm would stealthily elicit from his students the appropriate dependent and independent variables to characterize the system. After obtaining reasoned defenses from the students for the selection of these variables, he divided the class into groups of three and set them loose to design their own procedures with the apparatus available.

The students had to make sense of the experiment themselves. Malcolm would allow them to fail. The apparatus would be around for several days should they need it. After allowing time to prepare whiteboards, Malcolm would select one person to present an oral account of his group's experimental procedure and interpretation. Typically, the interpretation consisted of graphical and mathematical models for the system investigated. For Malcolm, the class's interpretation of experimental data was the origin of principle and the end of argument.

I was struck by Malcolm's responses to student questions. He invariably sought to elicit the answer from the students themselves, and to induce them to assume responsibility for their own explanations. Sometimes, when students were thoroughly nonplused, he would suggest that they find out what other students were doing. Malcolm assiduously avoided the role of authority—this was a matter of principle with him. The belief that learning science is acceptance of what the text or teacher declares was regarded by Malcolm as an obstacle to valid understanding by the students. In this respect he stands with Feynman, who said that "science is a belief in the ignorance of experts." The struggle for understanding was fostered and facilitated by Malcolm, but never mitigated.

Computers played a prominent role in Malcolm's classroom, but that role was defined by Malcolm's pedagogy. Computers became tools for analyzing experimental data and for simulating physical systems when real, clean, and reliable experiments were not available. Computers helped students create good models of physical systems and generalize their results into theoretical statements. They helped provide the physical theory developed in the course with a firm experimental foundation to which the students continually had to appeal to justify their work. Computers were not just a nice addition to the course, they were indispensable. The foundational experiments that Malcolm used to span the desired dimensions of physics could not have been done without them. Never had I seen computers used so effectively and frequently to facilitate the struggle for understanding.

As exhibited in his classroom, Malcolm's method has a clear moral: Teaching by telling is ineffective. Coherent understanding cannot be transferred from teacher to student by lucid explanations or brilliant demonstrations. Students construct their own understanding. The teacher is a facilitator. Malcolm labored to guide students to a coherent and, therefore, lasting understanding of physics. He sought to change their view of learning from collectors of information to expectant creators of this coherent understanding. He was more concerned with what students would think about his course five years later than with what they thought about it during the school year. To Malcolm it must have been the ultimate tribute when one of his former students gave thanks not for teaching him what to think but how to think!

V. MODELING CYCLE

The atmosphere in Malcolm's classroom was not simply the product of a talented teacher doing his stuff. It was the result of careful preparation, planning, and deliberate execution of a definite method. Let us describe his method in more detail.

A synopsis of the *modeling method* is enclosed in Box 2.

Box 2: MODELING METHOD Synopsis

The Modeling Method aims to correct many weaknesses of the traditional lecture-demonstration method, including the fragmentation of knowledge, student passivity, and the persistence of naive beliefs about the physical world.

Coherent Instructional Objectives

- To engage students in understanding the physical world by ***constructing and using scientific models*** to describe, to explain, to predict and to control physical phenomena.

- To provide students with ***basic conceptual tools*** for modeling physical objects and processes, especially mathematical, graphical and diagrammatic representations.

- To familiarize students with a small set of basic models as the ***content core*** of physics.

- To develop insight into the ***structure*** of scientific knowledge by examining how ***models*** fit into ***theories.***

- To show how scientific knowledge is ***validated*** by engaging students in *evaluating* scientific models through comparison with empirical data.

- To develop skill in all aspects of modeling as the ***procedural core*** of scientific knowledge.

Student-Centered Instructional Design

- Instruction is organized into ***modeling cycles*** which move students through all phases of model development, evaluation and application in concrete situations — thus promoting an integrated understanding of modeling processes and acquisition of coordinated modeling skills.

- The teacher sets the stage for student activities, typically with a demonstration and class discussion to establish common understanding of a question to be asked of nature. Then, in small groups, students ***collaborate*** in planning and conducting experiments to answer or clarify the question.

- Students are required to present and justify their conclusions in oral and/or written form, including a ***formulation*** of models for the phenomena in question and ***evaluation*** of the models by comparison with data.

- Technical terms and concepts are introduced by the teacher only as they are needed to sharpen models, facilitate modeling activities and improve the quality of discourse.

- The teacher is prepared with a definite ***agenda*** for student progress and ***guides*** student inquiry and discussion in that direction with "Socratic" questioning and remarks.

- The teacher is equipped with a ***taxonomy*** of typical student misconceptions to be addressed as students are induced to articulate, analyze and justify their personal beliefs.

The instructional objectives are appropriate for any implementation of a modeling approach to instruction. The instructional design is more specific to Malcolm's inquiry approach. The centerpiece of this design is the modeling cycle, which organizes class activities into *coherent* units with similar procedural structure.

The modeling cycle can be regarded as a refinement of the *learning cycle* developed by physicist Robert Karplus for the *Science Curriculum Improvement Study* (SCIS). It greatly elaborates the role of models and modeling in the cycle. We have recently heard from Anton Lawson that there was an unresolved debate among scientists on the SCIS development team as to whether *models* or *theories* should play the central role in the curriculum. Biologist Chester Lawson championed *theory* while Karplus was firmly in favor of *models*, though, in deference to his colleague, he allowed his position to be somewhat diluted in the curriculum. The Karplus view has been keenly described by Victor Pollock.[13] We believe Karplus would come out strongly in favor of the modeling cycle if he were around today.

Before describing the modeling cycle, let us briefly review the three stages of the learning cycle (*exploration*, *invention*, *discovery*) from a modeling perspective.

Exploration. Typically, in this stage students are given some physical phenomenon to investigate with hands-on activities. Students are given minimal guidance so they can make their own observations and formulate their own conclusions. The main instructional difficulty with this stage is that it tends to degenerate into aimless "messing about" under too little guidance or become unimaginative under too much. The modeling method resolves this difficulty over several cycles by teaching students a *general method of scientific inquiry*. Students learn that in every investigation it is essential to develop a *model* of the physical system, and they continue to grow in their understanding of what modeling involves. When investigating some general physical concept like "energy conservation," they learn that it cannot be explored experimentally apart from a specific model. The model supplies a *context* for the exploration. Thus, in investigating a new phenomenon, students learn to focus quickly on identifying particular systems to be modeled and on quantitative measures of their properties.

Invention (or concept introduction). This stage recognizes that modeling cannot go beyond simple description without the *invention* of new concepts and symbolic tools to represent them. Chief among these are the inventions of algebra and calculus, which make it possible to formulate quantitative relations among variables. The mathematical tools make it possible to formulate "universal" principles like Newton's Laws, which facilitate mechanics modeling in (nearly) every situation.[4,5]

Students cannot be expected to invent the concepts and notations introduced in this stage. But they must discover for themselves the utility of the concepts for modeling phenomena from the exploration stage. From the modeling perspective, that is the main objective of the invention stage.

The stage name "concept introduction" is usually preferred over "invention," because it is supposed to be more descriptive of what is actually done. However, that very name may encourage the serious pedagogical mistake of introducing concepts piecemeal and out or context, in the misguided belief that complexities are mastered by concentrating on one concept at a time. The very strength of the learning cycle is that *new concepts are introduced within the context of modeling and for the purpose of modeling*. The modeling approach makes this explicit. The emphasis on models rather than single concepts makes instruction more *coherent*, for model construction requires the coordinated use of a whole set of concepts.

The new concepts introduced in this stage are usually nontrivial and fully deserve to be recognized as inventions, often great inventions! Students and teachers need to appreciate the power that such inventions confer on the user. For this reason, we think the stage name invention is well chosen.

Discovery (or concept application). Likewise, we prefer the original name "discovery" for this stage. It is not usually a single concept that is applied in this stage, but the whole model that was developed in the first two stages. The model is abstracted from its original physical context and applied to new situations. The applications often require genuine (though not original) discoveries by the student, so why not celebrate that with the word discovery? Rather than "model applications," we speak of "model deployment" below, to emphasize strategic and tactical aspects of modeling which are not so straightforward as the term "application" suggests.

Now let us turn to the modeling cycle. The modeling cycle has two stages, involving the two general classes of modeling activities: *Model development* and *model deployment* (See Refs. 4 and 5 for more details). Roughly speaking, model development encompasses the exploration and invention stages of the learning cycle, while model deployment corresponds to the discovery stage. It will be noted that the "modeling terminology" is more descriptive of what the students actually do in the cycle.

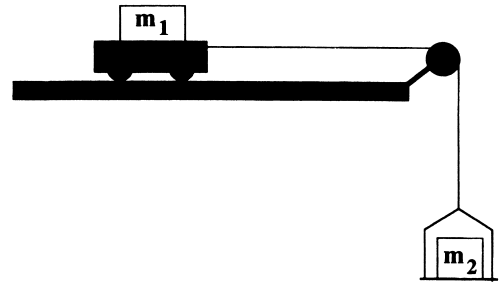

Fig. 4. *Modified Atwood Machine.* A (low friction) cart with mass m_1 is connected to a mass m_2 suspended by a string over a pulley. Values of the masses can be varied. The diagram raises some questions about accounting for the masses.

The *two-stage modeling cycle* has a generic and flexible format which can be adapted to any physics topic. In its high school physics implementation, the cycle is two or three weeks long, with at least a week devoted to each stage, and there are six cycles in a semester, each devoted to a major topic. Each topic is centered on the development and deployment of a well-defined mathematical model, including investigations of empirical implications and general physical principles involved.

Throughout the modeling cycle the teacher has a definite agenda and specific objectives for every class activity, including concepts and terminology to be introduced, conclusions to be reached, issues to be raised, and misconceptions to be addressed. Though the teacher sets the goals of instruction and controls the agenda, this is done unobtrusively. The teacher assumes the roles of activity facilitator, Socratic inquisitor, and arbiter (more the role of a physics coach than a traditional teacher). To the students, the skilled teacher is *transparent*, appearing primarily as a facilitator of student goals and agendas.

To make the present discussion of details in the modeling cycle more concrete, we choose a specific topic which appears in both high school and university physics courses. Accordingly, as major objectives for the instructional agenda in the cycle, we aim to develop student conceptual understanding of the following: *Target model*: Motion of a material particle subject to a constant force. *Physical principle*: Newton's second law of motion. *Experimental context*: Modified Atwood's machine (Fig. 4).

Prerequisite: Before beginning this cycle, the students should have previous experience with kinematic models (two cycles in the high school course), so they have fairly clear concepts of velocity and acceleration. *Many students still have only a shaky grasp of these concepts at this point*, and more experience with the concepts in a variety of contexts is necessary to consolidate them. Conceptual development takes time, and it will be haphazard unless instruction is carefully designed to promote it systematically.

Stage I is designed to lead students systematically through the four main *phases of model development: description, formulation, ramification and validation* (Refs. 4 and 5), though students are not introduced to this fancy terminology. Students are not simply presented with the target model; they are induced to invent and evaluate the model for themselves in an experimental context where it is meaningful.

Stage I begins with the presentation of, for example, the modified Atwood machine for the class to consider. Eventually they will realize that a scientific understanding of the system requires (1) the specification of a model to represent it conceptually, and (2) an evaluation of the fidelity of the representation—but they are not told this until they have the experience necessary to understand it by reflecting on what they have done already. Modeling begins with description. Throughout the *descriptive phase* the teacher functions as a moderator, nonjudgmentally recording all suggestions, asking occasionally for further clarification as to meaning while insisting that all terms used in a technical sense be given valid operational definitions. Technical terms, such as "frame of reference, one-dimensional motion, and system" are introduced by the instructor *only* in situations where they serve to clarify the discussion. Ample opportunity to introduce important technical terms occurs as the course proceeds. Beginning students may state, for example, that an object is accelerating but when asked what they mean by acceleration, they often reply "speeding up." The teacher continues to ask probing questions until the students articulate a satisfactory quantitative characterization of the concept. The teacher strives to remain unobtrusively in control of the agenda throughout the discussion, never acting as an authority or a source of knowledge.

At the conclusion of the descriptive stage, the students are directed, collectively, to identify quantitatively measurable parameters that might be expected to exhibit some cause–effect relationship. A variable under direct control by the experimenters is identified as the *independent variable*, while the effect is identified as the *dependent variable*. This is a critical step in the modeling process. It is at this point that the students learn to differentiate aspects of the phenomenon to which they must attend from those which are distracters. While this issue of *identifying and controlling variables* is critical to modeling, it is scarcely addressed in traditional instruction, where a lab manual typically provides students with the lab purpose, procedure, evaluation of data, and even questions suggesting appropriate conclusions. This critical issue is also missed in conventional homework and test problems, which typically provide only that information necessary to accommodate the *author's choice* of solutions.

Having completed the *descriptive phase* of modeling by settling on a suitable set of descriptive variables, the instructor guides the class into the *formulation phase* by raising the central problem: to develop a functional relationship between the specified variables. A *brief* class discussion of the essential elements of the experimental design (which parameters will be held constant and which will be varied) is pursued at this time. The class then divides into teams of two or three to devise and perform experiments of their own.

Before starting data acquisition, each team must develop a detailed experimental design. Except where the design might pose risk of injury to persons or equipment, the teams are permitted to pursue their own experimental procedures without intrusion by the instructor. For a post-lab presentation to the class, the instructor selects a group which is likely to raise significant issues for class discussion—often a group that has taken an inappropriate approach. At that time, the group members are expected to present a detailed explanation and defense of their experimental design and conclusions.

Each lab team performs its own data analysis cooperatively, using computers and striving to construct graphical and mathematical representations of the functional relationships previously posited. The principal goal of the laboratory activities is to lead students to develop a conceptual correspondence between targeted aspects of the real world phenomenon and corresponding symbolic representations.

Every lab activity is concluded by each lab team preparing, on a whiteboard, a detailed post-lab analysis of the activity and reasoning that led to the proposed model(s). The teacher then selects one or more of the lab groups to make presentations before the class, explaining and defending their experimental design, analysis of data, and proposed model.

Laboratory reports for each activity are written up in a laboratory notebook according to a given format. It is stressed that the purpose of the laboratory report is to articulate a coherent argument in support of their model construction. While each student must prepare and submit a lab notebook, most of the work is done in class in their cooperative study groups. Grading is done by selecting one report at random from each group and selecting different members of the group to defend different aspects of the report. This induces students, during the preparation of reports by the groups, to ensure that every member of the group understands all aspects of the model that they have developed, thus instilling a sense of *shared responsibility* for the knowledge. This concludes Stage I.

The end product of Stage I is a mathematical model together with evidence for a claim that accurately represents the behavior (or structure) of some physical system, in this case the Modified Atwood's Machine. Students have verified that the equation $a = F/m$ accurately describes the acceleration when F and m are varied independently. They are encouraged to consider the possibility that this equation represents a general law of nature, but they should be led to realize that there is *no such thing as an experimental proof of a general law*. At best, experiment can validate specific models which conform to the law, as in the present case.

Stage II is devoted to *deployment* of the model developed in Stage I to a variety of new physical situations in a variety of different ways. This helps free the students' understanding of the model from the specific context in which it was developed. The model may be deployed to describe, to explain, to predict, or to design a new experiment. Though some of the activities in Stage II involve the laboratory, most are more like traditional problem solving, except the work is done cooperatively in small groups. Most of the work is done in class.

Each study group develops solutions for each problem in the study set. Each group is then assigned one of the problems in the set to prepare, on the whiteboards, for class presentation. One member of the group is then selected to make the presentation. The same recitation grade is given to the entire group, and it depends on the quality of the presentation. During the presentation, if questions are asked by fellow students that the selected presenter cannot answer, other members of the group may offer assistance. If however any assistance from other members of the group is required to satisfy the questioner, the recitation grade awarded the group may be reduced. The recitation scores of the groups are enhanced if the members ask valid, well thought out questions during the presentations (*shared responsibility*).

On each pass through the modeling cycle the students' understanding of models and modeling is progressively deepened; students become more independent in formulating and executing tasks and more articulate in presenting and defending their points of view. The ultimate objective is, of course, to have them become autonomous scientific thinkers, fluent in the vicissitudes of mathematical modeling.

VI. CULTIVATION OF TEACHING EXPERTISE

What does it take to become a master teacher like Malcolm Wells? The skill and training required for expert teaching are generally underestimated and undervalued. Accolades and awards for teaching are often based on superficial criteria. Malcolm's example sets a higher standard—one to be emulated if teaching is to be elevated.

An extensive review and analysis of the literature on expert performance has identified essential conditions for the acquisition of expert skill in most domains.[14] The chief condition is *prolonged effort to improve performance* extending for a minimum of 10 years. A striking conclusion of the study is that individual differences, even among elite performers, are primarily due to intense practice rather than innate talent. Music, sports, chess, scientific research and literature are among the several domains examined in the study. Teaching was not included, of course, but there is no reason to doubt that the general conditions for acquisition of expertise apply there as well. Assuming so, we can draw some important conclusions about the professional development of teachers.

Our first conclusion is that *standard teacher preparation and in-service teaching experience is not sufficient to develop a high level of teaching expertise*. Consider what is involved. Even assuming that a physics teacher has acquired adequate "content knowledge" from a B.A. or even an M.A. in physics, the relevant pedagogical training is practically nil. After landing a teaching position, the tyro teacher may scramble for a couple of years to organize lab materials and activities, problem sets and homework, grading procedures and the rest into a smoothly running course. By this time the teacher has adopted a personal style and a teaching routine which makes it possible to cope with the perpetual exigencies of everyday teaching.

Most physics teachers are dedicated to their job and care deeply about their students. But caring and dedication are not enough! The experience of routine teaching over many years, even when conducted with dedication and enthusiasm, will not contribute significantly to the development of teaching expertise—just as plug-and-chug practice does little to promote problem solving skill! There is strong empirical support for this kind of assertion from the domain of chess.[5,14] Tournament chess players are assigned numerical performance ratings which are extremely reliable predictors of their tournament results. The fact is that, after an initial increase when learning the game, the average rating of an avid amateur scarcely changes over the years no matter how many games are played. Thus routine chess playing does not improve chess competence. Likewise, we conclude, *routine teaching does not improve teaching competence*. Most teachers become trapped in a routine that prevents them from coming close to realizing their true potential.

How to rise above it?

First consider how Malcolm did it. The schools have so crowded the teacher's daily schedule that no room is left for cultivating expertise. Malcolm, of course, did it on his own time—evenings, weekends, vacations—routinely working into the small hours of the morning. For Malcolm, teaching is a calling, not just a job. He was unrelenting in his efforts to improve—continuously monitoring the progress of his students, revising assignment and activities, designing and building new apparatus, always on the lookout for some other teacher's good idea. Malcolm is a counterexample to the myth of the "born teacher." Unlike the typical award-winning teacher, Malcolm is not a master showman. Rather, he goes out of his way to give the students center stage. Malcolm's success has come from hard work leading to technical mastery of his craft, from continuous critical evaluation of his own teaching performance, and from meticulous attention to every detail, large and small. "The devil is in the details!"

Few can match the prolonged and dedicated effort of Malcolm Wells, but many can aspire to his level of teaching expertise, because Malcolm has prepared the way. This paper aims to pass on some of Malcolm's hard won insights. However, most of Malcolm's expertise is bound up in teaching skills. Such skills cannot be transmitted verbally; they can only be passed on through personal interaction and deliberate practice in the classroom.

To develop a practical means for training teachers in the modeling method, we joined Malcolm in designing and conducting a series of NSF summer workshops for in-service teachers. A brief account of the experience provides some background for future action.

Two groups of high school physics teachers participated in the project. In teaching experience they ranged from novice to state teacher of the year, and in academic background, from one year of College Physics to a Masters in physics education. The first group of 17 teachers attended five-week workshops in the summers of 1990 and 1991 with a follow-up one-week workshop in the summer of 1992. They were also brought together for half-day workshops at regular intervals during the school year to discuss progress and problems with implementing the new method. All the teachers employed the new method in their regular high school physics teaching during their two years with the project, and they have continued using it since.

After initial hesitancy in the first workshop, teacher enthusiasm for the new modeling method grew to a stupendous level by the middle of their first year of teaching with it, and all teachers reported big improvements in student interest and activity. By the usual anecdotal measures the program was a great success. However, the *Force Concept Inventory* gave us an objective measure of gain in teaching effectiveness by comparing the score of each teacher's class just before the workshop with the one just after. The result was a sobering 4%—barely significant! We could identify several reasons for the limited gain: (1) The written curriculum materials tailored to the new method were inadequate; (2) the teachers were so caught up in the mechanics of the computer-based laboratory activities that they overlooked crucial pedagogical features that make the method effective, and (3) too much lecturing about the method (shame!).

In the second summer workshop, the teachers were involved in developing the necessary curriculum materials, and this gave them a satisfying sense of ownership in the program as well as rich experience collaborating with their peers. Also, pedagogical techniques were given renewed emphasis. This contributed to a clearly significant 22% average gain on the *Inventory* for all teachers. That, however, is still well short of the results consistently achieved by Malcolm Wells. Moreover, though there was some improvement on our other measure of student competence, the *Mechanics Baseline*, it is not worth reporting.

In the summer of 1992, a new group of 14 teachers attended a single five-week "Modeling Workshop." With the printed curriculum materials available, this workshop proceeded more smoothly and quickly than the previous ones. Most important, the workshop design was improved to enable the teachers to practice the new methods on their colleagues almost every day. From our personal observations, we are confident that this new group made as much progress in one summer as the original group did in two. Unfortunately, we were unable to validate this conclusion with an objective follow-up evaluation.

Overall, we regard the workshops as moderately successful. The teachers were unanimous in high praise for the experience. As a consequence, all of them have radically and permanently changed their teaching methods. As far as we know, their teaching is now laboratory based, computer enhanced, student centered, and activity oriented. They report that their students are more engaged and enthusiastic than ever. They are especially delighted with the enhanced student participation stimulated by the whiteboards. In short, the workshops succeeded fully in getting teachers to adopt a *cooperative inquiry* method of teaching. They were less successful in leading teachers to understand the rationale for the

Box 3: MODELING WORKSHOP Description

Participants will be introduced to the Modeling Method as a systematic approach to the design of curriculum and instruction.

- They will collaborate on the redesign of the high school physics course to enhance learnability and exploit technology.
- They will learn how to use computers and electronic networks as an integral part of their teaching practice.
- They will implement a student-centered instructional strategy which engages students in active *scientific inquiry, discourse and evaluation of evidence.*
- They will examine implications of educational research for physics teaching.

CURRICULUM

- **Standard** topics will be covered (including mechanics, optics, electricity and magnetism), but they will be organized into a systematic and coherent curriculum.
- **Flexible** curriculum design will facilitate future upgrades of computers and software and incorporation of new topics or activities.
- **Structured** curriculum for the introductory physics course will be supplemented by a **project-oriented** curriculum for an advanced course or extracurricular activity.

INSTRUCTION

- Since "teachers teach as they have been taught," workshops will include extensive practice in implementing the curriculum as intended for high school classes.
- Participants will rotate through roles of student and instructor as they practice techniques of guided discovery and cooperative learning.
- Plans and techniques for raising the *level of discourse* in classroom discussions and student presentations will be emphasized.

modeling method. For example, a video of one teacher's class shows enthusiastic students in intense and animated discussion over a whiteboard, but the teacher failed to focus the discussion, so it went nowhere. Another teacher inadvertantly subverts the objectives of guided-inquiry lab experiments by summarizing the findings instead of requiring the students to do so. On the other hand, the *Inventory* scores show that the teachers have been greatly sensitized to student misconceptions and are learning to address them; although only a few of them have learned to appreciate the deeper aspects of the modeling method. This is reflected in the minimal improvements of *Baseline* scores. Considerable advances in workshop design and execution will be needed to achieve a satisfying outcome along this dimension.

We are now prepared to draw some strong conclusions about what is most needed to improve high school physics. *Teacher expertise is the critical factor*. The teacher, above all, determines the quality of student experience in the classroom. Equipment and school environment are secondary factors. To reach and maintain his/her full potential, the *teacher must be engaged in lifelong professional development*. It will take at least ten years to reach the teacher's highest level of competence. Mere accumulation of academic credits and hours of classroom teaching count for little, unless the teacher is consistently engaged in deliberate effort to improve.

Teacher commitment is essential, and individual teachers, like Malcolm, can go far in designing and executing their own programs for personal development. However, even Malcolm needed help to reach his peak, so the *ultimate success of every teacher depends on opportunities to draw on the resources of the physics community*. Teachers need a support system in the physics community to nourish their professional development. The infrastructure for such support is in terrible shape across the nation.

From many quarters, especially the National Science Foundation, we hear a clarion call for nationwide systemic reform of science and math education. It signals widespread recognition of a need to rebuild the educational infrastructure. But systemic reform will fail unless it focuses on developing and sustaining teacher expertise. This is a problem of immense proportions, but we need not wait for someone else to attack it. The physics community must assume responsibility for establishing and maintaining an infrastructure for high school physics reform. To be fully successful it must be a collaborative effort involving all segments of the physics community—in high schools, colleges, universities, and professional societies. Here is how we propose to attack the problem.

We have recently been awarded a NSF grant to conduct a nationwide program of *Modeling Workshops* for in-service high school physics teachers beginning in summer 1995. Besides the authors, the Project team includes Larry Dukerich, Ibrahim Halloun, and Jane Jackson. The Workshop is described in Box 3.

It builds on the design pioneered by Malcolm Wells, and it is aimed at cultivating Wells-like expertise among teachers. We are *dedicated to using the Modeling Workshop as an instrument for high school physics reform*. We are keenly aware that the impact of the program depends critically on the dedication and local support of the participants. Consequently, participation in the first round of workshops is competitive, with preference to applications showing the most promise for local reform. If the first round is successful, we have plans and funding to expand the program, and we would like nothing better than to make the workshop available to all interested teachers. For further information about the program, write the *Modeling Workshop Project Director*, Dr. Jane Jackson, at D.H.'s address.

MALCOLM WELLS has started something!

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Research-design model for professional development of teachers: Designing lessons with physics education research

Bat-Sheva Eylon and Esther Bagno
The Science Teaching Department, Weizmann Institute of Science, Rehovot, Israel, 76100
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How can one increase the awareness of teachers to the existence and importance of knowledge gained through physics education research (PER) and provide them with capabilities to use it? How can one enrich teachers' physics knowledge and the related pedagogical content knowledge of topics singled out by PER? In this paper we describe a professional development model that attempts to respond to these needs. We report on a study of the model's implementation in a program for 22 high-school experienced physics teachers. In this program teachers (in teams of 5-6) developed during a year and a half (about 330 h), several lessons (mini-modules) dealing with a topic identified as problematic by PER. The teachers employed a systematic research-based approach and used PER findings. The program consisted of three stages, each culminating with a miniconference: 1. Defining teaching and/or learning goals based on content analysis and diagnosis of students' prior knowledge. 2. Designing the lessons using PER-based instructional strategies. 3. Performing a small-scale research study that accompanies the development process and publishing the results. We describe a case study of one of the groups and bring evidence that demonstrates how the workshop advanced: (a) Teachers' *awareness* of deficiencies in their own knowledge of physics and pedagogy, and their perceptions about their students' knowledge; (b) teachers' *knowledge* of physics and physics pedagogy; (c) a systematic research-based *approach to the design* of lessons; (d) the formation of a *community of practice*; and (e) acquaintance with central findings of PER. There was a clear effect on teachers' practice in the context of the study as indicated by the materials brought to the workshop. The teachers also reported that they continued to use the insights gained, mainly in the topics that were investigated by themselves and by their peers.

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I. INTRODUCTION

In the past decade physics education research has accumulated a significant body of knowledge relevant to teachers' practice.[1] The Resource Letter—PER (physics education research),[1] published in the American Journal of Physics, offers an exhaustive bibliography of research papers categorized according to empirical studies, theoretical perspectives, and research-based instructional materials. McDermott and Redish, the authors of this paper, write in their abstract: "The purpose of this Resource Letter is to provide an overview of research on the learning and teaching of physics. The references have been selected to meet the needs of two groups of physicists engaged in physics education. The first is the growing number whose field of scholarly inquiry is (or might become) physics education research. The second is the much larger community of physics instructors whose primary interest is in using the results from research as a guide for improving instruction." While research in physics education has influenced the practice of some college physics instructors,[2] there are still many practitioners both at the college level but mostly at the high-school level who are not aware of the PER endeavor and do not consume its results into their practice. As pointed out by Smith and Neale,[3] even if teachers are aware of the PER results, the increased knowledge of students' understanding does not ensure that they can respond in appropriate ways when students exhibit misconceptions.

How can one increase the awareness of teachers to the existence of a vast body of knowledge gained through physics education research? How can one bring them to change their views regarding the importance of PER results? How can one provide teachers with capabilities to use PER-based innovative instructional strategies and integrate them into their existing practice? In this paper we describe a model that attempts to respond to these needs and a study of its implementation with high-school physics teachers. In addition to the central goal of professional development in the area of using PER, the model aims at other central goals singled out as important in teachers' expertise and accomplishment.[4,5] These goals include teachers' content knowledge, pedagogical content knowledge, systematic design of lessons, and collaboration with peers (belonging to a "community of practice"). We will show below how the model advances the goal of using PER simultaneously with all the other goals.

Research on teachers' professional development shows that bringing about profound changes in teachers' views and practices requires a long-term comprehensive program.[6–8] Many of the successful professional development programs engage teachers in inquiries based on real classroom contexts.[9] Since in this paper we are concerned with the use of PER results, we suggest that aspects of PER would become an integral part of the inquiries carried out by teachers and that they will experience the consumption of its results in their classrooms. Accordingly, in the program described in this paper, teachers develop over a long period of time several lessons (minimodules) dealing with a topic identified as problematic by PER. The teachers employ a systematic research-based approach of development and use the PER findings. They start from the diagnosis of students' prior knowledge, design lessons aimed at predefined learning goals, use PER-based instructional strategies, and carry out "assessment for learning".[10] The approach involves successive refinements of the lessons—a design study methodology.[11]

We described above the importance of promoting *the goal of using PER*. In the following paragraphs we elaborate briefly on each of the central goals of the program

Goal 1: Awareness. Teachers' awareness of the need to learn is a prerequisite for any professional development.[12] Loucks-Horsley *et al.*,[13] in their chapter about strategies for professional learning, select the strategies according to the purposes they have to fulfill. Increasing awareness and eliciting thoughtful questioning on the part of the teachers is the first goal on their list. In the European research and development project, "Science Teacher Training in an Information Society,"[14] each set of workshop activities was built as a coherent sequence, starting from developing an awareness of the issues the teachers had to deal with. The need to address this goal was crucial in the program described in this paper. This program was planned to be carried out with experienced physics teachers possessing a strong background in the discipline. These teachers would agree that they lack expertise in a contemporary topic such as astrophysics, but would not admit a lack of knowledge in the basic topics taught in school (e.g., what is the mechanism driving the current in an electric circuit). Similarly, they would admit a lack of expertise in some new laboratory techniques such as using sensors, or using a spreadsheet to build models of physics phenomena, but would not identify the need to participate in programs aimed at upgrading their pedagogical content knowledge (see below). Therefore, the first and most important goal of the program was to raise teachers' awareness of deficiencies in certain aspects of their knowledge and practice and how PER can contribute to these aspects.

Goal 2: Knowledge (content knowledge and pedagogical content knowledge). A report of the NCTAF[15] mentions two critical findings regarding teachers' content and pedagogical content knowledge: First, the teacher's expertise is one of the most important factors in student learning "Teachers who know a lot about teaching and learning and who work in environments that allow them to know students well, are the critical elements of successful learning."[16] Second, teachers' knowledge of the subject matter, student learning and development, as well as teaching methods are all important elements of teacher effectiveness.

Content knowledge. Teachers must have a rich and flexible knowledge of content in order to foster students' conceptual understanding.[17] In addition, teachers must understand the processes used to establish new knowledge and determine the validity of claims.[18–21] Hollon, Roth, and Anderson,[22] show, however, that good mastery of the disciplinary knowledge does not guarantee that teachers can effectively use this knowledge in their teaching. Thus, pedagogical content knowledge is an essential component of teachers' expertise as described below.

Pedagogical content knowledge (PCK). First introduced by Shulman,[4,23] this type of teachers' knowledge is distinguished from general pedagogical knowledge by being intertwined with content knowledge. There are varied conceptualizations of PCK in the literature.[24] For the purpose of this paper we adapted the description of Magnusson, Krajcik, and Borko,[25] who identified five important elements of PCK: teachers' orientations towards teaching science (knowledge and beliefs about the goals and processes of teaching science at a particular grade level), teachers' knowledge of science curricula, teachers' knowledge of students' understanding of science, teachers' knowledge of instructional strategies, and teachers' knowledge of assessment of scientific literacy (what and how to assess).

Goal 3: Systematic research-based design of lessons. This is a fundamental pedagogical skill that each teacher must possess. Here we emphasize the integration of this skill with content knowledge and pedagogical content knowledge in order to transform and represent knowledge in forms suitable for particular students' learning.[25,26] The use of PER methodologies and results are important in achieving this goal. The development of this skill, essential for every practicing teacher, is evident in the Japanese "lesson study" approach,[8] where teachers work collaboratively in planning, teaching, observing, and reflecting on lessons they develop. Stigler and Hiebert,[27] recommended to test this approach in the US, and there is a growing interest in its use in teacher development programs.[28]

Goal 4: A community of practice. Since many high-school physics teachers in Israel and in other countries are the only physics teachers in their school, they do not have opportunities to collaborate with colleagues. Borko,[17] in her AERA presidential address, pointed out that strong professional communities of teachers can foster teacher learning. Little,[29] provides evidence relating instructional improvement to communities of practice. Although there is no direct linkage between teachers' interactions and their students' achievement, researchers report some anecdotal evidence that teacher communities have an effect on students.[30] Collaboration between teachers is only the first step towards forming a "community of practice". Communities involve also "development of group identity and norms for interaction, communal responsibility for the regulation of norms and behavior and willingness of community members to assume responsibility for colleagues' growth and development".[30]

In the following sections we elaborate on the structure of the model. We then describe an in-service program for physics teachers that implemented the model, and an empirical study that accompanied its implementation. The impact of the program was examined during the implementation as well as several years later.

II. THE MODEL

A. Rationale

Physics educators, responsible for preservice training, have developed several models to raise the awareness of prospective teachers to PER and its use in teaching. For example, one of the approaches involves teachers reproducing segments of existing research.[31] Another way of bringing the results of research to teachers is through PER-based curricula or frameworks, e.g., "Modeling Workshops,"[32] or the "Tutorials."[33] As mentioned above, in this study the core of the professional development program involved the design of lessons. This strategy is recommended in the literature,[13] and is thought to promote mainly the practice of teaching as well as the building of knowledge (p.46). Additional strategies recommended by Loucks-Horsley *et al.*[13] involve action research, examining student work and study groups. These strategies are important in advancing additional desired goals such as developing awareness and reflection on practice. In her summary of effective professional development programs, Roth,[9] lists the following features: "··engaging teachers actively in collaborative long-term problem-based inquiries, treating content learning as central and intertwined with pedagogical issues, and allowing teachers to investigate teaching and learning issues in real classroom contexts focused on specific curriculum used in their own classrooms." The approaches mentioned above can be described as having the four characteristics described by the National Research Council (NRC) study,[34] concerning teachers' learning: learner-centered; knowledge-centered; assessment-centered; and community-centered.

The model that we designed blends these strategies and attempts to respond to teachers' needs. Our rationale for asking teachers to develop the minimodules was based on the assumption that teachers would find it natural to design a lesson, since this is what they do all the time. Moreover, this kind of activity is a natural arena for them to manifest their knowledge in physics teaching, giving them the respect that is so essential for professional development. The other components of the model, e.g., collaboration and the systematic research-based approach, are less natural to teachers and require special training. We hoped that as a result of getting the teachers involved in the process of designing lessons, implementing them in their classes, and examining their students' work, they will change their views regarding the importance and use of PER. Moreover, we hoped that this process will bring about the professional development of teachers regarding their physics knowledge and their pedagogical content knowledge.

B. Description of the model

The model consists of the following ten consecutive steps organized into three stages. Each stage culminates with a miniconference. Each step is carried out through guided activities involving detailed instructions and guidance in how to carry out the step as well as feedback. The development of the minimodules is carried out in the context of the whole class and group work.

1. Stage I: Defining teaching and/or learning goals based on content analysis and diagnosis of students' prior knowledge

(1) initial definition of goals; (2) review of the literature; (3) diagnosis; (4) revision of goals; Conference I.

2. Stage II: Designing the lessons

(5) innovative learning strategies; (6) initial planning; (7) design of lessons; Conference II.

3. Stage III: Performing a small-scale research study that accompanies the development process and publishing the results

(8) design and implementation of the study; (9) summary of research; (10) a paper summarizing the process; Conference III.

Rationale. The first stage of the model attempts to get teachers to realize the need to introduce some innovation in the particular topic. Unlike the usual process of planning a teaching sequence, where the goals of the lessons are predefined by external authorities, such as the syllabus, stage I of the model, enables teachers to identify problems encountered by them (as learners) and by their students (through diagnosis) and can motivate them to design lessons customized to their own needs.

The summary in the first conference serves as a means for consolidating the knowledge gained by teachers during this stage and by focusing and redefining the goals for the lessons. The second stage is aimed at advancing the planning, starting with an acquaintance with new instructional strategies, the model leads teachers through a process of successive refinements of goals and means, an approach taken by expert curriculum developers. The process involves several means: expert consultation, critique by peers, and observation of the instructional strategies used by colleagues. This experience forms the basis for the design of the minimodules. The conference can provide an additional opportunity to examine the product and can lead to some adjustments. The third stage is based on the assumption that the activities carried out in the previous stages of the model would motivate the teachers to evaluate the instruction that they have developed, study their students' learning, and report on their results to participants and other colleagues.

III. THE STUDY

A. Context and sample

The model was implemented as a workshop within a three-year program aimed at the professional development of leading-teachers. The study was carried out in the context of this workshop. A group of about 50 senior high-school physics teachers signed up for the program, 22 of them were selected for this program on the basis of recommendations and an interview. The teachers met once a week for a full day (8 h) for three years. The development of the "minimodules" workshop lasted about a year and a half, for a total of 330 h.

The teachers formed four groups of 5–6 teachers each that were interested in developing a certain topic. The members of each group switched responsibility in organizing the various assignments of the workshop topic and had one of the program leaders as a mentor. During the meetings, the activities were carried out in the whole class and in groups. In-between meetings the groups met to carry out assignments. During the meetings the mentors acted as facilitators and also helped in organizing the flow of work in and between the meetings.

B. Goals and research question

The study was concerned with the contribution of the workshop to the professional development of the participating teachers in terms of the goals outlined above: awareness, knowledge (content, PCK and PK), systematic design of lessons, and community of practice. Accordingly, the following research question was studied: How did the model contribute to the attainment of the desired goals?

C. Methods of investigation

The study employed both qualitative and quantitative methods of analysis. Data were collected on all the groups participating in the workshop during its implementation and several years later. The data consist of the following elements:

(1) Documentation of the meetings: observations and transcriptions of audiotapes of all the whole class meetings and the discussions among the teachers during the group work as well as the materials developed by the teachers during the workshop (e.g., teachers' concept maps regarding the topic "from electrostatics to currents," diagnostic questionnaires, versions of the minimodules).

(2) Students' work brought by teachers to the workshop.

(3) Informal conversations with teachers.

(4) The journal of the course-leaders: it included plans of the meetings and remarks reflecting on the implementation.

(5) Questionnaires about teachers' views of the contribution of the course, immediately after the course and six years later.

Because of lack of space, in this paper we describe in detail a case study of six physics teachers who worked as a group on the topic "From electrostatics to currents" and substantiate the findings with data emerging from the other groups. We shall not report in detail the results of the questionnaires, but will mention the major findings.

D. The topics of the minimodules

The selection of appropriate topics to be offered to teachers is essential for the success of the model. There are several considerations in choosing the topics of the minimodules: relevance to the teachers' ongoing practice, topics identified as problematic in the educational research literature, topics requiring abstract reasoning that requires concretization, topics dealing with powerful ideas, etc. In the present study the teachers were offered, in the beginning of the workshop, the following four topics for choice: (1) The relationship between Newton's first and second laws. (2) Introduction to waves.[35] (3) From electrostatics to currents.[36] (4) Electromagnetic induction.[37] Each teacher chose a topic, and four groups were formed accordingly.

IV. ANALYSIS AND RESULTS

In this section we describe a case study of one of the groups; relevant results from the work of other groups; results from teachers' self-reports immediately after the completion of the course and several years later. We will show how the workshop advanced: (a) Teachers' *awareness* of deficiencies in their own knowledge of physics and pedagogy, and their perceptions about their students' knowledge; (b) all aspects of teachers' *knowledge*; (c) a systematic research-based *approach to the design* of lessons; (d) the formation of a *community of practice*; and (e) acquaintance with central findings of PER. The section concludes with a summary of the evidence supporting the above claims for each of the goals.

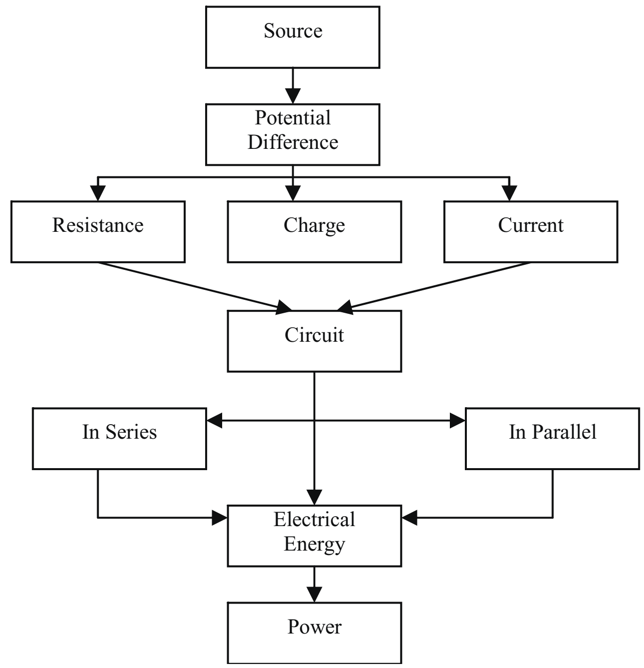


FIG. 1. The concept map drawn initially by the "From electrostatics to currents" group describing the central concepts involved in the transition from electrostatics to currents.

A. A case study of six teachers

1. Stage I: Defining teaching and/or learning goals based on content analysis and diagnosis of students' prior knowledge

Step 1: Initial definition of goals. Teachers construct a concept map describing the concepts and principles involved in their planned minimodule. They construct the maps initially as individuals, and then compare and discuss the maps with their peers, attempting to reach a consensus, and ultimately coming up with one or more group maps. In general, this was the mode teachers worked together along the whole workshop. They attempted to identify commonalities but respected different views.

Results. Figure 1 shows the concept map drawn by the "From electrostatics to currents" group. The teachers did not initially see the significance of this task and the importance of the topic. In other words, the "teachers did not know that they do not know." The process of creating and discussing a concept map turned out to be very illuminating to all the groups in terms of their physics knowledge as well as the pedagogy of teaching the topic.

As can be seen, there is almost no linkage between electrostatics and currents: The concept of the electric field is

TABLE I. Teachers' present their review of the literature.

(a) **Issues regarding the physics raised by the review**

1. How does the current "know" how to split in a junction?
2. If the electric field exerts force on the charges, why is the drift velocity constant?
3. How do the charges know how to move in a meandering wire?

(b) **Selected insights regarding the teaching and learning of physics from the review**

1. How do students explain current flow in an open circuit and what can be done about it?
2. There is a gap between students' conceptions of electric fields in the contexts of electrostatics and electric circuits: electric field in electrostatics is usually conceived by students as a force that causes charges to move, whereas in circuits, the electric field is conceived as a theoretical concept derived from the concept of the potential difference. Introducing the changes in the distribution of surface charges in electric circuits can help in bridging the gap.
3. The analysis of dc circuits is usually based on energy considerations without referring to the microscopic aspects inside and outside the circuit.

(c) **Selected instructional strategies from the review**

1. Murzin, for example, describes Drude's model as an explanation of charge flow in a circuit and the relationship between j and E.
2. Parker and Chabay & Sherwood use the surface charge distribution to explain the electric field inside and outside a current-carrying conductor.
3. Jefimenko suggests interesting experiments demonstrating electric fields inside and outside meandering wires.

missing; the concept of charge is not related to the concept of current; and the directions of the arrows relating to the concepts do not reflect a coherent understanding. These results are consistent with previous research findings.[36]

An analysis of the teachers' discussions during this session confirmed that the causal relationship between the electric field and current was deficient. They were frustrated to find out that in spite of their experience, they still lacked basic knowledge of physics.

The following are excerpts from these discussions:

(i) Although the topic of currents seems to be very simple, the truth of the matter is that I have an uneasy feeling when I teach it.

(ii) Well, sometimes I smooth things over.

(iii) The whole issue of an electromotive force (EMF) source is like a black box for me. What does the battery do? I suspect that even chemistry teachers cannot provide an answer.

(iv) I suggest asking Zvi (an expert physics teacher) to come to the next meeting.

In the course-leader journal, written after this session, it was noted that the teachers had a hard time with the physics of this topic and they asked for extra time to learn more physics.

Step 2: Review of the literature. Teachers review the literature on physics as well as physics learning relevant to their topic, and report on the main learning difficulties and instructional strategies. The process is guided by the course leaders, but teachers are asked to expand the suggested list of references.

Results. The teachers were referred to the literature concerning the physics of surface charge distribution that causes the charges to flow, and to papers about innovative instructional strategies in this topic.[38] Table I presents the original list of the teachers' review of the literature as presented in conference I.

After discussing the review of the literature, one of the teachers said:

"You know what? The physics here is really complicated; it is nice to find out that people tackle the same problems everywhere."

Step 3: Diagnosis. Teachers design, administer, and analyze a diagnostic questionnaire consisting of a few "simple" questions to examine students' understanding.

Results. Teachers usually compose examinations quite easily. However, the requirement to compose a diagnostic tool aimed at well-predefined goals was a new experience for many of them. Besides the enrichment of their subject matter knowledge and their pedagogical content knowledge, this stage of the workshop enriched their general pedagogical knowledge as well. Teachers raised questions and dwelled on issues unfamiliar to them such as: "What is a diagnostic tool? Does it have to be a questionnaire? What do we want to find out about students' understanding? What do we mean by understanding?" According to the course-leader journal, following the development of the diagnostic tool, the teachers suggested changing the plan of the course and asked for additional lectures supplying information about the ideas of "diagnosis" and "understanding."

The group designed questions focusing on the relationship between the electric field and current at different points of a dc circuit at different times. Since the electric field between the plates of a capacitor is studied in electrostatics and the charging of a capacitor is studied in dc circuits, the teachers decided to focus the questionnaire on the charging of a capacitor. Table II presents the list of goals for the diagnostic questionnaire.

TABLE II. Goals of the diagnostic questionnaire as listed by the teachers.

Goals of the diagnosis:

1. To examine how students explain the process of charging a capacitor and/or flow of current in an open circuit.
2. To examine whether students differentiate between the electric field in a static situation and in a dynamic situation.
3. To examine whether students relate the concept of current (direction and magnitude) to the concept of electric field (direction and magnitude).
4. To expose students to qualitative questions ("why" and not only "how much").

Since all the topics of the minimodules were based on the existing high-school physics syllabus, teachers were able to find quite easily the appropriate lesson for administering the diagnostic questionnaire. This choice of topics enabled them to incorporate research-based materials into their practice. The diagnostic questionnaire was administered to 93 high-school students studying A-level physics, after they had finished electrostatics, dc circuits, and the charging and discharging of a capacitor. We asked the teachers to collect their students' answers and to analyze the results cooperatively with their colleagues in the group and the mentor. Table III describes the diagnostic questionnaire, the analysis of the results, and representative statements of teachers regarding the data.

The following are comments made by the teachers during the analysis of the data:

(i) Generally speaking, most of the students explain dc phenomena through energy-based considerations and not through forces on charges.

(ii) They relate electric fields in dc circuits to potential differences and not to charges.

(iii) Students have difficulties with transients: electric fields between the plates of a capacitor and in the wires of the circuit.

(iv) I imagined that all my students would know that after charging there is an electric field between the plates of a capacitor, I'm disappointed.

(v) You know what? A few students even said that this questionnaire caused them for the first time to think about dc circuits in terms of an electric field.

Step 4: Redefinition of goals and conference I. Teachers change the initial goals on the basis of findings emerging from steps 2 and 3. In the conference teachers summarize the first stage of the model. They share their ideas with colleagues, invited scientists, and science educators. They discuss their initial concept maps; the review of the literature; the diagnostic tool developed to identify students' difficulties; the results of administering the diagnostic tool in the classrooms; and some preliminary thoughts for the planned minimodule. The teachers summarize in a booklet all these outcomes including the input of the conference participants.

Results. Presenting ideas to an audience is not a new experience for teachers. Nevertheless, the requirement to present the outcomes of the first stage of the model to colleagues and distinguished guests was an intriguing and exciting event for most of the participating teachers. All teachers worked hard crystallizing and summarizing their own insights regarding the relevant subject matter and utilized the data gathered from their classes. The exposure to learning and teaching problems identified by their peers also increased their awareness of the various difficulties, legitimated free discussions, and increased teachers' motivation to learn more about physics and the teaching of physics. The following are excerpts of statements from an interesting discussion held among the teachers and the guests about the physics of the topic and the recommended ways to teach it.

(i) Is there a nonconservative electric field in the battery?

(ii) It is really difficult to explain what is going on in an open circuit.

(iii) It is easy to explain currents through potential and energy-based considerations, but how is it done with forces?

(iv) It is written in the literature that the electric field is not produced by the moving charges. There are static charges on the conductor that make the current flow. Now here is my question: Do these static charges produce an electric field outside the conductor and no electric field inside?

As a result of the conference, the group was able to define more precisely the scope and the goals of the minimodule. As one of the teachers put it: "We should focus on strengthening the continuity between electrostatics and currents. We should also show that both the electrostatics and the electrodynamics phenomena originate from Coulomb's law and the appropriate surface charge distribution."

The main goal of the minimodule, as summarized in the booklet prepared for conference I was: To apply the principles of electrostatics—forces, fields, and electric potential, to dc circuits.

Figure 2, presented in the conference, explicitly represents this new conception of goals.

The following is the list of new goals as stated by the teachers: The physics of the minimodule will focus mainly on the "missing link"—between the two dashed lines in the concept map.

(a) Distribution of charges: Reasons for the distribution; shapes of the distribution.

(b) Direction of the electric field inside and outside the conductor.

(c) Magnitude of the electric field and its dependence on the parameters of the conductor: lengths, area, and type of the material.

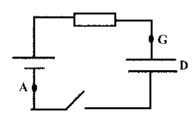
(d) Influence of local factors vs the emf of the source on the electric field in certain points of the conductor.

(e) The current in an open circuit, the capacitor.

TABLE III. The diagnostic questionnaire designed by the teachers, their analysis of data collected from 93 high-school students, and statements from their presentation of the results in conference I.

The diagnostic questionnaire

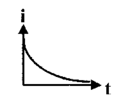
In the circuit shown, there is an ideal emf source, an uncharged capacitor, a resistor and a switch.
A, G, and D, are positions in the circuit.



(a) The switch is open.

Draw circles around the positions where there is an electric field. Draw arrows representing the directions of the fields.
A________ D________G________

(b) The switch is closed.
The graph shows the current in the circuit vs the time.
Explain briefly the graph.



Draw circles around the positions where there is an electric field immediately after the switch has been closed. Draw arrows representing the directions of the fields.
A________ D________G________

(c) Draw circles around the positions where there is an electric field a long time after the switch has been closed. (The capacitor is charged now.) Draw arrows representing the directions of the fields. If the magnitude of the fields has been changed, show it.
A________ D________G________

(d) For each of the cases you have claimed that there is electric field in D, explain briefly its producer.

(e) For each of the cases you have claimed that there is electric field in G, explain briefly its producer.

Presentation of results by the teachers

Existence of the electric field for questions (a);(b);(c)[a]

Switch	Electric field at **A**	Electric field at **G**	Electric field at **D**
Open	No (96%)	Same as A (most students)	Yes (11%)
Closed during charging	Yes (56%)	Same as A (most students)	Yes (87%)
Closed after charging	No (95%)	Same as A (most students)	Yes (62%)

Directions of the electric field for questions (a);(b);(c)

During charging, at positions A and G:
(i) 80% of the students' arrows representing the direction of the electric field imply that it is the same as the direction of the current.
During charging, at position D:
(ii) 55% of the students' arrows representing the direction of the electric field imply that it is the same as the direction of the current.

Possible sources of the electric field

(i) The opposite charges of the capacitor.
(ii) The emf source that delivers charges from plate to plate.
(iii) The emf source that is responsible for the potential difference between the plates.
(iv) The potential difference between the upper plate of the capacitor and the positive terminal of the battery.

Representative statements of the teachers

Let us start with the good news: Most of the students do understand that positions A and G are similar in terms of the electric field.

Only half of our students were aware of the electric field in the wires during the charging of the capacitor.

Students tend to overgeneralize: The fact that there is no current in the circuit is interpreted by students as indicating that there is no electric field anywhere, even between the plates of the capacitor.

I wonder what about the 45% of the students who do not relate the electric field in a wire to the motion of the charges.

[a] The entries in the first subtable of the second column list the correct answers and the percentages of students providing them.

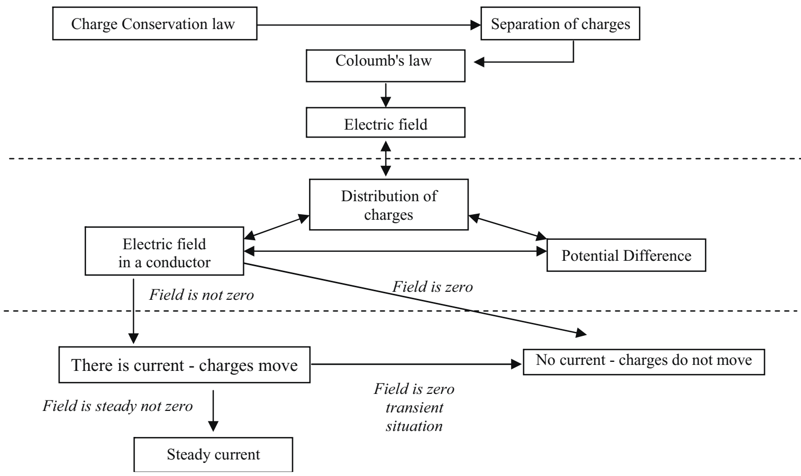


FIG. 2. The concept map and list of new goals, presented by the "From electrostatics to currents" group in conference I. This concept map has three main components (separated by the two dashed lines): some concepts of electrostatics, some concepts of electric circuits, and an interface relating the two, defined by the teachers as the new target of their minimodule.

As can be seen, this is a much more focused set of goals than the initial goals presented in the initial concept map (see Fig. 1).

2. *Stage II: Designing the lessons*

Steps 5 and 6: Innovative learning strategies and initial planning. In step 5, each group is requested to read about a research-based instructional strategy,[39] present it to the whole class, and lead a discussion relating to the challenges and the advantages of the strategy. In addition, teachers learn about the initiatives of fellow expert teachers. A special day is dedicated to step 6 in which teachers present their initial ideas using some of the strategies in step 5 and consult expert physics teachers, physics educators, and physicists. This activity leads to a preliminary plan for the minimodule entitled "The Story of the minimodule." The plan consists of a short description of the goals and the rationale for the means of achieving them using the innovative instructional strategies. The story of each minimodule is presented to the whole class and critiqued by peers.

Results. At this point after the systematic and research-based plan that narrowed down the set of goals, the teachers were eager to design lessons "solving" the problems identified through the previous steps of the workshop. They requested to extend the time allocated for the development of the minimodules. We reminded the teachers to screen again the materials offered previously in the "Literature review" step.[38] The "From electrostatics to currents" group dealt with Chabay and Sherwood's textbook, which they found to be very useful.

Four expert physics teachers from the Science Teaching Department offered consultation to the groups regarding the design of the lessons. In order to scaffold the design process, we gave the teachers a structured form to guide the "The Story of the minimodule"—an abstract describing the future plan of the lessons. The plan was critiqued by peers (see Table IV).

During this session, the following remarks were made by the teachers:

(i) Usually we decide what to teach and we just teach it. This planning game is really interesting and it is not a waste of time.

(ii) Well, this planning activity clarifies what is really important when you design a lesson.

(iii) I'm so glad to have the opportunity to meet all these expert physics teachers and to learn from them. Zvi's movie about the electric field in the vicinity of a current-carrying conductor is a wonderful teaching tool.

Step 7: Design of lessons and conference II. Teachers design a version of the materials based on the information compiled regarding students' difficulties as well as techniques developed by the teachers to overcome these difficulties. In conference II teachers present and discuss the rationale of the lessons and the relevant learning materials.

Results. Teachers were expected to design the lessons within the framework of the meetings and allocate some minimal time in their home. Although it was not required, all the groups communicated via emails, forums, and phone calls, and developed the lessons accompanied with all the relevant materials. Further contributions of the scientists, physics educators, and peer teachers in conference II refined the product and turned it into a comprehensive set of lessons used until now by all the teachers in the group. The minimodule developed by the group is a 21-page booklet that includes the following: an introduction, a rationale explaining how to teach dc circuits in relation to electrostatics and a detailed description of all the lessons accompanied with the materials.

3. *Stage III: Performing and publishing the results of a small-scale research study that accompanies the development process*

Steps 8 and 9: Design and implementation of a study; summary of research and conference III. In step 8 the teachers formulate research questions, design the structure of the study, design research tools, implement the minimodules in their classes, conduct the relevant research, and check the effectiveness of the innovative lessons on their students' learning. In step 9 the teachers analyze the results of the study and present them to their peers. Conference III is the highlight of the workshop. Teachers report their findings and reflect on the whole process.

Results. Since the topics of the minimodules were chosen according to the existing high-school physics syllabus, the

TABLE IV. The "The Story of the minimodule"—an abstract describing the future plan of the lessons as presented by the "From electrostatics to currents" group.

The story of the minimodule "From electrostatics to currents"

Possible place in the teaching sequence: One out of three possibilities.

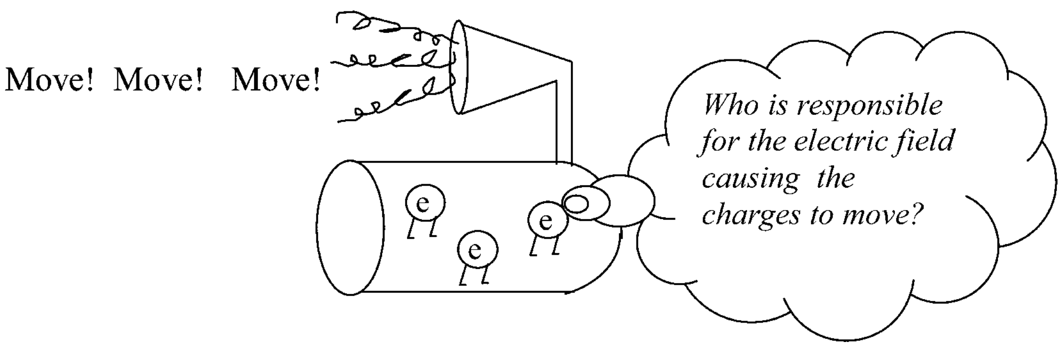
1. After teaching electrostatics as an introduction to dc circuits.
2. After the "traditional" teaching of dc circuits, as an introduction to capacitors.
3. After teaching electrostatics and dc circuits as a summary topic

Goals of the minimodule: To apply the principles of electrostatics (forces, fields, and electric potentials) in dc circuits.

Lesson 1: Introduction

Goal: To stimulate students' motivation and curiosity.

Strategy: Presenting "funny" intriguing questions and discussing them in small groups. For example:



Lesson 2: The electric field in a current-carrying conductor.

Goal: To demonstrate the electric field in the vicinity of a current-carrying conductor.

Strategies: Shlomo Rosenfeld's[a] experiment; Zvi Geller's[a] movie.

Lesson 3: Charge distribution and its effect on the electric field.

Goals: To understand the relationship between concepts in electrostatics and phenomena in current-carrying conductors; To understand the microscopic processes in a conductor when the circuit is closed.

Strategies: Work sheets for analyzing various situations—open circuits, closed circuits with one conductor, closed circuits with a resistor (according to Sherwood's book); theoretical summary of charge distribution (by the teacher).

Lesson 4: Summary

Strategy: Summarizing exercise.

[a]Expert physics teachers.

implementation of the minimodules, developed in the workshop, was natural for the teachers and did not require any logistical arrangements. Moreover, teachers were eager to identify "significant" differences between students who were exposed to this approach, and the "other" students.

85 students from three different schools were exposed to various aspects of the minimodule, immediately after they had finished the topics of charging and discharging of capacitors and before they had started learning about magnetism. The diagnostic questionnaire, described in step 3, served as the pretest for these students,

As a result of teaching the minimodule, the teachers assumed that their students would easily form the missing link between electrostatics and currents, in terms of electric fields and potentials. They proposed a posttest examining this assumption. The posttest was administered to the 85 students who studied the lessons ("experimental group") and to the matched classes of 68 students from the same schools ("comparison group"). The posttest and a qualitative analysis of the data were presented in Conference III (see Tables V and VI).

Because of the heavy teaching load and time constraints, teachers did not analyze students' responses to this posttest

TABLE V. The posttest designed by the teachers.

Posttest.
1. Draw a circle around the correct answer: Is there a relationship between electrostatics and dc circuits? Yes (go to questions 2,3) No (go to questions 4,5)
2. If you claim that there is a relationship between these two topics, name one concept that relates these topics.
3. Briefly explain the relationship.
4. If you claim that there is no relationship between these two topics, name one concept that belongs to electrostatics and not to dc circuits and one concept that belongs to dc circuits and not to electrostatics.
5. Explain briefly why there is no relationship between these two topics.

quantitatively. The group carried out a qualitative analysis in the following manner: First, each teacher read through all the posttests of his/her class, and summarized the major findings supported with selected examples. Then, the group convened to compare and contrast the findings and reached consensus on several conclusions. The teachers further supported the conclusions via discussions in their classes. Finally, the group was able to report on the superiority of the experimental group over the comparison group in some aspects but not in some other crucial aspects.

The teachers claimed that the ultimate goal of the minimodule, i.e., relating electrostatics to currents, was not fully accomplished. More specifically, the experimental group outperformed the control group only in aspects (a), (b), and (c) (see Table VI). Presumably, they expected their students to gain the same level of understanding as they themselves had gained in this program.

As one of the teachers said: "I'm kind of disappointed; I really hoped that it will work out better for the students."

Another teacher said: "We should examine more carefully what really happened in these classes. Maybe we should interview a few students to find out if there was progress in their understanding".

They decided to rewrite certain parts of the minimodule and to reemphasize the relationship between field, potential, and currents. These steps concluded the development of the minimodule.

Step 10: Paper summarizing the process. Each group writes a paper summarizing the process and submits it to "TEHUDA" the journal of Israeli physics teachers.

Results. The "From electrostatics to currents" group wrote a paper published in TEHUDA bringing together their products described in the previous steps. The teachers described the rationale promoting the development of the minimodule, the diagnostic tool, and the analysis of students' answers, the detailed structure of the module, the posttest, and its analysis. They concluded the paper with further information regarding the difficulties they encountered with the implementation of the minimodule and how they plan to improve the materials. In the conclusions of the paper they describe their own benefit from the whole process (including writing the paper), mainly through an increased sensitivity to students' difficulties and their desire to find new ways to deal with these difficulties.

B. The other groups

The case study that we have described thus far illustrates how the workshop indeed provided opportunities for the teachers to achieve the different goals that the model set forth to support. Very similar results were found for the other three groups as well. In this paper we cannot describe them in detail; the following are a few examples.

The "Electromagnetic induction" group went through the same process. At the beginning of the workshop they questioned the benefit of developing a minimodule for such a

TABLE VI. Teachers' analysis of data collected from 85 "experimental group" students and 68 "comparison group" students.

Presentation of results by the teachers
(a) The experimental students regarded the concepts of potential and electric fields as meaningful concepts relating electrostatics and currents.
(b) The experimental students regarded charges in electrostatics as identical to charges in dc circuits.
(c) The experimental students preferred the relationship between current and electric field rather than the relationship between current and potential difference.
(d) Frequent use of the relationship between the electric field and potential was not found in the experimental group.
(e) The experimental students did not really grasp the idea that the static and dynamic phenomena in a dc circuit share a common feedback mechanism.

"banal" topic. For example, one of the teachers said: "There is nothing surprising about it, teachers know exactly how to do it." Therefore, the initial plan of their minimodule included all the concepts and laws listed in the syllabus, such as flux, induced EMF, and Faraday's law and it was supposed to be taught in 14 lessons.

As a result of the group's analysis of the diagnostic questionnaire, the teachers modified their initial plans and narrowed the scope of the minimodule. Instead of the whole topic of electromagnetic induction, they decided to focus on the introduction to electromagnetic induction. In particular, a. designing demonstrations presenting the various mechanisms producing an EMF and especially the induced EMF, and b. composing qualitative questions discussing the role of the magnetic field in transforming work to electric energy during the motion of a loop in a magnetic field.

Another example from the "Introduction to waves" group illustrates the importance of working within a community of practice. This group designed a clumsy didactic means for demonstrating the concept of "waves." With the help of their colleagues they improved the model and turned it into a useful and inexpensive device.

C. Teachers' views about the contribution of the workshop

Immediately after completing the program, the teachers were asked to single out a framework or activity that was most meaningful, useful, and/or important to them.

About 80% of the teachers singled out the development of the minimodules.

Six years after the completion of the course, we located 15 teachers who had participated in the course and administered to them a questionnaire examining: a. the contribution of the minimodule workshop to the desired goals and b. the possible contributions of the minimodule workshop to the development of teachers' *awareness* of the importance of PER and to the actual use of the PER results in their present practice. The results indicate that even six years after the completion of the workshop, the teachers reported on the importance of all the goals, and about the significant contribution of the workshop to their attainment. Most of the teachers also claimed that they continue to use in their practice, PER-based materials or insights originating from PER.

D. Summary of results

In summary, the results reported in this section indicate the contribution of the workshop to the attainment of the goals mentioned above. Table VII summarizes the evidence supporting the conclusions for each of the goals. As can be seen, each step of the model contributed to the attainment of several goals. Another indication for the contribution of the model comes from the regional workshops, led by the teachers after completing our program. We monitored these regional workshops for several years and administered different questionnaires. In addition, Shayshon[40] conducted a case study for four years in one of the regional programs. One of the most popular activities turned out to be the development of a minimodule. For example, in a regional workshop, observed by her, teachers developed such minimodules in optics, mechanics, and electrostatics. While the first implementations of the model in the regional workshops followed rigorously the model described above, later implementations involved customizations to local needs.

As to the effects on actual practice, in the context of the study there was a clear effect as indicated by the materials brought to the workshop by the teachers. The teachers also reported that they continued to use the insights gained mainly in the topics that were investigated by themselves and by their peers. However, additional research is needed to verify these reports.

V. DISCUSSION

The detailed description of the case study as well as the immediate and long-term results about teachers' views indicate that the desired goals concerning physics education research were accomplished. The results also suggest that in addition to the goals concerning PER, other important goals have been promoted. Teachers realized that even in the standard topics of high-school physics there is more to learn both about content and about pedagogical content knowledge—an important outcome for the experienced audience that we worked with. Furthermore, the fact that what we teach is not necessarily what students learn,[41] and the need to better match the two was a main insight by the teachers, which was repeatedly mentioned in the different steps of the workshop. It should be noted that one cannot expect teachers to become expert curriculum developers who routinely use a research-based approach and follow rigorously the process that was modeled in the workshop. Indeed this was not a goal we were aiming at. Rather, we anticipated that the fact that teachers had an opportunity to go through this experience would provide them with anchors to future work. We expected that teachers who go through such a process would become better consumers of innovative materials and approaches since they acquired tools to customize them to their practice. This claim needs further investigation.

The long-term intensive nature of teachers' activities in this program enabled the teachers to develop professionally. However, this same characteristic of the program led to several implementation difficulties because of the large investment required from the teachers. Since we worked with these teachers previously and won their trust, they were willing to give us the credit and join the journey. With experience, teachers realized the importance of the long process. This same strategy may not be successful in occasions in which teachers do not give such credit to the professional development program providers. Hence one has to reconsider how to carry out the model in such occasions, while preserving its central characteristics. For example, one can use formats focusing more on the diagnostic stages and less on development, or alternatively, formats for introducing innovative curricula into schools by using existing materials and revising them instead of designing lessons from first principles.[42] What is common to all these versions is the systematic and research-based approach to instructional design.

A central insight emerging from this research and being used in our present instruction in teachers' programs is con-

TABLE VII. Summary of claims and evidence for impact of the workshop.

Claims	Evidence supporting the claims
Goal 1: Teachers developed awareness of deficiencies in their knowledge of physics, of pedagogy, and of their students' knowledge. They experienced difficulties as learners. They were willing to extend their knowledge.	(1) Teachers indicated surprise at the difficulties that they encountered as learners (e.g., in constructing concept maps of central ideas). (2) They requested to meet experts to help with issues raised in constructing the maps. (3) They described new revelations concerning the physics topic and its learning. (4) They reported mismatch between their expectations and their students' poor performance in the posttest.
Goal 2: Teachers advanced their content knowledge, pedagogical content knowledge, and pedagogical knowledge.	**Artifacts:** (1) The final concept maps represented the missing link between electrostatics and current which was absent from the initial maps. (2) Teachers' redefinition of goals and the diagnostic questionnaire related to the missing link and was closely aligned with the final maps. (3) Teachers' review of the literature emphasized important pieces of knowledge regarding the physics and learning of the topic. (4) The lessons reflected the new knowledge by using research-based instructional strategies and applying a student-centered approach. **Discourse and reports:** (5) Teachers expressed satisfaction regarding the opportunity to learn more physics and the teaching of physics. (6) They reported on the benefit in the TEHUDA paper, and in feedback questionnaires. (7) They were able to explain students' mistakes in terms of deficiencies in understanding. (8) They discussed the implications of aspects such as diagnosis to their teaching in general.
Goal 3: Teachers carried out a goal driven, diagnosis-based iterative design process supported by the resources that were supplied by the workshop.	**Coherence between the various aspects of design:** diagnostic questionnaire with the literature review; redefinition of goals with review of the literature and the diagnosis; the structure of the minimodule reflected the review of the literature as well as the diagnosis and the contribution of expert teachers; the posttest examined the intended goals. **Teachers reports:** in interviews and questionnaires about the importance of the systematic-research based design approach and on the contribution of the workshop to this aspect.
Goal 4: Development of a community of practice. This aspect of the workshop was highly appreciated by the teachers.	This claim is supported mainly by our observations, informal talks with the leaders of the course, and acquaintance with some of the teachers. **Teamwork developed as time went on:** (1) From formats dictated by the course to initiatives by the teachers. (2) From concerns to expose to other participants deficiencies in one's knowledge, towards friendships and readiness to share frustrations and even ask for help. (3) Teachers shared responsibility in the various assignments. (4) Teachers continued to collaborate after the completion of the workshop. **Teachers reported** in interviews and questionnaires on the importance of a community of practice and the model's contribution to its attainment.
Overarching goal: Learning about PER findings and their relevance to their practice. The attainment was interwoven with the other goals.	Each step contributed to somewhat different aspect of the PER goal as shown by the following examples: (1) Learning about students' conceptual difficulties, and tools how to assess understanding (step 3); (2) Innovative PER-based teaching strategies (step 5); (3) Implementation of the lessons and its evaluation made extensive use of the PER results (step 8).

cerned with cognitive conflicts activated by examining students' work. Teachers in the workshop described in this paper experienced cognitive conflict processes several times. In the diagnosis step teachers realized that there is a gap between what "*I've taught*" and what students actually learned motivating them to "fix" their previous teaching by trying out new instructional strategies. Towards the end of the workshop they encountered an additional cognitive conflict as a result examining again their students' answers to the posttest. They found a gap between what they tried to achieve and the actual disappointing outcomes. This cognitive conflict could have served as a starting point for a follow-up workshop with the same teachers aimed at changing their perceptions about the relationship between teaching and learning.[41] This follow-up support of teachers was not carried out and was a weakness of the approach.

The insights gained from this workshop, about the power of a cognitive conflict intertwined with examining, reflecting, and discussing one's practice (referred to as an "evidence-based approach"[43]), paved the way to new professional development programs. We found repeatedly that the careful iterative examination of students' work demonstrates dynamically the stepwise gradual nature of changes in students' learning and enables the teachers to customize their teaching accordingly.

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