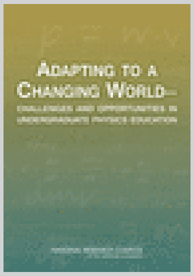

Adapting to a Changing World--Challenges and Opportunities in Undergraduate Physics Education

ISBN
978-0-309-28303-8

143 pages
7 x 10
PAPERBACK (2013)

Committee on Undergraduate Physics Education Research and Implementation; Board on Physics and Astronomy; Division on Engineering and Physical Sciences; National Research Council

ADAPTING TO A CHANGING WORLD—

CHALLENGES AND OPPORTUNITIES IN UNDERGRADUATE PHYSICS EDUCATION

Committee on Undergraduate Physics Education
Research and Implementation

Board on Physics and Astronomy

Division on Engineering and Physical Sciences

NATIONAL RESEARCH COUNCIL
OF THE NATIONAL ACADEMIES

THE NATIONAL ACADEMIES PRESS
Washington, D.C.
www.nap.edu

THE NATIONAL ACADEMIES PRESS 500 Fifth Street, NW Washington, DC 20001

NOTICE: The project that is the subject of this report was approved by the Governing Board of the National Research Council, whose members are drawn from the councils of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine. The members of the committee responsible for the report were chosen for their special competences and with regard for appropriate balance.

This study was supported by Grant No. PHY-1003414 between the National Academy of Sciences and the National Science Foundation. Support for this study was also provided by the W. K. Kellogg Foundation Fund of the National Academy of Sciences. Any opinions, findings, conclusions, or recommendations expressed in this publication are those of the author(s) and do not necessarily reflect the views of the organizations or agencies that provided support for the project.

International Standard Book Number-13: 978-0-309-28303-8
International Standard Book Number-10: 0-309-28303-5
Library of Congress Control Number: 2013940085

Additional copies of this report are available from the National Academies Press, 500 Fifth Street, NW, Keck 360, Washington, DC 20001; (800) 624-6242 or (202) 334-3313; http://www.nap.edu; and the Board on Physics and Astronomy, National Research Council, 500 Fifth Street, NW, Washington, DC 20001; http://www.national-academies.org/bpa.

Printed in the United States of America

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Preface

We live in turbulent but exciting times!

The U.S. economy is struggling to recover from a great recession. As we do so, the circumstances within which we hope to rise are not those from which we came. We are entering what some have termed "The Third Industrial Revolution." In this new world, what characterizes a leading economy is not factory production lines producing well-designed machines. Rather, it is the ability to serve the information and communication needs of populations approximating those of the entire Earth. Specifically, the United States can no longer enjoy an unchallenged position of leadership in this new world. Our preeminence is being challenged by many countries and societies from both the developed and developing worlds.

In this new world, much depends on the capabilities of a nation's citizens in high technology. Those capabilities depend critically on the quality and levels of education of those citizens, from kindergarten through graduate school. It is, thus, not surprising that the performance of education institutions in the United States has become the subject of national concern. Where once we could take pride in being at the top of the world in education, comparative international studies show that we are sliding down into the middle of the pack, not so much because we are failing to meet our traditional standards, but because other nations are on innovative and creative tracks that enable them to overtake and surpass us.

This is of particular concern because this new world requires a citizenry well informed about technical matters and well educated in the STEM (science, technology, engineering, and mathematics) subjects. It is not solely economic issues that require such skills, but many political issues as well, including environmental and energy issues. For example, climate change (or disruption) has become a central problem for all of us, including our children.

The first letter of STEM is for science. The component parts, including physics, chemistry, biology, and Earth sciences, are not interchangeable. Physics is the fundamental science that provides the foundation for all others. Education in physics, at all levels, forms the gateway into technological competence and expertise in almost everything of importance in our new world. Evidence indicates, however, that the physics community remains in a traditional mode in which the primary purpose of physics education is to create clones of the physics faculty. Yet there are notable exceptions. Over the past several decades, active research by physicists into the teaching of their subject has yielded important insights about what can be done to heighten the quality of students' understanding of the universe—at all levels. But this new knowledge is slow to find significant adoption, nor is it fully understood by physics faculty.

This report was commissioned by the National Science Foundation to examine the present status of undergraduate physics education, including the state of physics education research, and, most importantly, to develop a series of recommendations for improving physics education that draws from what is known about learning and effective teaching. Our committee has endeavored to do so, with great interest and more than a little passion.

Our committee was composed of a broadly diverse pool of concerned physicists. These individuals brought a considerable breadth of experience and expertise and an understanding of the landscape of current physics education as well as an appreciation for how education research has begun to transform understanding of student learning. What they all shared is a deep dedication to physics and the ways of thinking that characterize it. That's where the passion came from. There are two popular maxims about physics: "Physics is a social science," and "Physics is a contact sport." Both were demonstrated in our work. I thank all the members of the committee for their deep engagement in and devoted attention to meeting our charge. It was a great pleasure to work with them.

Finally, let me thank the talented members of the NRC staff who supported us. They include Jim Lancaster and Caryn Knutsen, who kept us on track, and Don Shapero, representing the Board on Physics and Astronomy.

Donald N. Langenberg, *Chair*
Committee on Undergraduate Physics Education Research and Implementation

Acknowledgment of Reviewers

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the National Research Council's (NRC's) Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their review of this report:

Michael Brown, Swarthmore College,
David Daniel, University of Texas, Dallas,
Fred Eiserling, University of California, Los Angeles,
Eugenia Etkina, Rutgers, The State University of New Jersey,
Ken Heller, University of Minnesota,
Ernest M. Henley, University of Washington,
Kenneth Krane, Oregon State University,
Tom O'Kuma, Lee College, and
Howard Stone, Princeton University.

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations, nor did they see the final draft of the report before its release. The review of this report was overseen by Julia Phillips, Sandia National Laboratories. Appointed by the NRC, she was responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

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APPENDIXES

Summary

The Committee on Undergraduate Physics Education Research and Implementation was established in 2010, under the auspices of the Board on Physics and Astronomy, by the National Research Council. This report is the committee's response to its statement of task, which is given in full in Appendix A. Its central charge is as follows:

> The committee will produce a report that identifies the goals and challenges facing undergraduate physics education and identifies how best practices for undergraduate physics education can be implemented on a widespread and sustained basis. In so doing, the committee will assess the status of physics education research (PER) and will discuss how PER can assist in accomplishing the goal of improving undergraduate physics education best practices and education policy.

THEMES

In the course of the committee's work several themes emerged:

- ***PHYSICS IS FUNDAMENTAL AND FOUNDATIONAL:*** Undergraduate physics education provides students with unique skills and ways of thinking that are of profound value to the students and to society.
    a. Physics explores and answers the most fundamental of questions: the origin of the universe, the nature of matter and energy, and symmetries and laws that shape everything. It provides a framework and discipline for probing these questions, whose range of applicability extends far beyond the physical sciences.

  b. Physics students learn to develop conceptual and mathematical approaches to models to help them understand complicated systems and solve complex problems. As a result of learning the inquiry process and ways of thinking used in physics, students with a physics education are prepared for success in complex analytical professional programs such as medicine, business, finance, and law.
  c. Physics is concerned with topics that underlie most other branches of science and engineering, and it is relevant to current societal concerns such as energy, nanotechnology, and national security.

- ***SYSTEMIC TENSIONS:*** The familiar college environment in which physics is currently taught is threatened by powerful, rapidly changing external forces, and U.S. physics departments will either adapt and improve or fade.
  a. Although many students (~500,000/year) study introductory physics, only about 1 percent end up with physics degrees. At many institutions, the number of majors is so low that it invites merging of the physics department with other science departments.
  b. Electronic communication and networking technologies are transforming, in both positive and negative ways, all educational institutions and programs, including physics.
  c. Economic realities are pressing undergraduate physics education (and all of higher education) to achieve reduced costs and improved outcomes.
  d. Universities and colleges, including their physics departments, have generally been slow to make changes that adequately respond to these challenges.

- ***MAJOR CHALLENGES:*** Current practices in undergraduate physics education do not serve most students well.
  a. Important groups remain underserved by the current paradigm (women, underrepresented minorities, prospective high school teachers).
  b. As evidenced by pre- and post-testing, most students taking introductory physics do not gain a genuine understanding of the concepts, practices of inquiry, or mental habits used in the discipline.
  c. Improvements are needed in the initial and subsequent professional training provided to physics teachers, particularly those teaching in K-12.
  d. Impediments to needed change include economic constraints, traditional academic cultures, and institutional structures.
  e. The subject matter and skills that undergraduates study have remained largely static for more than 50 years. Students learn little about current discoveries and research, which they might find exciting or relevant to their lives.

- ***IMPROVEMENTS EXIST:*** Substantial improvements in undergraduate physics education have been made with existing knowledge and resources in a variety of contexts; encouraging and preserving these gains requires a symphony of efforts by many different participants, and improving on them requires continuing research and development.
    a. Novel curricula, materials, and approaches to instruction exist that have demonstrated improved results, not only in students' conceptual and quantitative knowledge of physics, but also in their ability to engage in scientific inquiry.
    b. Some physics departments have demonstrated how to be attentive to their student communities, attract more students to physics, retain them through the major, and support them in a variety of career aspirations.
    c. There is a substantial and growing research base on which institutions can draw to improve educational practices.
    d. Implementing change will require concerted efforts at a range of levels, from individual physics faculty and departments to top administrative levels in universities, state and federal governmental agencies, research funding sources, and professional associations.

- ***SCIENTIFIC APPROACH TO PHYSICS EDUCATION:*** Future improvement of undergraduate physics education depends critically on a vigorous physics education research enterprise and effective application of its findings.
    a. Physics education research has emerged relatively recently as an important element of the broader academic exploration of the science of teaching and learning.
    b. Physics education research has yielded findings that are being applied in the development of better educational practices in some institutions and that could be more universally adopted.
    c. Education research in physics is a rapidly growing field and is still finding answers to important questions about learning and pedagogy. Physics education research needs systemic support to fuel future improvements in education.

These challenges and potential solutions are explored in detail in Chapters 1 through 3.

RECOMMENDATIONS

In Chapter 4, the committee offers suggestions and recommendations to each of the major audiences whose active and concerted engagement is essential to

BOX S.1
Places to Start

Websites with easy-to-access information that discusses or provides links to sources that cover many of the topics in this report include comPADRE (http://www.compadre.org) and the PER Users' Guide (http://perusersguide.org/).

building a successful future for undergraduate physics education. Following is a summary of key recommendations and related detailed recommendations. Additional detailed recommendations are presented in Chapter 4.

Recommendations for Individual Physics Faculty

Individual physics faculty should improve their courses, using objective evidence to judge success. Faculty members should:

- Become knowledgeable about educational innovation in physics and the importance of active engagement of students in the learning process (see Box S.1).
- Engage colleagues in discussions of learning goals, measures of outcome, and strategies for a scientific approach to teaching and evaluating students' learning, and observe successful approaches to engagement in classroom settings.
- Review and modify courses to reflect the needs of different segments of the student community, including those who might succeed in physics with some additional or different types of help.
- Assess the knowledge, skills, and attitudes of students by using research-based instruments and methods.
- Engage students in a discussion of why and how evidence-based methods that engender effective learning require changing the teaching and learning processes.

Recommendations for Physics Department Leadership

Department leadership should create a culture of continuous improvement in which educational innovation is encouraged, sustained when it succeeds, and tolerated when it fails. Departmental leaders should:

- Discuss and consider how to implement physics-specific learning goals, recognizing the needs of varying student constituencies, the needs of future employers and teachers of these students, and the views of alumni.
- Establish collective responsibility and a commitment to incremental improvement, based on research on programs and courses.
- Provide and participate in professional development opportunities for faculty.
- Provide leadership to implement and support reforms.

Recommendations for Higher-Level Academic Administrators

Academic leadership should encourage faculty groups to seek improvement and should reward faculty and departments that are successful at implementing positive changes. Administrators should:

- Set the tone at the top.
- Establish a teaching and learning group or unit to advise and support faculty engaged in pedagogical improvements.
- Provide incentive funding to faculty who wish to implement evidence-based pedagogical improvements.
- Support faculty who conduct discipline-based education research and the establishment of faculty lines and/or interdisciplinary units to help develop the growth of education research in university science, technology, engineering, and mathematics (STEM) departments.
- Include, for all faculty who teach, education research and development among the factors considered in reward structures, not just for those faculty who conduct discipline-based education research.

Recommendations for Funding Agencies

Funding agencies should support positive change at all levels and should support fundamental educational research, development, adoption, and dissemination. More specifically, agencies should:

- Support a balanced portfolio that includes dissemination of good practices as well as applied and foundational education research.
- Educate principal investigators in all areas of physics research about how PER methods and PER-based materials can help them build a relevant educational component for their research projects so that they have a broader impact on the formal or informal education of broad and diverse populations of learners.

- Support development, validation, and implementation of new assessment instruments and provide standards for their interpretation.
- Promote dissemination strategies and research on such strategies that more effectively help faculty and departments incorporate the results of education research into their courses.
- Support research into the impact of instructional improvements on students from groups underrepresented in physics and the impact on capable students who choose not to pursue physics.

Recommendations for Education Researchers

Physics (and other) education researchers should focus some of their efforts on critical areas, including improving fundamental understanding of learning and instruction, and developing and disseminating improved assessment tools and instructional methods and materials. Researchers should:

- Develop assessments to include all components of expert physics learning, including physics reasoning, problem solving, experimental practices, effective study habits and attitudes, and other capabilities important for a good education.
- Develop and disseminate homework and exam problems that require and assess desirable skills.
- Study what makes effective teaching assistants and learning assistants and provide guidance for those preparing and training them.
- Apply physics education research more extensively to upper-division courses.
- Continue and expand research on the impact of research-based instructional improvements on underrepresented groups and on students who are capable but now drop out of physics.
- Continue research efforts that develop a foundational knowledge base for physics education.

Recommendations for Professional Societies

Professional societies should emphasize the importance of education research and play a major role in the dissemination of its results, recognizing those who successfully improve instruction. Professional societies should:

- Publicize the results and endorse the importance of educational developments.
- Collect, review, and make available Web-based resources for individual faculty.

- Convene community leaders and practitioners on a regular basis to discuss and share implementation of better practices.
- Publish physics education research in the general physics journals (e.g., *Physical Review Letters* and *Reviews of Modern Physics*) and review in society journals other types of teaching-learning applications in addition to textbooks.
- Expand at meetings the presence of sessions on educational innovations and practices.
- Help guide students' expectations and improve students' understanding of pedagogical improvements.

We must all act, and now! In the words of Johann Wolfgang von Goethe: "Knowing is not enough; we must apply. Willing is not enough; we must do."

1

Introduction: Physics Is Amazing and Practical and Must Be Taught Better

Physics is the curiosity-driven study of the inanimate natural world at a very fundamental level that extends across all nature—from the extremes of empty space itself, time, light, energy, elementary particles, and atoms through many orders of magnitude to stars, galaxies, and the structure and fate of the universe. At all levels it shares the objective of a deep conceptual and mathematical understanding. Physics is widely appreciated for the beauty of its concepts, but it is valued for its immense range of predictive power and life-improving applications.

People's overall economic well-being is roughly measured by gross domestic product (GDP) per person. Amazingly, this index was essentially flat from Egyptian times up to the mid-18th century (Hansen and Prescott, 2002). Since then, GDP per person has increased 20-fold in the United States and other "first world" countries where circumstances allowed innovators to apply knowledge originating in various subfields of physics to societal problems. From this perspective one sees that successive revolutions in fundamental physics have been tightly interconnected with technological advances that have each substantially improved our lives:

- *Newtonian mechanics*—Industrial revolution based on engineered machines;
- *Thermodynamics*—Steam engines to power machines, railroads, steamboats;
- *Electricity and magnetism*—Electrical power distribution system, motors, lights, telegraphs, electronics;
- *Quantum mechanics*—Lasers, atomic clocks, chemistry;
- *Nuclear*—Atomic energy, medical diagnosis and treatments;

- *Condensed matter physics*—Transistors and integrated circuits, computers, fiber optics, materials like liquid crystals (e.g., liquid-crystal displays), polymers, superconducting technology and materials; and
- *Modern physics research*—Mining large data sets, the World Wide Web.

This vast amount of understanding resulted from a new way of thinking about natural phenomena—the scientific method—in which hypotheses are expressed in a precise, generally mathematical, form that enables exact predictions; then testing these hypotheses and generally exploring nature with insightful and precise experiments; and then refining those hypotheses or, when merited, replacing them with new ones. Among the fruits of this process is the ability to make models of natural processes that predict the behavior of things in advance, e.g., the number of looms that can be powered by a particular waterfall, the effect of cross-connections on a polymer or a highway system, the takeoff speed of an airplane, and so on.

The beauty of this intellectual approach and its remarkable cornucopia of insights, knowledge, and applications has captured the imaginations of people for centuries and attracted them to study, research, and develop applications in physics.

Some undergraduates are attracted to take and major in physics by the beauty of its intellectual approach and finesse of the related experiments and apparatus. However, many more take physics as a required course in another major's curriculum because of the foundational role it plays in developing an understanding for other branches of science and engineering. In fact, only slightly more than 1 percent of students who take an introductory physics course end up obtaining an undergraduate degree in physics.

Too often, introductory physics has been cast as a subject that only a tiny elite could truly master. As a result, many students have viewed it as too difficult or unpleasant, and so have chosen not to pursue physics and other STEM majors. This has detrimentally affected not only the health of undergraduate physics and other STEM programs, but also the intellectual health of the nation.

Currently undergraduate physics education is especially challenged by financial constraints and by limited success in appealing to many of the demographic groups that represent an increasing fraction of today's incoming students and in providing enough physics teachers for high schools. Addressing these challenges requires that the physics community take a close look at the issues related to undergraduate physics education and pursue paths that can lead to improved student understanding of physics, reasoning skills, and attitudes toward physics. As shown in this report, recent developments in physics education research, computer-based instruction, and social networking can guide undergraduate physics education to more positive outcomes.

UNDERGRADUATE PHYSICS EDUCATION IN A RAPIDLY CHANGING WORLD

Higher education is beset by change on many fronts: changes in the student populations, transformations in societal needs, financial pressures, and technologies that enhance and threaten to replace the college and its classrooms. Higher education must prepare students for a world in which intelligent systems allow anyone to find even arcane bits of knowledge, which greatly reduces the value of knowing a large number of detailed facts. Robots and intelligent programs make possession of specialized information and skills less valuable and have reduced the number of routine, middle-skilled jobs, as well as some jobs thought to be immune from automation, such as librarians, lawyers, and, potentially, teachers. In addition to providing the basic scientific competency in physical sciences that is needed in many professions (AAMC-HHMI, 2009), higher education must prepare its graduates to do nonroutine highly skilled work that

> . . . cannot be reduced to an algorithm that is programmed into a computer or robot, or easily digitized and outsourced abroad. These jobs involve critical thinking and reasoning, abstract analytical skills, imagination, judgment, creativity, and often mathematics. They require the ability to read a situation, to extrapolate from it, and to create something new—a new product, a new insight, a new service, a new investment, a new way of doing old things, or new things to do in new ways in an existing company. (Friedman and Mandelbaum, 2011, p. 75)

While Friedman and Mandelbaum discuss the abilities needed for employment, these aptitudes are essential if future citizens are to function effectively and to make intelligent decisions about many aspects of life in a contemporary democratic society. Today, higher education must prepare graduates for an international arena in which being competitive requires the ability to learn new things, understand complex systems, manage large sets of data, think creatively and critically, communicate, and collaborate. As a discipline, physics has much to contribute, not only for the subject matter—the phenomena, concepts, and theories—but also for the disciplinary practices of empirical and theoretical inquiry. As emphasized earlier, the former are of foundational importance across all of science and engineering, while the latter are non-routine skills of critical importance in our constantly changing modern society.

In STEM fields especially, these developments are forcing faculty to rethink their roles as teachers and researchers. They must understand pedagogical advances, identify the needs of current-day students, and effectively employ new technologies in all aspects of their professional lives. Higher-education faculty must also understand the developments in distance learning, respond to external and internal financial pressures, and above all, they must continually reevaluate their role in educating a diverse citizenry and its future teachers.

Recent research in physics education and cognitive studies has revealed far more about the way humans learn physics than was known in the past. The ability to mine data about detailed student performance and habits, conduct relatively clean learning experiments in online environments, and process educational research data much more comprehensively could accelerate this educational understanding. This knowledge can potentially enable the physics community to constructively address the many new pressures on it and to better help students enjoy the excitement of learning physics and its methods. However, doing so will require that physics faculty become more aware of these developments and be willing to adopt them.

The lecture-recitation-laboratory approach to physics education was developed more than a century ago, when the student body was far more uniform than today and the opportunities for students to learn using technology and via experiences outside college were virtually nonexistent. Physics education will clearly need to adapt and change in response to changes in the students and their experiences on the one hand, and advances in the understanding of learning on the other. Together, this will require changes that are foreign to most faculty members' experience and will challenge institutional inertia. At the same time, social, economic, and governmental forces are transforming the environment in ways that are relentless, unavoidable, and not always welcome.

The need for the physics community to engage the many challenges facing undergraduate physics education and to solve them using a research-based approach that generates sustainable improvement is the driving force for this report.

Technology—Engine of Change

Disruptive applications of technology to education offer both enhancements and challenges to traditional ways of teaching, especially by offering novel learning experiences that are inexpensive and scalable. As discussed in Chapter 2, online simulations can supplement or even replace traditional laboratories, and online homework tutorial systems such as MasteringPhysics.com or Andes.org have replaced graded homework. Currently, both commercial organizations (Coursera and Udacity) and a consortium of universities (edX) offer free online introductory physics courses, which can ultimately be accompanied by a verified certificate of completion. Additionally, new approaches to educational data mining and online intelligent tutors show promise for providing assessments of student learning habits and their relationship to their future rate of learning (Baker et al., 2011). The combination of educational data mining with various types of complete online learning environments offers an unprecedented opportunity to study and improve free online learning and to blend it with on-campus learning.

Building communities of practice or interest is a key component of these new learning environments for both students and teachers. Such communities can exist both in the moment (e.g., skyping together three students puzzled by the same question) and as permanent means of support (e.g., teachers in different small departments teaching the same course). While communities of 40 years ago were often limited to individuals in our classes or on our campuses, communities of learners today transcend boundaries of geography, culture, and language. At the same time, these communities often form around interest rather than being constrained by geographic lines. Research has demonstrated that interactions (student-to-student, student-to-teacher, student-to-content, and so on) are important to learning and are critical to addressing learning disparities and underrepresentation, and so these interactions must remain an integral part of even the most technologically advanced learning environment (Seymour, 1995; Seymour and Hewitt, 1995; Springer et al., 1999; Brahmia and Etkina, 2001).

Economic Forces

Over the past dozen years, the United States has endured two major economic downturns. For public higher education, these economic pressures have resulted in major decreases in public support, with the net effect often being the transfer of more of the cost of education to students. These pressures have also resulted in significant cost cutting, which has often affected physics departments directly. In private higher education, the rapid increase of tuition above the rate of inflation has compelled many institutions to lower their standards of admission in order to find paying students and to rely increasingly on adjunct faculty to provide instruction. Many of these factors have combined to push college loan debt to more than 1 trillion dollars,[1] where it raises general concern, especially in the face of the inability of many recent college graduates to find well-paying jobs.

The deterioration of U.S. investment in undergraduate STEM education and the resultant anticipated damage to the national economy have been well documented in other studies, such as *Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future* (NAS-NAE-IOM, 2007); its sequel, *Rising Above the Gathering Storm Revisited: Rapidly Approaching Category 5* (NAS-NAE-IOM, 2010); and *Engage to Excel: Producing One Million Additional College Graduates with Degrees in Science, Technology, Engineering, and Mathematics* (PCAST, 2012). These studies document that the other large and growing economies (for example, those of Brazil, Russia, India, and China) have chosen to increase investment in higher education—especially in science and engineering—while the

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[1] See FinAid Page, LLC, "Student Loan Debt Clock," available at http://www.finaid.org/loans/studentloandebtclock.phtml.

United States has chosen to reduce these investments. Thomas Friedman's series of books—from *The World Is Flat: A Brief History of the Twenty-First Century* (Friedman, 2005) to *That Used to Be Us: How America Fell Behind in the World It Invented and How We Can Come Back* (Friedman and Mandelbaum, 2010)—have brought this disastrous situation to the attention of a wide public audience.

To address these challenges the report by the President's Council of Advisors on Science and Technology (PCAST), *Engage to Excel,* advocates an increase of 1 million STEM graduates over the next decade. The report notes that "increasing the retention of STEM majors from 40 to 50 percent would, alone, generate three quarters" of this target (PCAST, 2012, p. 5). This retention goal must be achieved for physics majors, of course, but even more important is that introductory physics is required of nearly all STEM majors. Therefore, many of the students who drop the course or fail it are forced to abandon their dream of a STEM career. Increasing the retention rate while maintaining a quality education for future physicists and other STEM majors is a necessity for our nation.

The risk inherent in the economic pressures of declining state resources was illustrated by policy changes in Texas in the Fall of 2011. The Texas Higher Education Coordinating Board decided to close physics programs with fewer than 25 majors graduating in the past 5 years (Matthews, 2011; Luzer, 2011). An express motivation was to increase STEM graduates by diverting students, and ultimately resources, away from inefficient and inequitable programs, which happened to include many physics programs. According to the American Physical Society, if such a policy was applied nationwide, it would close more than 60 percent of all physics departments nationally—forcing the closure of 174 physics programs in public institutions alone. Of particular concern, implementation of this criterion would terminate the physics programs of all but 2 of the 34 historically black colleges and universities, causing a huge impact on the diversity of the physics community (Hodapp, 2011).

The committee notes, in passing, that the research enterprise as practiced in the large research universities is also feeling the pressure of state cutbacks and draconian cuts to federally funded research. As the American Institute of Physics (AIP) reported in 2011, "the President's Council of Advisors on Science and Technology (PCAST) met to hear from experts about the future of research endeavors in the United States. To open the meeting, PCAST Co-Chair John Holdren noted that fiscal restraints created by the difficult budget environment will make it harder to make the investments necessary in science and technology to maintain American dominance in these fields" (Kronig, 2011).

This situation places physics higher education in a dilemma: the urgent need to become more effective (in terms of learning and retention for both physics majors and other students served by physics educators) without additional resources to enable that change. Thus, the physics community needs to make bold changes in direction that are needed to ensure the opportunity to thrive in the coming decades and to educate the next generations who will maintain a strong global science- and technology-based economy. Dramatic advances to be made at unpropitious times are not unprecedented in U.S. history. For example, at the height of the Civil War in 1862, President Lincoln signed the Morrill Act to create the land grant colleges, which have since developed into most of the flagship and other highly respected public universities.

Is the physics community prepared to respond in a way that can forestall national decline? Doing a much better job teaching the students that it touches is a crucial aspect of an adequate response. These students include both future physics majors and those who will enroll in a physics course while they concentrate in other fields.

Changing the Educational Paradigm

Traditional undergraduate physics education, as practiced in much of the 20th century, centered on teaching facts and procedures using the lecture-recitation-laboratory format to a student body largely made up of white males. The preeminent goal now is to educate students in what are sometimes called 21st-century skills—things like self-learning, complex problem solving, critical thinking, and collaboration. Moreover, the students who must learn these skills today are representative of current U.S. demographics, not the select group of the past century. Obviously, the traditional educational paradigm for teaching undergraduate physics must change.

For much of the 20th century, physics was crucial to national defense, the value of physics was accepted by most college students, and introductory physics was often used as a filter to select the most desirable physics majors. Times change: The Union of Soviet Socialist Republics became the former Soviet Union, the accolade “nuclear physicist” for a smart person was replaced by “rocket scientist,” and even experimental physicists can no longer repair their automobiles. Yet physics has maintained its selectivity and, over the 40-year period from 1965 to 2005 (see Figure 2.1), has limited itself to a 20 percent growth in numbers of majors, while STEM majors overall have increased 200 percent. For many of the institutions where physics is now taught, maintaining physics as a viable undergraduate major requires that introductory physics courses attract more students to physics. For the good of the country, introductory physics must also help to attract more majors to STEM and other majors for which it is a required course. This is particularly true with respect to women and minorities—a demographic that now comprises around 73 percent of college students.[2] In fact, the declining fraction of college

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[2] According to the National Center for Education Statistics, in 2010 slightly more than 21 million students were enrolled in degree-granting institutions, and approximately 5.6 million of them were white males. Digest of Education Statistics 2011, Table 238. Available at http://nces.ed.gov/pubs2012/2012001.pdf.

students majoring in physics these days is largely a reflection of the fact that only a very small fraction of these demographics are attracted to the physics profession. While many factors are at play, at least part of the reason why more students from these demographics chose not to pursue physics is that they fail to see the excitement and joy that physicists feel in the process of studying, experimenting with, and understanding the natural world, seeing only the drudgery of performing well on the next test (Krogh and Thomsen, 2005; Sharp, 2004; Scott and Martin, 2012). Students do not realize that appreciation of a sunset or a rainbow can be enhanced by the explanation that physics provides for these phenomena. They do not realize that a wide range of everyday devices—from an MRI to the scanner at the grocery store—depend critically on the discoveries of physics, as do many branches of science and engineering. While recognizing that many of the students taught in introductory physics courses have specific physics knowledge goals that must be met, those teaching such courses also should engage students in thinking about physics in a broader context. Rather than simply memorizing answers for the next test, they should be puzzling about some of the profound and unanswered questions currently being addressed in physics, such as dark matter or relativity. Some work (Treisman, 1992; Brahmia, 2008; Beichner, 2008) has demonstrated that innovations that increase student engagement, whether pedagogical or technological, are critical to all students and particularly important to retention of students from underrepresented populations.

Over the past few decades, research in physics education and cognitive science has helped to increase understanding and inform the process of learning and teaching physics. In particular, physics education researchers—an interdisciplinary community centered predominantly in departments of physics—have been engaged in complementary efforts to understand how students learn physics and how to use that knowledge to improve physics teaching and learning. Much of this knowledge has been translated into practices with demonstrated improvements in student learning. (See Chapter 3.) The physics education community has also learned that the widely used lecture-based classroom instruction is not nearly as effective in teaching students or creating positive attitudes toward physics as many have assumed. Discovering the limits of the lecture-based paradigm of instruction ironically coincides with a growing collection of excellent lectures delivered by prestigious lecturers for free over the Internet. They may render the traditional large university lecture classes obsolete more quickly than the discoveries of learning theory. Much more needs to be learned, but researchers are beginning to understand why some practices are more effective than others. While some undergraduate physics educators have responded to this new flow of information, ideas, and technologies, the community of physicists is in an early stage as a formal discipline of both research in physics education and the application of its results.

An overarching theme has emerged from educational research: *Learning improves when students are interactively engaged with their peers, their instructors, and the material being learned, and when they are integrating the newly learned concepts with their previous ideas, whether learned in a formal classroom or in everyday life.* While this statement does not sound revolutionary, it does emphasize that success in learning is more strongly determined by how successfully and frequently students are engaged in the learning experience than by the content knowledge or the delivery skill of the instructor. This research finding does not devalue an instructor's role, but it indicates the most accessible path to improving effectiveness.

To address these findings, some physics education researchers have focused on the creation of new instructional tools that can be incorporated into conventional course structures and then learning outcomes with these new tools are measured. These efforts include student response systems (or "clickers") that can help make lectures interactive; interactive small group activities based on research about specific conceptual difficulties; structured collaborative group work; undergraduate peer instructors or "learning assistants"; computer-based laboratory instruments and software to facilitate real-time data collection and analysis; and Web-based systems for simulations, class preparation, lectures, and homework. Other physics education researchers have focused on wholesale course redesign, creating unified in-class activities where students work together to make sense of concepts, problems, and experimental phenomena rather than maintaining the traditional separation of lecture, recitation, and laboratories.

These new tools and courses, some of which are described in Chapters 2 and 3, have been evaluated and refined through extensive research in a large number of undergraduate classes. As this report documents, they show evidence of significant gains in student learning, in particular with respect to conceptual understanding. Further, evidence indicates that retention of majors increases when students are involved in active engagement during the beginnings of their undergraduate careers (PCAST, 2012, p. 8). In these ways, physics education research has provided guidance for significant, near-term improvement of physics instruction.

THEMES

During the committee's extended deliberations, five basic themes recurred frequently. These themes, discussed briefly above, permeate this report. They and their components are listed below, along with some comments on where in this volume they are discussed further.

Physics Is Fundamental and Foundational

Undergraduate physics education provides students with unique skills and ways of thinking that are of profound value to themselves and to society.

a. Physics explores and answers the most fundamental of questions: the origin of the universe, the nature of matter and energy, and symmetries and laws that shape everything. It provides a framework and discipline for probing these questions whose range of applicability extends far beyond the physical sciences.
b. Physics students learn to develop conceptual and mathematical approaches to models to help them understand complicated systems and solve complex problems. As a result of learning the inquiry process and ways of thinking used in physics, students with a physics education are prepared for success in complex analytical professional programs such as medicine, business, finance, and law.
c. Physics is concerned with topics that underlie most other branches of science and engineering, and it is relevant to current societal concerns such as energy, nanotechnology, and national security.

These ideas are discussed above, and in Chapter 2.

Systemic Tensions

The familiar college environment in which physics is currently taught is threatened by powerful, rapidly changing external forces, and U.S. physics departments will either adapt and improve or fade.

a. Although many students (~500,000/year) study introductory physics, only about 1 percent end up with physics degrees. At many institutions, the number of majors is so low that it invites merging of the physics department with other science departments.
b. Electronic communication and networking technologies are transforming, in both positive and negative ways, all educational institutions and programs, including physics.
c. Economic realities are pressing undergraduate physics education (and all of higher education) to achieve reduced costs and improved outcomes.
d. Universities and colleges, including their physics departments, have generally been slow to make changes that adequately respond to these challenges.

These dangers are both internal and external and must be addressed by physicists and by all involved in undergraduate education. Some of these dangers have been discussed in this chapter; others will be included in the discussion of the present landscape in undergraduate physics education, Chapter 2.

Major Challenges

Current practices in undergraduate physics education do not serve most students well.

a. Important groups remain underserved by the current paradigm (women, underrepresented minorities, prospective high school teachers).
b. As evidenced by pre- and post-testing, most students taking introductory physics do not gain a genuine understanding of the concepts, practices of inquiry, or mental habits used in the discipline.
c. Improvements are needed in the initial and subsequent professional training provided to physics teachers, particularly those teaching in K-12.
d. Impediments to needed change include economic constraints, traditional academic cultures, and institutional structures.
e. The subject matter and skills that undergraduates study have remained largely static for more than 50 years. Students learn little about current discoveries and research, which they might find exciting or relevant to their lives.

This theme is discussed primarily in Chapter 2, which looks at the present landscape of undergraduate physics education and issues that have been raised by the changing content of physics, the nature of 21st-century students, and the skills needed by those students for addressing modern societal issues.

Improvements Exist

Substantial improvements in undergraduate physics education have been made with existing knowledge and resources in a variety of contexts; encouraging and preserving these gains requires a symphony of efforts by many different participants, and improving on them requires continuing research and development.

a. Novel curricula, materials, and approaches to instruction exist that have demonstrated improved results, not only in students' conceptual and quantitative knowledge of physics, but also in their ability to engage in scientific inquiry.

b. Some physics departments have demonstrated how to be attentive to their student communities, attract more students to physics, retain them through the major, and support them in a variety of career aspirations.
c. There is a substantial and growing research base on which institutions can draw to improve educational practices.
d. Implementing change will require concerted efforts at a range of levels, from individual physics faculty and departments to top administrative levels in universities, state and federal governmental agencies, research funding sources, and professional associations.

These points are elaborated in Chapter 3.

Scientific Approach to Physics Education

Future improvement of undergraduate physics education depends critically on a vigorous physics education research enterprise and effective application of its findings.

a. Physics education research has emerged relatively recently as an important element of the broader academic exploration of the science of teaching and learning.
b. Physics education research has yielded findings that are being applied in the development of better educational practices in some institutions and that could be more universally adopted.
c. Education research in physics is a rapidly growing field and is still finding answers to important questions about learning and pedagogy. Physics education research needs systemic support to fuel future improvements in education.

Chapter 3 gives a short review of physics education research and some of its applications to undergraduate physics education. This research provides a foundation on which to build the next generation of undergraduate physics education programs. Chapter 4 concludes with suggestions and recommendations about future directions for undergraduate physics education.

CONCLUDING THOUGHTS

The committee's judgment is that substantial improvement of undergraduate physics education will benefit the physics community, students, and our nation and must be undertaken because of the many challenges facing physics education today. Fortunately, physics educators have learned and continue to benefit from a robust and growing physics education research literature and community. The insights gained through this scholarship, and through an increasingly sophisticated set of assessments, allow evidence-based decisions on improving undergraduate education. Furthermore, information technology, although just beginning to touch physics education in profound ways, has the potential to significantly improve the way students engage with and learn physics on both large and small scales. The committee emphasizes that physicists and physics departments live in a broader community that, if ignored, will bypass physics to find solutions to important contemporary problems that are partially physicists' responsibility to help address. Included in this list are the effective preparation of high school physics teachers and the education of a workforce whose competence requires critical thinking, abstract analytical skills, and some knowledge of how physics relates to what they are doing. If the solutions developed without the physics community's involvement are of low quality, then the community will be partially to blame.

Finally, student perceptions, attitudes, social networks, and the environment in which they develop have changed profoundly over the last several decades, and the U.S. population is increasingly diverse in ethnicity and socioeconomic class. Failing to understand and address today's nontraditional students threatens to undermine our effectiveness in preparing scientists and a science-literate population for the coming generations.

The committee recognizes the difficulty of implementing change in the current environment of financial pressure and diminishing support for the physics enterprise. At research universities the intense pressure for research productivity leaves the faculty member with difficult choices about how to devote time and effort, and at many other institutions the requirement to teach several courses simultaneously prevents devoting efforts to implementing even established reforms in some of them. Often individual faculty members have little motivation to consider improvements in the teaching environment while their departments are faced with pressures to increase "efficiency" in order to save institutional resources. The committee also recognizes the historical inertia that leads most to teach as they were taught and to view with caution any proposed changes that require substantial effort. However, in spite of these issues the committee believes that our community can improve the undergraduate physics experience and that our community must make appropriate changes before it is coerced by outside forces. Thus, this report strongly encourages faculty, departments, administrators, funding agencies, and professional societies to take a scientific approach to our own practice and to inform themselves of the research and development that can help the physics community make measurable and desirable improvements in undergraduate physics education.

REFERENCES

AAMC- HHMI (Association of American Medical Colleges-Howard Hughes Medical Institute). 2009. *Scientific Foundations for Future Physicians*. Washington, D.C.

Baker, R., Gowda, S., and Corbett, A. 2011. Automatically detecting a student's preparation for future learning: Help use is key. Pp. 179-188 in *Educational Data Mining Conference Proceedings 2011*. Available at http://educationaldatamining.org/EDM2011/wp-content/uploads/proc/edm11_proceedings.pdf; accessed on April 23, 2013.

Beichner, R.J. 2008. "The SCALE-UP Project: A Student-Centered Active Learning Environment for Undergraduate Programs." Paper commissioned for Evidence on Promising Practices in Undergraduate Science, Technology, Engineering, and Mathematics (STEM) Education Workshop 2, October 13-14. Available at http://www7.nationalacademies.org/bose/Beichner_CommissionedPaper.pdf.

Brahmia, S. 2008. Improving learning for underrepresented groups in physics for engineering majors. PER Conference Invited Paper. Pp. 7-10 in *2008 Physics Education Research Conference*. AIP Conference Proceedings 1064. Available at http://www.compadre.org/Repository/document/ServeFile.cfm?ID=7981&DocID=698; accessed on February 19, 2013.

Brahmia, S., and Etkina, E. 2001. "Emphasizing the Social Aspects of Learning to Foster Success of Students at Risk." Paper presented at the Research at the Interface, 2001 Physics Education Research Conference, Rochester, N.Y., July 25-26, 2001. Available at http://www.compadre.org/per/items/detail.cfm?ID=4382; accessed on April 23, 2013.

Friedman, T.L. 2005. *The World Is Flat: A Brief History of the Twenty-First Century*. New York: Farrar, Straus and Giroux.

Friedman, T.L., and Mandelbaum, M. 2011. *That Used to Be Us: How America Fell Behind in the World It Invented and How We Can Come Back*. New York: Farrar, Straus and Giroux.

Hansen, G.D., and Prescott, E.C. 2002. Malthus to Solow. *The American Economic Review* Sept.:1205-1217.

Hodapp, T. 2011. The economics of education: Closing undergraduate physics programs. *APS News* 20(11):8. Available at http://www.aps.org/publications/apsnews/201112/backpage.cfm.

Krogh, L.B., and Thomsen, P. 2005. Studying students' attitudes towards science from a cultural perspective but with a quantitative methodology: Border crossing into the physics classroom. *International Journal of Science Education* 27:281-302.

Kronig, D.A. 2011. PCAST examines future of scientific research in U.S. *FYI: The AIP Bulletin of Science Policy News* 93, July 21. Available at http://www.aip.org/fyi/2011/093.html.

Luzer, D. 2011. Physics as a luxury. *Washington Monthly*, September 28. Available at http://www.washingtonmonthly.com/college_guide/blog/physics_as_a_luxury.php.

Matthews, J.N.A. 2011. Texas cuts 'low-producing' physics programs. *Physics Today* 64:31. Available at http://www.physicstoday.org/resource/1/phtoad/v64/i12/p31_s1.

NAS-NAE-IOM (National Academy of Sciences, National Academy of Engineering, Institute of Medicine). 2007. *Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future.* Washington, D.C.: The National Academies Press.

NAS-NAE-IOM. 2010. *Rising Above the Gathering Storm, Revisited: Rapidly Approaching Category 5*. Washington, D.C.: The National Academies Press.

PCAST (President's Council of Advisors on Science and Technology). 2012. *Engage to Excel: Producing One Million Additional College Graduates with Degrees in Science, Technology, Engineering, and Mathematics*. Washington, D.C.: Executive Office of the President. Available at http://www.whitehouse.gov/ostp/pcast.

Scott, A.L., and Martin, A. 2012. *Dissecting the Data 2012: Examining STEM Opportunities and Outcomes for Underrepresented Students in California*. San Francisco, Calif.: Level Playing Field Institute. Available at http://toped.svefoundation.org/wp-content/uploads/2012/04/Achieve-LPFIstudy032812.pdf.

Seymour, E. 1995. The loss of women from science, mathematics, and engineering undergraduate majors: An explanatory account. *Science Education* 79:437-473.

Seymour, E., and Hewitt, N. 1995. *Talking About Leaving: Why Undergraduates Leave the Sciences*. Boulder, Colo.: Westview Press.

Sharp, G. 2004. A Longitudinal Study Investigating Pupil Attitudes Towards Their Science Learning Experiences from a Gender Perspective. Unpublished Ph.D. thesis. Milton Keynes, Open University.

Springer, L., Stanne, M.E., and Donovan, S.S. 1999. Effects of small-group learning on undergraduates in science, mathematics, engineering, and technology: A meta-analysis. *Review of Educational Research* 69:21-51.

Treisman, U. 1992. Studying students studying calculus: A look at the lives of minority mathematics students in college (the Mary P. Dolciana Lecture). *The College Mathematics Journal* 23:362-372. Available at http://www.utpa.edu/avid/Documents/Research/Studying_Students_Studying_Calculus_A_Look_at_the_lives_of_minority_mathematics_students_in_college.pdf.

2

The Current Status of Undergraduate Physics Education

The first step in improving undergraduate physics education is understanding the landscape in which the subject is being taught. Among the external forces that are shaping higher education, some offer opportunities not available even a few short years ago, while others constrain possibilities that could spur innovation. Internal factors associated with curriculum, instructional practices, and diversity also help define the challenges the physics community faces in trying to achieve widespread and sustained improvement in undergraduate physics education. This chapter surveys the landscape, identifying areas of concern, sources for optimism, and strategies worth supporting.

Among the most predominant characteristics of the landscape is the existence of change. Classes have gotten bigger, student demographics have shifted, and technology is transforming the way students communicate with each other and with educators. Strong economic pressures are bearing down on educational institutions such that discussions about "value added assessment" and "accountability," which have had a significant impact on K-12 public education, are now affecting post-secondary education as well.

Change is also taking place in the way that undergraduate physics is taught. In recent decades, researchers, many of them physicists, have been engaged in efforts to understand the processes of learning and teaching physics. Some of that knowledge has been translated into practices that have been demonstrated to have positive impacts on student learning. Other techniques have turned out to be not nearly as effective as may have been thought (or hoped).

The first section of this chapter, "The Students," addresses the most important part of the evolving landscape—the students themselves. This section can be thought of as the "who, where, and why" of undergraduate physics education, starting by reminding readers of the variety of reasons that students take undergraduate courses in physics. Basic data about enrollment trends are presented, including figures relevant for physics majors, groups that are traditionally underrepresented in science-based careers (women and certain minorities), and future K-12 teachers. These data set the stage for the discussions in the following section.

The second section, "The Educational Landscape," addresses the "what and how" of undergraduate physics education. It is the committee's judgment that the future of physics depends on undergraduate programs that maximize the effectiveness of instruction, educate students in both fundamental physics and contemporary topics, recruit and retain the most talented students from all segments of the population, and ensure that tomorrow's K-12 teachers can prepare tomorrow's K-12 students for the challenges of higher education. Meeting these challenges in turn relies on the existence of tools for gauging the extent to which changes produce the desired outcomes, and on physics faculty who are both equipped to engage in educational innovation and supported in doing so.

Throughout this chapter, recent national studies are drawn upon that have examined a particular aspect of physics education in depth, such as teacher preparation, the status of women and minorities in physics, or characteristics of thriving programs. A list of these studies and other resources can be found in Box 3.1.

THE STUDENTS

Undergraduate Education in General

Many of the changes taking place in undergraduate physics classrooms reflect more general transformations happening across higher education. The demographics of those enrolled in undergraduate institutions are shifting. Overall enrollment is increasing, as are the fraction of students who are part-time and the fraction who are over 25 years old.[1] These "nontraditional" students may have different experiences and expectations, and often they are seeking degrees while working and raising families and, thus, have very different constraints than the full-time, on-campus students that many of us think of as the norm.

The fraction of students from ethnic minorities is also increasing, especially at two-year colleges (TYCs). According to a recent study, "these large percentage enrollments among underrepresented students mirror the ethnic populations in the geographic communities of the two-year colleges" (Monroe et al., 2005, p. 60).

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[1] See National Center for Education Statistics, "Fast Facts," available at http://nces.ed.gov/fastfacts/.

College-level education is increasingly being offered in environments not traditionally associated with undergraduate education. Almost one-third of all higher education students now take at least one course online (Sloan Consortium, 2011). Organizations that collect and disseminate "open educational resources" have grown out of the original "open courseware" movement. YouTube videos and online discussion forums offer students a wide range of learning opportunities that go beyond the curriculum offered by their instructors. Prestigious institutions are among those offering free "massive open online courses" (MOOCs). Online courses are of varying quality, but in some cases, test scores and student satisfaction are at levels equal to or greater than traditional learning environments (Lovett et al., 2008; Higher Education Funding Council for England, 2012; National Survey of Student Engagement, 2008). While distance education is hardly new, the rapid growth in the number of such courses being offered is forcing many educational institutions to look seriously for the first time at both the educational and financial implications.

College-level instruction is also increasingly common on high school campuses. The National Center for Education Statistics reported that in 2003 more than 800,000 students at public schools were enrolled in dual credit courses, including Advanced Placement (AP) physics courses, in which they earn college and high school credit simultaneously. About two-thirds of these students were taking the courses at a postsecondary institution, the others at a high school. As these numbers increase, the availability of highly qualified high school teachers becomes critical.

Undergraduate Physics Education

In any given academic year, about 500,000 students take an introductory undergraduate physics course somewhere in the United States. Of those, 20 percent are at a 2-year college (White, 2012). Students take introductory physics for a variety of reasons. Some are attracted to the beauty and power of physics, which may lead to a major or minor in the subject, often beginning with an honors-level introductory course. For students pursuing degrees in education, the arts, social sciences, or humanities, their interests may lead them to enroll in a nonquantitative physics course (as with titles like "physics for poets" or "physics for future presidents"). However, the majority of students take physics as a foundation for other sciences and engineering or as a foundation for training in the health sciences. The programs that require physics do so for a variety of reasons, but it is not strictly for the content of introductory courses. Equally valued (or, in some cases, more valued) is the sense that physics is where students can learn to appreciate the essence of building predictive models of the world, verifying them, and using them to model reality (Van Heuvelen, 1991; Greca and Moreira, 2002; NRC, 2003).

These goals and statistics are mentioned here because they are important to keep in mind when discussing the current status of physics education and future directions. In particular, only 3 percent of all undergraduates are enrolled in an undergraduate physics course at a given point in time;[2] of those, only a small percentage, slightly over 1 percent, end up with a physics degree. These numbers serve as a reminder that most students never take a physics course. Those who do have mostly practical reasons for doing so and stop as soon as they have fulfilled program requirements.

The diversity of students' motivations and interests and the range of mathematical skills they bring to the study of physics complicate the selection of goals and topics for any introductory course. The common practice is to emphasize a wide variety of topics that differ little between algebra- and calculus-based courses. This chapter later discusses a few innovative efforts that attempt to differentiate introductory courses—tailoring them to suit the needs of different groups of students, while preserving, or even increasing, the emphasis on the fundamental ways of reasoning about the world that characterize physics.

Segments of the Physics Student Population

Different subpopulations of physics students present different challenges for developing an effective strategy for improving undergraduate physics education. Some brief statistics are given below about three such groups—physics majors, students from populations that are traditionally underrepresented in science-based careers, and future K-12 teachers. Other groups of students, such as those who take physics courses to fulfill general education courses, are also important but are not the focus of this report.

Physics Majors

For many physics faculty, physics majors are seen as the principal means by which the field is perpetuated, and for many outsiders, the number of majors enrolled in a department is viewed as the principal means for measuring that department's vitality. Thus, despite the fact that they represent a very small fraction of the students who take physics courses, physics majors are crucial for the discipline. Three statistics are important to note. First, a large minority (~30 percent) of physics graduates earn degrees in departments that produce, on average, five or fewer majors per year. While local factors, such as institutional size and mission, help determine the "right" number of majors for a given department, as discussed in "Economic Forces" in Chapter 1, those departments perceived as having low

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[2] According to the National Center for Education Statistics, in 2010 slightly more than 21 million students were enrolled in degree-granting institutions (Digest of Education Statistics 2011, Table 238, available at http://nces.ed.gov/pubs2012/2012001.pdf).

enrollment may be vulnerable to cost-cutting measures that depend heavily on the number of majors.

Second, while the number of physics undergraduates has increased in the past decade, over the past 40 years that number has been relatively unchanged, in contrast to the number of graduates in all other science, technology, engineering, and math (STEM) disciplines (see Figure 2.1). The President's Council of Advisors on Science and Technology recently called for producing 1 million additional college graduates with STEM degrees to help retain U.S. preeminence in science and technology and to meet critical future workforce needs. In the committee's judgment, increasing the number of students holding physics degrees should be an important component of the response to that call (PCAST, 2012).

Third, as noted in "Future K-12 Teachers" below, only one-third of those teaching physics have a major in physics or physics education (Neuschatz et al., 2008). Increasing the number of physics majors has been called out as an important step in addressing this shortage (Mulvery et al., 2007).

The diversity of goals for students in introductory courses extends to physics majors as well. About 35 percent of those who obtain a bachelor's degree continue to graduate study in physics or astronomy, with another quarter entering graduate

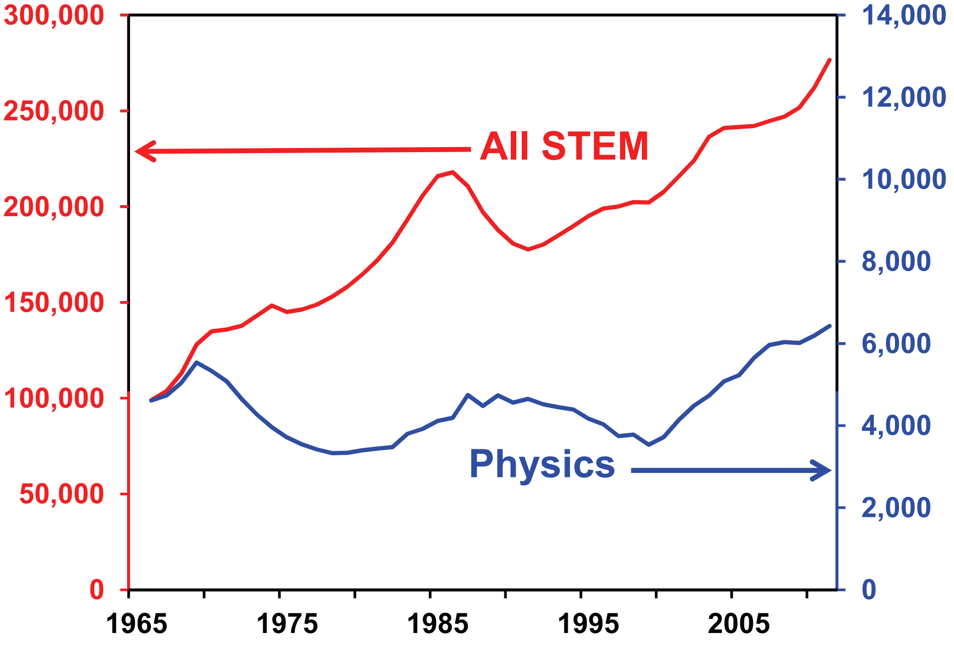

FIGURE 2.1 Annual graduates in all STEM fields and physics for the past 40 years. SOURCE: Data from the National Center for Education Statistics; graph from Ted Hodapp, American Physical Society.

studies in other areas, while another 35 percent enter the workforce upon graduation (Tesfaye and Mulvey, 2012)in a wide variety of careers (see Figure 2.2). These numbers have implications for the design of programs that prepare majors to succeed in a variety of endeavors. However, for those physics majors who will be responsible for teaching physics to future generations, the undergraduate courses they take should serve as models for how the subject should be taught. Later in this chapter, some strategies for taking these factors into account are mentioned.

Underrepresented Groups

There is a well-documented shortage of African American, Hispanic, Native American, and female workers in physical science- and math-based careers (Huang et al., 2000). The short supply of well-trained workers from diverse backgrounds can be traced to both the racial/ethnic and the gender representation gaps among STEM bachelor recipients (Chen and Thomas, 2009). Physics is an important

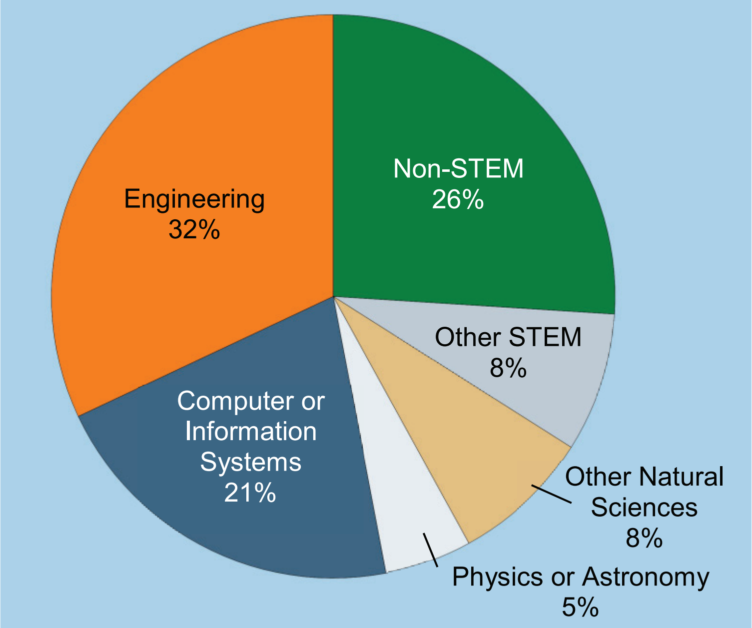

FIGURE 2.2 Field of initial employment for physics bachelor's in the private sector. STEM in this graph refers to positions in natural science, technology, engineering, and math. SOURCE: C.L. Tesfaye and P. Mulvey, Physics Bachelor's Initial Employment—Data from the Degree Recipient Follow-Up Survey for the Classes of 2009 and 2010, *Focus On,* September 2011, American Institute of Physics Statistical Research Center, Figure 3, available at http://www.aip.org/statistics/trends/reports/empinibs0910.pdf, accessed on September 20, 2012.

feeder discipline into STEM careers, yet U.S. colleges and universities are not producing a very diverse group of professional physicists.

The percentage of students from these demographic groups who take physics in college is disproportionately small when compared with the demographics of the population of students (Huang et al., 2000). Both females and underrepresented ethnic minorities are less likely to pick a physics-based major initially, and if they do, they are less likely to remain in that major (Chen and Thomas, 2009). Physics majors have the lowest percentile representation of African American, Hispanic, Native American, and female students in the liberal arts and science disciplines (Figure 2.3; Native American representation is so low that it is not visible on the scale shown).

The gender representation gap in physics initially appears late in high school. There is gender parity during the first high school physics course: female students are just as likely to take and successfully complete a high school physics course as their male counterparts. But a disproportionately small percentage elects to take the most challenging subsequent high school physics courses that prepare them for physics in college (White and Tesfaye, 2011a). This differential in course-taking during high school has been linked both to the gender representation gap and to a proportionally lower persistence rate of female students in STEM majors (Griffith, 2010; National Science Board, 2007).

Research suggests that the affective domain, which includes factors such as student motivation, attitudes, perceptions and values, can significantly enhance, inhibit, or even prevent student learning in the sciences (Simpson et al., 1994). These factors may partially account for female underrepresentation in physics. Although many physicists see their discipline as a fun-filled, curiosity-driven endeavor, college physics courses are sometimes characterized as unwelcoming, and the average course grades tend to be lower than in many other disciplines (Rojstaczer and March, 2010). In a large-sample, multiyear study conducted at Cornell University, researchers examined the effect of course grades and peer interactions on students' persistence in science. While the researchers saw no effect on the male students and the life science students, they found that these factors strongly influenced female students' persistence in physical science majors (Ost, 2010). Physics instructors and curriculum designers have experimented with the affective domain to improve student learning with some successes. We describe later in this chapter several programs that address the affective aspects of the physics classroom.

Just as there is no strong link between gender and mathematical ability, there is no support for a biologically based explanation of racial or ethnicity gaps in physics. There is strong evidence, however, that socioeconomic status accounts for much more variation in SAT scores than race and ethnicity does (White and Tesfaye, 2011b; Carnevale and Strohl, 2010). Given that high school math level is a predictor for success in college physics (Sadler and Tai, 2001), students from

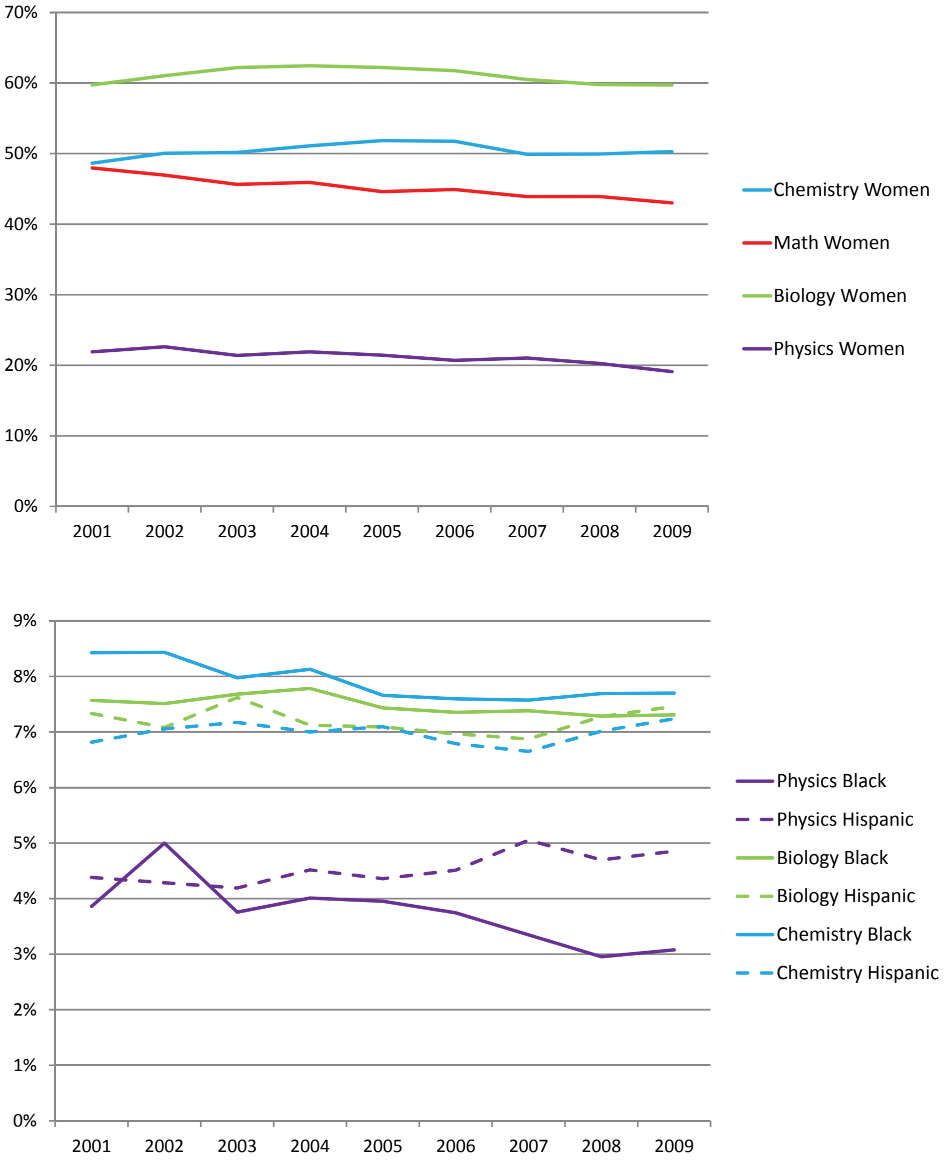

FIGURE 2.3 The percentage of the bachelor's degrees granted to women from 2001 to 2009 (*top*). The percentage of the bachelor's degrees granted to select underrepresented minorities from 2001 to 2009 (*bottom*). SOURCE: Data from National Science Foundation, "Women, Minorities, and Persons with Disabilities in Science and Engineering," National Center for Science and Engineering Statistics, available at http://www.nsf.gov/statistics/wmpd/tables.cfm; accessed on June 20, 2012. Graphs courtesy of Dean Zollman, Kansas State University.

economically disadvantaged backgrounds (and correspondingly weak college preparation) are understandably less inclined to choose a career path for which they feel they are not prepared. The racial/ethnicity gaps are related, at least in part, to a more fundamental problem—a gap in representation based on, and perpetuated by, poverty (Marder, 2012).

For those who do intend to pursue a STEM major, it is less likely that students from underrepresented groups will persist after the first year (Griffith, 2010). Institutional characteristics can influence persistence in STEM majors. It has been shown that STEM field students from underrepresented groups at selective institutions that have a large graduate-to-undergraduate student ratio and that devote a significant amount of spending to research have lower persistence rates than similar students at other institutions (Griffith, 2010). Thus, large research universities are less likely than smaller institutions to retain students from underrepresented groups in STEM majors.

Two-year colleges (TYCs) provide an opportunity to improve the racial and ethnic diversity of the physics student population. Nearly half of the African American college students and more than half of the Hispanic and Native American college students start at a community college (White, 2012). But the percentage of students at TYCs who take physics is still only a small fraction of the students who attend TYCs. Given the overrepresentation of ethnic and racial minority freshmen at TYCs, effective recruiting and educational transformations at TYCs may have the potential to increase the diversity in the STEM workforce. In addition, policies that encourage recruitment and eliminate barriers for potential transfers to 4-year institutions could be especially fruitful.

Similarly, recruitment and educational transformations at minority-majority 4-year institutions could provide an opportunity for decreasing the ethnic representation gap in physics. Some historically black colleges and universities (HBCUs) are already excellent models, because they produce about 45 percent of all African American B.S. physics graduates annually and about one-quarter of the African American Ph.D.s. Of the institutions that averaged the most African American B.S. physics graduates during 2004-2006, all are either an HBCU or a black serving institution (Mulvey and Nicholson, 2008). Successful programs at minority serving institutions can inform improvements to current programs at majority institutions, especially the large research universities.

Future K-12 Teachers

Undergraduate students who become teachers of physics or physical science in K-12 schools present both special opportunities and considerations. As shown in Figure 2.4, the percentage of students enrolled in physics at the high school level has essentially doubled since 1990.

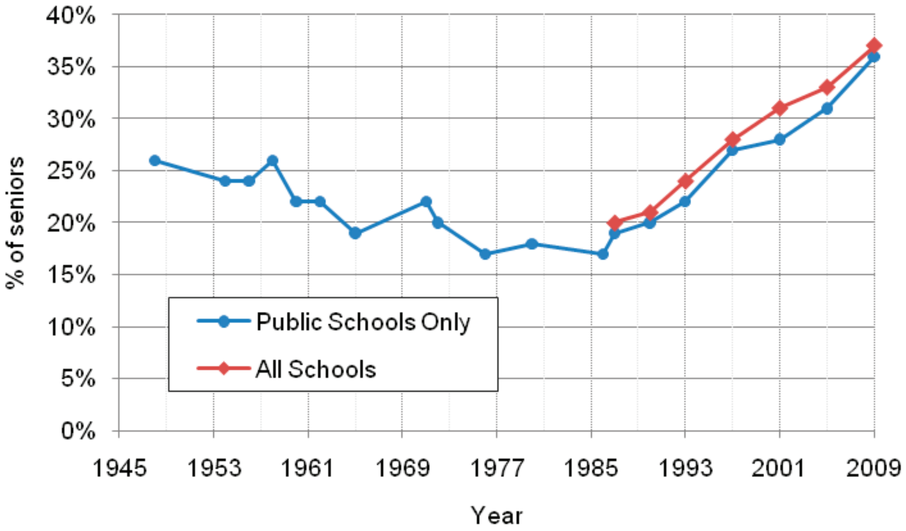

FIGURE 2.4 Enrollment as a function of time for high schools physics. SOURCE: S. White and C.L. Tesfaye, High School Physics Courses and Enrollments—Results from the 2008-09 Nationwide Survey of High School Physics Teachers, *Focus On,* August 2010, American Institute of Physics Statistical Research Center, Figure 1, available at http://www.aip.org/statistics/trends/reports/highschool3.pdf, accessed on June 19, 2012.

This trend is significant for two reasons. First, the production of high school physics teachers is not keeping pace with the growth in high school physics enrollment. In fact, physics teacher education programs throughout the United States are producing only about one-third of the number needed annually. According to the 2010 report of the National Task Force on Teacher Education in Physics, fewer than one-fourth of U.S. colleges and universities have graduated a student certified to teach physics in the past 2 years, and only a handful of institutions graduate more than one physics teacher per year on average: "Consequently, more students than ever before are taking physics from teachers who are inadequately prepared" (National Task Force on Teacher Education in Physics, 2013, p. xi). A recent AIP report shows that only one-third of those teaching physics have a major in physics or physics education (Neuschatz et al., 2008). Strategies at national and local levels to improve this situation are discussed later in this chapter. The second reason increasing high school enrollment is notable is that it has not translated into increased numbers of students seeking to major in physics.

THE EDUCATIONAL LANDSCAPE

The challenges of undergraduate physics education have been considered before. In fact, many of the issues raised in reports dating back to the 1950s—and many of the recommendations that emerged—are consistent with those found in this report. For instance, a 1991 paper, "The Undergraduate Physics Major" (Abraham et al., 1991), cited a shortage of high school physics teachers and the underrepresentation of women and minority students among their concerns. The paper also mentioned a deterioration in students' mathematical skills and in their oral and written communication abilities. Will the situation change substantially before yet another group undertakes a major study? There are two factors that suggest that it might: (1) the explosive growth of information and computer technology and (2) the emergence of research on the learning and teaching of physics. Both were mentioned in the 1991 document, but that report did not anticipate the degree to which these factors would transform the landscape in which physics is taught. The role of research on learning and teaching is discussed explicitly below. The role of technology permeates the discussion of instructional innovations. The committee cautions that it is not implying that technology will, by itself, solve subtle educational problems that have existed for decades. However, the coupling of a range of tools now available with insights gained from the scientific study of physics learning offers the strongest basis yet for sustained progress in physics education.

To organize the discussion below, the current status and trends in six areas are considered: (1) the instructional methods in physics education, (2) the content and structure of physics courses and degree programs, (3) the diversity of the student body, (4) the preparation of future teachers, (5) the assessment of courses and programs, and (6) faculty development. Interested readers will find that many of the issues raised are addressed in greater depth in Chapter 3. Recommendations for supporting the most promising emerging practices can be found in Chapter 4.

Instructional Methods

This section begins with perhaps the most difficult task: acknowledging the shortcomings in the ways in which physics is being taught in many, if not most, institutions. All of the members of the committee, and perhaps most readers of this report, were educated in ways that worked for them and for the prominent physicists who have shaped our discipline (and to a great extent, the world around us). Sharp criticism of these methods is, thus, not always welcome, and claims about their ineffectiveness should be treated with appropriate skepticism. However, it is worth noting that only about 1 in every 500 students in introductory physics will eventually enroll in a graduate program in physics. Students are not necessarily all the same. What worked (or worked well enough) for some does not necessarily work for everyone.

As part of this study, committee members examined the extensive research literature concerning undergraduate physics teaching, looking for robust findings that have been replicated at different institutions and that have "stood the test of time." Given the complexity of the learning process and the large number of variables involved in any classroom, few studies are definitive in isolation. However, the picture that emerges from the collective body of research is clear. Below, two major studies are highlighted that were groundbreaking and are still consistent with the current state of knowledge about physics teaching. These studies are meant to motivate a discussion of some innovative practices that have resulted in improved instruction. Further discussion of research findings on these and other topics of physics education research can be found in Chapter 3. Most of the innovative techniques mentioned in this report were developed by physicists, some of whom devote their major scholarly efforts to physics education research (PER), and some of whom maintain research programs in other areas. It is notable that some innovations native to physics departments have spread significantly to other disciplines.

Research on the Traditional Lecture-Recitation-Laboratory Model

Traditionally, much of physics has been taught in a lecture-based mode in which students watch, listen, and (presumably) take notes while the instructor defines quantities, explains concepts, laws, and theorems (often with the aid of demonstrations), and solves sample problems. This method of instruction has a long history in education. However, for physics it was criticized as early as the beginning of the 20th century (Mann, 1912). More recently, physics education researchers have studied the learning that occurs in these lecture classes, as well as the recitations and laboratories that frequently accompany them. These studies have repeatedly shown over the past 30 years that students learn much less than many instructors assume and much less than students who have other modes of instruction.[3]

In particular, research (primarily at the introductory level) has documented how traditional instruction reliably results in (1) limited or no gains in conceptual understanding and (2) *deterioration* in students' attitudes toward and beliefs about science. Of course there are many other goals for physics courses, such as developing the ability to solve quantitative problems or to "think like a physicist." The research literature is not as clear on how to make progress toward many of these

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[3] This issue has been discussed in some detail in the literature. See, for example, the AAPT Millikan Medal Lectures of McDermott, Zollman, Redish, and Mazur and the references cited in Meltzer and Thornton (2012).

other goals, as is discussed in Chapter 3. However, it appears that gains in conceptual understanding and attitudes need not come at the expense of achievement in other areas. Nor do they necessarily involve an increase in faculty time devoted to teaching. The following two studies demonstrate these findings:

- *Conceptual understanding.* A study that was published in the 1990s pulled together results from a wide variety of courses and institutions. Although many other studies have followed, Hake's seminal report on the effectiveness of interactive engagement methods remains an important contribution to undergraduate physics education (Hake, 1998). The article presents results from the Mechanics Diagnostic (MD) (Halloun and Hestenes, 1985) and its successor, the Force Concept Inventory (FCI) (Hestenese et al., 1992), given before and after instruction on Newtonian mechanics in a variety of courses taught using different approaches. The FCI is a widely used multiple-choice test that contains 30 items intended to distinguish "Newtonian thinking" from thinking based on common misconceptions. For instance, students shown a figure of a cannon ball fired horizontally from a cliff are asked to choose the correct trajectory from among several possibilities. The MD is similar, but not as widely used. The plot reproduced in Figure 2.5 shows the average gain in score (the percentage of correct answers on the posttest minus the percentage of correct answers on the pretest) against pretest score. Two main features of the plot are that (1) overall, scores are low and do not increase much as a result of instruction; and (2) in the courses in which the largest increases were reported, some sort of interactive technique was used. The test used the calculation of "normalized gain" and the categorization methods used by Hake, which have all come under criticism in the research literature (Marx and Cummings, 2007). However, the conclusion, that more effective instructional approaches involve active learning, has been supported by many other studies using different methodology (Meltzer and Thornton, 2012; Hoellwarth et al., 2005).

- *Student attitudes toward physics and physics courses.* Another study published in the 1990s examined students' attitudes and expectations about physics (Redish et al., 1998). Redish and colleagues devised a survey—the Maryland Physics Expectations Survey (MPEX)—in which students indicate the degree to which they agree or disagree with statements such as "Physics is related to the real world, and it sometimes helps to think about the connection, but is rarely essential for what I have to learn in this class," or "Problem solving in physics basically means matching problems with facts or equations and then substituting values to get a number." Experts (undergraduate physics instructors) generally concur on whether agreement with a given statement is favorable or unfavorable. When students are given the MPEX at both the beginning and end of an introductory course, they typically regress toward more "unfavorable" responses.

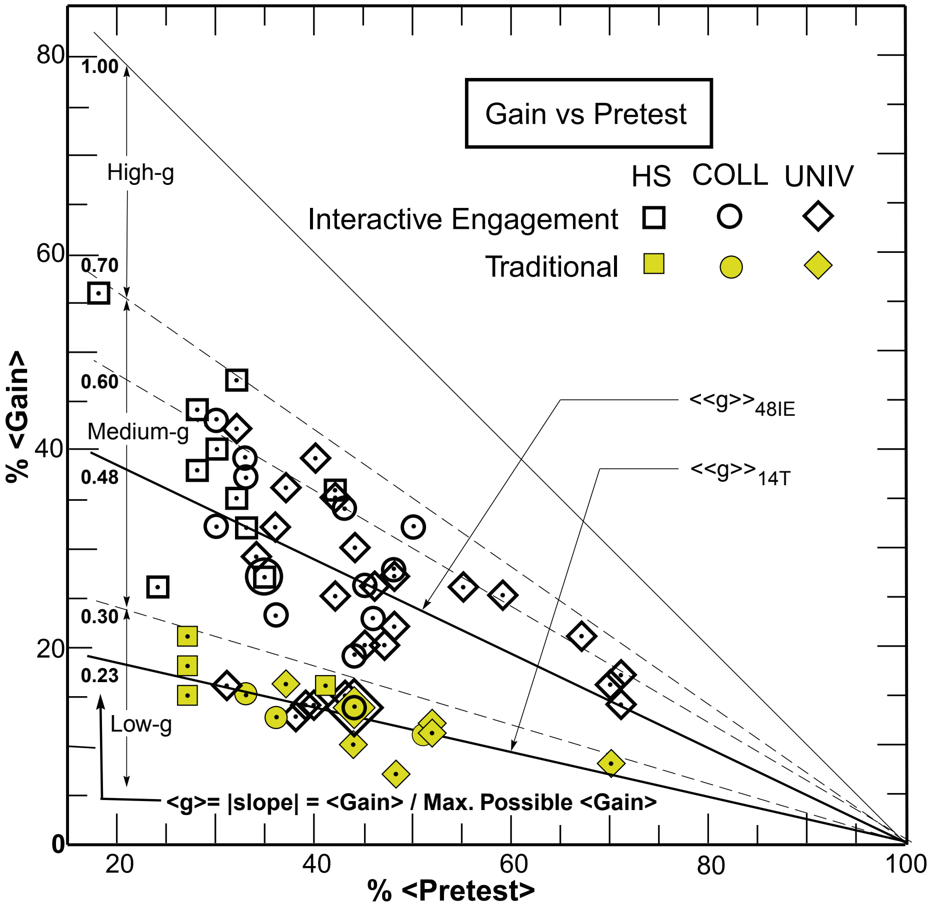

FIGURE 2.5 Gain versus pretest score on the conceptual Mechanics Diagnostic or Force Concept Inventory tests for 62 courses enrolling a total N = 6,542 students. The courses included 14 traditional (T) courses (N = 2,084), which made little or no use of interactive engagement (IE) methods, and 48 IE courses (N = 4,458), which made considerable use of IE methods.The slope lines for the average of the 14 traditional courses, <<g>>14T, and the 48 IE courses, <<g>>48IE, are shown, as explained in the text. SOURCE: Reprinted with permission from R. Hake, Interactive-engagement versus traditional methods: A six-thousand-student survey of mechanics test data for introductory physics courses, *American Journal of Physics* 66(1):64-74, 1998, Figure 1, Copyright 1998, American Association of Physics Teachers.

Like the Hake paper, these results have been supported by other studies using different methodology.

Both of the studies mentioned above featured multiple-choice tests that drew on a body of research on students' ideas that had been published between the late 1970s and the early 1990s. The studies involved interviews and open-ended written questions to probe student thinking in depth. This research base has since grown substantially, as discussed in Chapter 3.

The results of studies such as those mentioned here have spurred changes in instruction at many institutions, especially in introductory physics courses. In upper-level courses, change has been much more limited. However, research has been conducted among students in upper division courses, and the findings are essentially consistent with those at the introductory level.

Research-Inspired Initiatives

Many of the instructional methods that have been introduced over the past few decades are referred to as active or interactive learning methods. While the details vary, a recent review by Meltzer and Thornton (2012, p. 479) identified a set of non-prioritized characteristics common to all of them:

> (a) Instruction is informed and explicitly guided by research regarding students' pre-instruction knowledge state and learning trajectory . . . .
> (b) Specific student ideas are elicited and addressed.
> (c) Students are encouraged to "figure things out for themselves."
> (d) Students engage in a variety of problem-solving activities during class time.
> (e) Students express their reasoning explicitly.
> (f) Students often work together in small groups.
> (g) Students receive rapid feedback in the course of their investigative or problem-solving activity.
> (h) Qualitative reasoning and conceptual thinking is emphasized.
> (i) Problems are posed in a wide variety of contexts and representations.
> (j) Instruction frequently incorporates use of actual physical systems in problem solving.
> (k) Instruction emphasizes the need to reflect on one's own problem-solving practice.
> (l) Instruction emphasizes linking of concepts into well-organized hierarchical structures.
> (m) Instruction integrates both appropriate content (based on knowledge of students' thinking) and appropriate behaviors (requiring active student engagement).

The list of instructional materials and tools that are consistent with these characteristics is long. The following is an overview of some of the most important, successful, and enduring innovations. It is not the committee's intent to promote or endorse any particular tool, method, or set of instructional materials. Rather, it seeks to illustrate the range of approaches that are available, from adopting tools that support incremental change to comprehensive strategies that restructure how a department teaches physics. The best examples are based on research on learning. Perhaps more importantly, most have been evaluated and refined through extensive research in a large number of undergraduate classes. While technology features in many approaches, it is usually not the driving force behind the innovations, but it enables research-based strategies that would be cumbersome, time consuming, or even impossible otherwise.

It is also important to note that, as with any tool or method, the quality of implementation is critical. It is possible for students to engage in shallow discussions in class and to complete meaningless hands-on tasks. Learning is complex; simple solutions are not realistic. Nonetheless, there are ample opportunities for *any* instructor, department, or institution to provide students with better instruction while respecting local resources and constraints. Although the examples below were chosen by the committee, the organizational structure from the Meltzer and Thornton (2012) review is used facilitate use of that article's extensive references.

1. *Materials for use primarily in lecture sessions or lecture-based courses.* Polling students, using flashcards, or using personal response systems (sometimes known as "clickers") has become prevalent in large lecture classes as a mechanism for motivating student engagement. Clickers (handheld infrared or radio frequency transmitters, or networked devices) allow the rapid and convenient collection and display of student responses to multiple-choice questions posed by the instructor. These facilitate interactive engagement techniques, even in large lecture classes, by encouraging discussion among peers and by giving real-time feedback to students and instructors. Because these devices are easily used in most existing classrooms and lecture halls as an adjunct to traditional learning environments, they have found wide application.

2. *Materials primarily for use in the laboratory.* Laboratory experiments in physics courses serve many purposes, one of which is developing conceptual understanding. For this purpose, computers equipped with data acquisition devices and analysis software offer an advantage over more traditional techniques (e.g., using meter sticks, timers, and so on) by allowing rapid, or even real-time, display of results—bypassing the need to tabulate data and make graphs by hand. For example, students can graph their own position, velocity, and acceleration in real time, attempting, perhaps, to move in such a way that produces a particular graph—a strategy that can help address specific student difficulties in relating position, velocity, and acceleration. Sensors and entire laboratory activities exist for a broad range of topics in introductory physics.

Sophisticated but easy-to-use video analysis tools allow students to make direct measurements of the motion of objects in digital videos, which can be supplied by an instructor, found on the Web, or made by students themselves using inexpensive digital or cell phone cameras. The rapid production of graphs and other representations can help students focus on the physics concepts and enable discussions among peers.

Modeling tool sets facilitate student participation in an important aspect of physics: constructing a simplified model of a physical process, particularly a mathematical model, and subsequently exploring the relationship between the model and the actual phenomena, while noting the limitations of the models.

3. *Fully integrated courses.* While many of the methods listed here can be incorporated into existing course structures as part of lectures, laboratories, recitations or homework, at some institutions the entire traditional course structure has been replaced. New courses that integrate direct instruction (if any) with laboratory experiments, discussions, and problem-solving exercises allow the introduction of different activities with different goals when appropriate, rather than according to a predetermined timetable. Many of these fully integrated courses feature "studio-style" classrooms with large tables equipped with computers, which facilitate discussions among students. These approaches also promote coherence and consistency, which is difficult to achieve when different elements of a course are developed and implemented independently, as is often the case.

4. *Tutorials and problem-solving worksheets.* The term "tutorial" in physics education has become a generic term for research-based worksheets primarily intended for use in small groups to supplement instruction in lectures and laboratories. Tutorials are designed to lead students, working with small groups of peers, through the reasoning processes involved in constructing, interpreting, and applying fundamental concepts. Because many introductory physics courses have a lecture-laboratory-recitation structure, the introduction of tutorials in place of some or all recitations often requires little or no additional investment of faculty or teaching assistant (TA) time. However, as with all research-based instructional approaches that depend on them, TA preparation is critical for the effective implementation of tutorials.

5. *Computer simulations, intelligent tutors, and pre-instruction quizzes.* Carefully constructed and tested simulations make visible what was previously invisible. For example, students can watch microscopic models in action (electrical current, magnetic fields, gas molecules, and so on); examine how electrical, potential, and thermal energy changes during mechanical processes; and explore the shapes of wave functions associated with different potentials. All of these can facilitate instruction by helping students focus on the most important phenomena, giving them access to richer representations (e.g., three-dimensional models) and allowing them to explore the implications of increasing or decreasing friction, gravity, and so on.

Online homework is now the norm in college physics. The two largest online homework systems in physics, MasteringPhysics.com and WebAssign.com, have nearly 400,000 unique users in physics every year, and together these websites are used in more than half of more than 300 U.S. colleges surveyed recently. Homework systems by various other publishers reach an additional 20 percent of these colleges.[4] A large fraction of students complete and submit assignments online, providing students with instant feedback and instructors with a report containing a wealth of data for analysis. In many cases, the decision to adopt online homework systems is made for economic reasons, but many systems offer educational advantages as well. Some systems primarily use standard end-of-chapter problems drawn from popular texts, but others use specially designed problems that "tutor" students and target their difficulties. Of concern is evidence provided by online homework services which suggests that cheating does occur with online problem sets (Palazzo et al., 2010).

Readings (sometimes using multimedia) and quizzes can prepare students for in-class learning and allow instructors to tailor their lectures to target concepts that are causing the greatest difficulties. These methods, along with pre-recorded lectures, have been used in many physics classes for the past few decades and are now a defining characteristic of the so-called "flipped classroom" in which the presentation of facts and definitions occurs outside the classroom, and in-class time is devoted to discussion and activity.

The rapid growth of online tools in particular raises questions about the validity of the material and the degree of quality control (see Box 2.1). Resources like ComPADRE, the PER Users' Guide, and Meltzer and Thornton (2012) provide some guidance in determining which tools have been carefully validated. These also serve as resources for techniques that are not delivered online.

Course Content and Program Structures

While physics itself has been evolving, with entire new subfields emerging in the past few decades, the curriculum in most physics departments has remained essentially the same. There are good reasons to approach change cautiously. The traditional approach acknowledges the vertical structure of physics, in which most concepts build on others. However, the range of careers now open to physics students and the research efforts under way in many departments indicate that the courses offered, and the structure of degree programs themselves, should be examined. Below, two related studies are cited that examine thriving physics programs, and some examples of changes that have been undertaken are provided.

To understand the characteristics of departments that excel in attracting majors and preparing a broad spectrum of students for both further study and

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[4] Based on personal correspondence with representatives of the publisher of MasteringPhysics, Pearson, and Web Assign.

BOX 2.1
Incremental Change or Radical Restructuring?

In most physics departments in which some level of research-based instruction has been adopted, the traditional structure of lectures, laboratories. and recitations has mostly been preserved. One or more of these components may be modified, and additional elements such as online pre-lectures may be added, but the basic design remains the same. The net gain from this sort of incremental change can be large and the (short-term) cost to a department may be modest. Not insignificantly, faculty accustomed to a certain style of teaching and a certain division of labor may only need to change their practices minimally, if at all. Change may, therefore, be more palatable. However, there are missed opportunities with this approach. Coherence and consistency are difficult to achieve when different elements of a course are managed separately. Even concerted efforts by faculty to coordinate laboratory experiments with lectures may fall short, leaving the content in laboratories, recitations, and lectures intellectually disconnected. Moreover, many students continue to view laboratory sessions as subordinate to lectures, in direct contrast to the practices of physics (and science more generally) in which the didactic lecture finds a parallel only in talks, seminars, and colloquia, which play a different role for the professional physicist than does a lecture for a novice. Finally, and perhaps most importantly, the learning strategies supported by decades of research are most easily implemented in laboratory settings.

These considerations have led some departments to reinvent the introductory course from scratch, asking, What environment is best suited to learning? Integrated courses with a minimal (or nonexistent) lecture component where group work on complex problems and challenging experiments takes center stage have become the norm in these departments. A few decades of experience with these studio or workshop-style courses suggest that learning gains can outstrip those of minimally modified courses (see Box 3.2 for an example), but there are challenges. Redesigning classrooms to install large tables instead of fixed seats that face forward is not a minor undertaking. Faculty members can no longer use familiar lecture notes (with or without the addition of a few clicker questions), but instead roam the room monitoring progress and intervening when necessary to help student groups keep moving forward. This style takes considerable adjustment. However, for departments ready to take on these challenges, there are several successful models to follow. Workshop Physics developed at Dickinson College, the Student-Centered Active Learning Environment for Undergraduate Programs (SCALE-UP) project from North Carolina State, the TEAL approach developed at MIT, and the Studio model from RPI have all spread successfully beyond their original institutions.

the workforce, the American Association of Physics Teachers, the American Physical Society, and the American Institute of Physics sponsored the National Task Force on Undergraduate Physics. The task force visited 21 thriving departments and learned that "in all cases, the department as a whole took responsibility for the undergraduate program. . . . Most members of the department took part in discussions of what changes should occur, and most took part in figuring out what was working and needed repair" (Hillborn et al., 2003, p. 19). However, in many cases, the actual revision of a course or curriculum was accomplished by a single faculty member. (See Box 2.2 for the executive summary of the task force report, *Strategic*

BOX 2.2
Executive Summary of the 2003 SPIN-UP Report

[The National Task Force on Undergraduate Physics, in writing its report,] Strategic Programs for Innovations in Undergraduate Physics (SPIN-UP), set out to answer an intriguing question: Why, in the 1990s, did some physics departments increase the number of bachelor's degrees awarded in physics or maintain a number much higher than the national average for their type of institution? During that decade, the number of bachelor's degrees awarded in the physical sciences, engineering, and mathematics declined across the country. Yet in the midst of this decline some departments had thriving programs. What made these departments different? What lessons can be learned to help departments in the sciences, engineering, and mathematics that are—to put it generously—less than thriving? SPIN-UP, a project of the National Task Force on Undergraduate Physics, set out to answer these questions by sending site visit teams to 21 physics departments whose undergraduate programs were, by various measures, thriving. These visits took place mostly during the 2001-2002 academic year. In addition, with the aid of the AIP Statistical Research Center, SPIN-UP developed a survey sent to all 759 departments in the United States that grant bachelor's degrees in physics. The survey yielded a 74 percent response rate distributed broadly across the spectrum of U.S. physics departments.

The site-visit reports provided specific insight into what makes an undergraduate physics program thrive. In very compact form, these departments all have

- A widespread attitude among the faculty that the department has the primary responsibility for maintaining or improving the undergraduate program. That is, rather than complain about the lack of students, money, space, and administrative support, the department initiated reform efforts in areas that it identified as most in need of change.
- A challenging but supportive and encouraging undergraduate program that includes a well-developed curriculum, advising and mentoring, an undergraduate research participation program, and many opportunities for informal student-faculty interactions, enhanced by a strong sense of community among the students and faculty.
- Strong and sustained leadership within the department and a clear sense of the mission of its undergraduate program.
- A strong disposition toward continuous evaluation of and experimentation with the undergraduate program.

SOURCE: R. Hilborn, R. Howes, and K. Krane, eds., *Strategic Programs for Innovations in Undergraduate Physics: Project Report,* American Association of Physics Teachers, College Park, Md., 2003, available at http://www.aapt.org/Programs/projects/ntfup.cfm.

Programs for Innovation in Undergraduate Physics, Hilborn et al., 2003, referred to as the SPIN-UP report.) A similar investigation was conducted at 2-year colleges where physics is thriving. The resulting report, referred to as the SPIN-UP-TYC report (Monroe et al., 2005), provides profiles and recommendations for these institutions. Previous studies have shown that because of their smaller size, TYCs often are more flexible when it comes to implementing curricular change or adding new courses or program activities (Neuschatz et al., 1998).

A thorough evaluation of the efforts that have been undertaken to update course offerings and programs was beyond the scope of this report, but a few categories are highlighted here, ranging from updating the content of introductory courses to offering different "tracks" for majors with different career goals.

- *Updated introductory courses for life-sciences majors.* The National Research Council report *Bio 2010: Transforming Undergraduate Education for Future Research Biologists* (2003) acknowledges the increasingly quantitative and interdisciplinary nature of the life sciences and calls for changes in the physics courses offered for future biologists. The AAMC/HHMI report *Scientific Foundations for Future Physicians* (2009) addresses the needs of future health sciences professionals, who increasingly rely on physics-based technology. In response, many departments have rethought the content in introductory courses aimed at students in the life sciences.
- *Updated introductory courses for physics and engineering students.* Some physicists have questioned the traditional sequence of topics in introductory physics (beginning with kinematics, dynamics, and so on) and have developed courses organized around conservation principles and other "big" ideas. These courses typically introduce more modern topics at the expense of traditional topics such as geometrical optics, dc circuits, and so on. Textbooks that take these approaches are available from major publishers.
- *New courses for majors.* The SPIN-UP final report noted that "the 'core' upper-level courses (advanced mechanics, advanced electricity and magnetism, and quantum mechanics) are even more homogeneous [than introductory courses] with a relatively small number of standard textbooks used across the country" (Hilborn et al., 2003, p. 2). However, some departments now offer new courses that introduce students to areas and techniques that are important for current research in physics, such as biological physics and computational physics, and incorporate nontraditional instructional methods into traditional courses. These include efforts at Oregon State University in its Paradigms in Physics program (McIntyre et al., 2008) and at the University of Colorado, Boulder (Pollock et al., 2010; Goldhaber et al., 2009). The development of new courses represents a challenge to the existing curriculum, with its traditional requirements in quantum mechanics, electrodynamics, classical mechanics, statistical mechanics, and mathematical methods. Few departments can require more credits for a degree; increased flexibility is typically needed.
- *Different "tracks."* The career choices open to physics majors are diverse, but traditionally all majors have been prepared in essentially the same way, usually as if all would enter a graduate program in physics. In the past few decades, some departments have begun to tailor degree offerings to prepare students with specializations in, for example, applied physics, physics education, astrophysics, or biological physics; or to structure programs to facilitate double majors with

astronomy, engineering, applied mathematics, and so on. Other departments have included in their offerings student enrichment opportunities such as research, internships, and participation in international programs. Offering a B.A. as well as a B.S. degree is another way that departments can acknowledge the different aspirations of students who are interested in physics.

- *Undergraduate research.* The opportunity to participate in forefront research is often cited as important for recruiting and retaining students. National efforts like the National Science Foundation (NSF)-funded Research Experiences for Undergraduates program acknowledge the potential importance of such participation. Many universities encourage undergraduate participation in research through Undergraduate Research Opportunities Programs, while some departments require research experience as a graduation requirement.

Recruiting and Retaining Students from Traditionally Underrepresented Groups

While interactive teaching methods improve student performance in general, other aspects of the goals and culture of physics education also warrant consideration (Hazari et al., 2010; Mann, 1994; May and Chubin, 2003). A surprising example of the significant relationship between student performance and the affective domain is "stereotype threat," which was first described by social psychologist Claude Steele (1997). Steele and his collaborators performed experiments in which members of an underrepresented group (i.e., women in one study, African Americans in another) performed significantly worse on a math test when reminded that their particular group is not expected to do well in math. The effect is well validated and robust. Employing methods that reduce stereotype threat in the classroom have been shown to reduce achievement gaps for underrepresented students in mathematics (Beilock and Ramirez, 2011).

Another affective characteristic that relates to physics achievement is self-efficacy, first described by Albert Bandura (1986). According to Bandura's social cognitive theory, people with high self-efficacy—that is, those who believe they can perform well—are more likely to view difficult tasks as something to be mastered rather than something to be avoided. Students from underrepresented groups have measurably lower self-efficacy in physics than majority students (Kost et al., 2009; Sawtelle, 2011).

Focusing on course modifications designed to improve these affective aspects of the physics classroom has been shown to contribute to improved course grades, persistence in engineering, and narrowing of achievement gaps for students from underrepresented groups. What follows are five exemplary programs of reformed instruction that have reduced the achievement gaps for underrepresented students, implemented at a broad range of research universities. In all cases, students play a less passive role in their learning than they would in a traditionally taught lecture course; they collaborate with each other while participating more actively in the development of ideas. These features are consistent with recommendations for creating a more hospitable workplace for underrepresented students (Hazari et al., 2010; Mann, 1994; May and Chubin, 2003).

- The Extended Physics program at Rutgers University was the birthplace of the Investigative Science Learning Environment (ISLE) interactive teaching method (Etkina and Van Heuvelen, 2007), which provides a student-driven learning environment. In addition, the program has been specially developed to create inclusive classroom norms and has devised TA training and mentorship (Brahmia and Etkina, 2001) that are consistent with reducing stereotype threat (Beilock and Ramirez, 2011). This program has shown a narrowing of gaps for underrepresented students in course grades and test scores and has shown longitudinally a strong correlation with the elimination of the gender, racial, and ethnicity gaps in engineering degree completion (Brahmia, 2008; Etkina et al., 1999).
- At North Carolina State University, implementation of the SCALE-UP program has shown at least a 15 percent reduction in the failure rate for female and underrepresented minority students when the program replaced traditional instruction with a studio-style course that emphasizes interaction (Beichner, 2008).
- At Harvard University, a highly interactive full implementation of Peer Instruction (Mazur, 1997) is used in conjunction with *Tutorials in Introductory Physics* (McDermott and Shaffer, 1998). Their combination has been shown to eliminate the gender gap in final exam grades and concept inventory scores. The researchers also found a significant relationship between pedagogy in an introductory physics course and persistence in science (Watkins, 2010; Lorenzo et al., 2006).
- The University of Colorado at Boulder blends *Tutorials in Introductory Physics* (McDermott et al., 1998, 2002) with their pioneering learning assistant program (Otero et al., 2006) to create an environment that is both pedagogically rigorous and student supportive. Researchers there have found that with specific additional attention paid to developing self-efficacy (Bandura, 1986) and a strong physics identity for their female students (Hazari et al., 2010), they have been able to make a significant reduction in the gender achievement gap on concept inventories (Kost et al., 2009).
- At Florida International University, a Hispanic-majority institution, its particular implementation of Modeling Instruction (Halloun and Hestenes, 1987), together with its implementation of the Learning Assistant model, includes careful crafting of the learning environment designed to improve self-efficacy (Bandura, 1986) and to reduce stereotype threat (Beilock and Ramirez, 2011). They have measured significantly higher scores on concept inventories and 25 percent lower

drop-fail-withdraw rates when compared to traditionally taught courses at their institution (Brewe et al., 2010).

There are groups that are underrepresented in physics, not necessarily because they cannot do it, but because they often have no way of knowing that physics exists as a field of study and no indication that they can, in fact, participate. Reasons for this are quite complicated; however, research is increasingly demonstrating that interactive engagement methods of instruction improve the science experience for high school, middle school, and elementary students. At universities, physics faculty can think carefully about the education that is being provided for future physics teachers, including the physics curriculum for future elementary teachers.

Preparing Future Teachers

As noted in the section "The Students," the physics community is not producing enough highly qualified physics teachers to meet the growing need at the high school level. The report of the National Task Force on Teacher Education in Physics (2013; see Box 2.3) concluded that:

> The potential negative consequences of maintaining the status quo are far-reaching, both for physics as a discipline and for the U.S. economy and society as a whole. As international competition for science and engineering talent continues to increase, the United States' ability to recruit foreign-born talent to fuel the nation's technological innovation will become increasingly threatened. Interested in STEM fields but uninspired by physics instruction and unprepared for the challenges physics offers, an ever-smaller fraction of U.S. STEM majors are pursuing physics, and many drop out of STEM completely. Moreover, at a time of unprecedented scientific and technological complexity, many U.S. citizens are unable to participate in STEM-related economic opportunities or informed democratic decision-making. (National Task Force on Teacher Education in Physics, 2013, p. xi)

BOX 2.3
National Task Force on Teacher Education in Physics

To prepare future citizens to tackle 21st-century multidisciplinary problems, teachers need both a deep understanding of a discipline and of the teaching of that discipline. The urgency in fulfilling this need in physics is as intense and pressing. In response to the shortage of physics teachers in the United States and concerns over their effectiveness, the American Physical Society, American Association of Physics Teachers, and American Institute of Physics formed the National Task Force on Teacher Education in Physics. The task force was charged with documenting the state of physics teacher preparation and with making recommendations for the development of exemplary physics teacher education programs.

continued

BOX 2.3 Continued

The recommendations given below are a selection excerpted from the full recommendations of the task force (National Task Force on Teacher Education in Physics, 2013, pp. xii-xiii). These recommendations reflect a synthesis of relevant results from the literature on science teacher education and development and address the findings identified throughout the 2-year investigation of the task force. The task force recommendations are organized in terms of various stakeholders' *commitment* to physics teacher preparation and to the *quality* education opportunities for future physics teachers.

Commitment

Physics and education departments, university administrators, professional societies, and funding agencies must make a strong commitment to discipline-specific teacher education and support.

1. Institutions that consider the professional preparation of science, technology, engineering, and mathematics (STEM) teachers an integral part of their mission must take concrete steps to fulfill that mission.
2. Physics departments should recognize that they have a responsibility for the professional preparation of pre-service teachers.
3. Schools of education should recognize that programs to prepare physics teachers must include pedagogical components specific to the preparation of physics teachers; broader "science education" courses are not sufficient for this purpose.
4. Federal and private funding agencies, including the National Science Foundation and the U.S. Department of Education, should develop a coherent vision for discipline-specific teacher professional preparation and development.
5. Professional societies should provide support, intellectual leadership, and a coherent vision for the joint work of disciplinary departments and schools of education in physics teacher preparation.

Quality

All components of physics teacher preparation systems should focus on improving student learning in the pre-college physics classroom. Recommendations 9(a) and 9(b) are intended to be implemented together to ensure that a higher standard for quality of preparation does not increase the length and cost of the program nor decrease the number of teachers who are qualified to teach more than one subject.

6. Teaching in physics courses at all levels should be informed by findings published in the physics education research literature.
7. Physics teacher preparation programs should provide teacher candidates with extensive physics-specific pedagogical training and physics-specific clinical experiences.
8. Physics teacher education programs should work with school systems and state agencies to provide mentoring for early career teachers.
9. (a) States should eliminate the general-science teacher certification and replace it with subject-specific endorsements. (b) Higher education institutions should create pathways that allow prospective teachers to receive more than one endorsement without increasing the length of the degree.
10. National accreditation organizations should revise their criteria to better connect accreditation with evidence of candidates' subject-specific pedagogical knowledge and skill.
11. Physics education researchers should establish a coordinated research agenda to identify and address key questions related to physics teaching quality and effective physics teacher preparation.

The task of producing a well-prepared physics teacher is complex. Physicists who have been involved in teacher education for several decades point out that in addition to knowledge of physics content and knowledge of general pedagogy, a physics teacher must employ physics-specific pedagogical knowledge in the classroom (McDermott, 1990; Etkina, 2010). In particular, teachers need a nuanced understanding of the ways in which students think about specific physics topics.

The task force identified programs that focus on the development of physics-specific knowledge and skills for future teachers; however, these are not the norm. Within most universities, neither schools of education nor physics departments view physics-specific teacher preparation as their purview. Physics departments rarely offer prospective high school teachers more than the standard curriculum for majors, and faculty in colleges of education, which are typically responsible for preparing physics teachers, are seldom physics-trained. Collaborations between physics departments and colleges of education are rare. Many programs that prepare physics teachers do little to develop physics-specific pedagogical expertise. Thus, the typical experience for future physics teachers consists of the courses leading to the physics major, plus courses in general science teaching methods that are typically taught by science teacher educators with little or no experience in physics. It has been pointed out that the topics taught in typical high school curricula are those covered quickly at the introductory level and that further study of more advanced topics does not necessarily deepen understanding of topics covered earlier. Thus, the typical combination of physics courses and science methods courses usually provides neither the necessary depth of understanding of content nor foundations in physics-specific pedagogy (McDermott, 1990, 2006; McDermott et al., 2006).

The preparation of future elementary teachers is also a source of concern. While elementary school is where students first develop their ideas about science, and K-5 science curricula are full of physics topics, future elementary teachers typically take a small number of lecture courses for non-science majors and one science methods class in which little or no physics is taught.

The Physics Teacher Education Coalition (PhysTEC) (http://www.phystec.org/) was created by APS, AAPT, and AIP to help increase the number of well-prepared teachers of physics. Since 2001, it has provided direct funding and other resources to more than 25 physics departments that have launched physics teacher preparation programs. It has also enlisted more than 250 institutions "dedicated to improving and promoting physics and physical science teacher education." The program acknowledges that ensuring that students who choose to pursue K-12 teaching as a career are well prepared will not have enough of an impact if the number of these teachers remains at current levels. Therefore, one of PhysTEC's goals is to help departments ensure that students with even a slight interest in teaching have the opportunity to explore their interest and learn about their options.

Research-supported courses, curricula, and models that help physics departments become more deeply engaged in the preparation of future teachers are available. In particular, special physics courses that deepen teachers' understanding of the content and develop physics-specific pedagogical knowledge have been shown to have positive effects for future high school and elementary school teachers (McDermott et al., 2006; Goldberg et al., 2010; Harlow, 2010). Specialized content-specific, pedagogy courses for future physics teachers have also been developed (e.g., Etkina, 2010; Henderson, 2008). Among the efforts in this area are the material for teacher physics preparation of elementary teachers found in University of Washington's Physics by Inquiry program and the Physics and Everyday Thinking (PET) curriculum developed for elementary and high school teachers. A recent book produced in conjunction with the National Task Force, *Teacher Education in Physics* (Meltzer and Shaffer, 2011), is a compendium of research reports that, together, represent the state of knowledge in physics teacher education. A review of research contained within this volume concluded 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 (p. 3).

Research indicates that the involvement of physics faculty in recruiting and preparing teachers can have a large impact on the quality of physics teaching in secondary schools, the interest of students in studying physics, and the preparation of undergraduates who study physics (Mulvery et al., 2007; Otero et al., 2006). Some physics departments have taken a two-pronged approach that improves education for all students while improving the education of future physics teachers. The Colorado Learning Assistant model is an example. Physics faculty transform their courses to be more aligned with educational research through the help of undergraduate learning assistants, some of whom choose to become physics teachers. Such programs have shown to increase the number of physics teachers produced as well as improving student outcomes in learning assistant-supported courses (Otero et al., 2010; Hodapp et al., 2009).

Assessment

The decision to undertake changes should be based on careful consideration of goals, an assessment of the degree to which existing structures are meeting those goals, and plans to gauge the impact of any changes made. Without all of these elements, systematic and cumulative progress is unlikely. Improvement and assessment are thus inextricably linked. The increase in online education poses special challenges for assessment. Many educators assume that being on campus offers benefits to students, but it is not clear how the on-campus experience can be compared objectively to that offered by online courses.

In acknowledgment of this relationship between improvement and assessment, the committee was charged with examining the current status of assessment. It observed that while there is no shortage of suggestions for modifications to instruction, from adopting new textbooks to restructuring entire degree programs, in many cases there are no clear guidelines for evaluating the outcomes. The measures currently available include concept evaluations, attitude assessments, problem-solving assessments, course and examination grades, and retention rates. Unfortunately, assessments can cover a very small portion of what is considered to be education. Consequently, the limited number and limited breadth of these assessment instruments fundamentally limits our ability to improve or even delineate progress. There are no widely agreed-on measures for assessing the degree to which courses and programs prepare students for future study, for making creative contributions to research, or for the workforce in general.

One national examination does exist in physics, the ETS Major Field Test. However, like any standardized exam, this one has limitations and is primarily designed to evaluate preparation for graduate school in the canonical areas of physics. That said, it can be used to provide longitudinal information on a department's content preparation, but only in a fairly narrow band of skills. More broadly, the skills and knowledge that collectively constitute "thinking like a physicist" are subtle and difficult to define operationally in a way that would enable their measurement. Without such measures, it is difficult to distinguish between innovations that have a substantive impact on learning and those that do not. Accordingly, part of the effort in the area of assessments should be to evaluate the relative value of the different forms of assessment and focus on what can be known or at least measured. As resources become scarce, the ability to demonstrate the effectiveness of investment in education becomes ever more important.

Faculty Development

Faculty are the key to improvements in education, but many are hesitant about change, even when it's felt that the current system is not very effective (Henderson and Dancy, 2009). The reward structure that prevails in many colleges and universities does not adequately recognize the professional effort and creativity that is part of improving student learning. With little or no professional incentive for change, in today's climate of cutbacks, increasing class sizes, and dwindling grant funding, the lecture-course paradigm with little student activity continues to be the default practice. This issue is addressed in more detail in Chapters 3 and 4. Here, the committee points out that there are professional development opportunities that can help physics faculty assess their teaching and implement new techniques, even within the prevailing system.

Since 1996, the Physics and Astronomy New Faculty Workshops (NFW) program, sponsored by AAPT, APS, and AAS, and supported by NSF, has offered 17 workshops, each lasting 3 or more days. As of the time of this report, more than 650 newly hired faculty at master's and Ph.D. degree-granting institutions and 460 new faculty at bachelor degree-granting institutions have attended. In 2008, these attendees represented 52.6 percent of the newly hired faculty in physics. A primary goal of these workshops is to provide opportunities to learn about new and successful pedagogical approaches in physics and how to assess the impact of the implemented strategies.

There is strong evidence to suggest that the NFW program has been very successful at increasing participant knowledge about research-based instructional strategies and motivating participants to try these strategies (Henderson, 2012). For example, in a national survey of randomly selected U.S. physics faculty, those who had attended NFW had the largest correlation of 20 personal and situational variables indicating a respondent's knowledge about and use of at least one research-based instructional strategy (Henderson et al., 2012). See also a 2008 report on the effectiveness of the NFWs published in the *American Journal of Physics* (Henderson, 2008).

Since 1991, the TYC community has provided several workshop programs at the national level that provide opportunities to TYC faculty to learn about PER-based instruction and to develop and implement PER-based instructional materials, techniques, and assessments. Paralleling somewhat the NFWs for universities and 4-year colleges, the New Faculty Teaching Experience provides an 18-month training period for new faculty at TYCs to learn about alternative teaching strategies, laboratory activities, and assessments of course goals and student outcomes.

CONCLUSIONS

Undergraduate physics education is under a variety of stresses that cannot be ignored. These stresses affect curricular goals, methods of instruction, the types of students who are attracted to physics, and variables that are beyond the classroom. Moreover, the evolution of the discipline itself, advances in research on learning, and advances in technology all suggest that traditional courses and programs should be critically examined. Many local efforts to do just that have produced research-validated instructional strategies that provide opportunities for discussion, argumentation, and scientific exploration on the part of the student. Through implementation of these evidenced-based teaching practices, the learning process can be improved for all students taking physics. Collectively, these practices have raised standards for what instructors can expect students to gain from instruction. None of the innovations mentioned here is perfect or applicable to every setting. Local conditions, including course goals, resources, classroom design, and the availability of faculty, are important in deciding which approaches may be appropriate. In Chapter 3, some of the work being done to expand the range of available methods and materials is described. Chapter 4 contains recommendations for supporting both proven and promising innovations. It is also important to note that, despite the clear evidence of their shortcomings, many courses (perhaps most) continue to be taught in ways that fall short of what is currently possible, given the range of empirically validated course designs, materials, and tools available. This report points to many cases in which improved conceptual understanding, problem-solving performance, and retention have been achieved. Some of the barriers that impede more widespread improvements in instruction are addressed in Chapter 3.

While significant progress has been made in improving conceptual understanding in certain topics in introductory physics, less progress has been made toward other goals of instruction. For instance, even in courses that demonstrate improvements in conceptual understanding, many students tend to continue to see physics as unconnected to their everyday lives and as being concerned mostly with verifying known principles and substituting numbers into formulas. It is perhaps not a surprise that most students who take an introductory course do not pursue physics any further.

Low numbers of physics majors are jeopardizing some programs—but are enrollment trends a cause for concern at the national level? The committee believes they are, for several reasons. One is the need to heed repeated calls for increasing the number of STEM majors nationwide. Documents such as PCAST note that while the numbers of STEM majors are increasing, the demand for them is increasing more rapidly. While many students with talent and interest in STEM fields may prefer majors other than physics, unless one considers a bachelor's degree in physics to be of little value to the student who earns it (or to society more broadly), the physics community should be trying to increase the numbers of students who study physics. There is no reason to expect that lowering standards will do so. Many students who do well in introductory physics choose other majors for reasons that may reflect their interests or their perceptions of the career opportunities offered by other disciplines. This would not be of concern except that introductory courses presumably play a major role in these students' decisions, and if introductory courses do not accurately reflect the discipline, then students may not be making informed choices. If introductory physics courses were a valid reflection of the discipline, one could argue that physics is of innate interest to very few. The committee does not believe this is the case, but the rapid pace, rote problem solving, and highly artificial laboratory experiments that typify introductory physics courses have little do to with upper-division courses or the problems that physicists tackle today, which are as fundamental as the origins of the universe or as vital as novel energy resources or the mechanics of cell division.

Even if sheer numbers of physics majors were not a concern, the physics community should consider the implications of low participation of underrepresented groups on the *quality* of the physics student body. The discipline would surely be strengthened by recruiting talented students from throughout the population and not only from the groups that are traditionally well represented. The community should also question the implications of participation and achievement gaps in introductory courses (Sadler and Tai, 2001; Kost et al., 2009; Aud et al., 2010), which may be deterring capable students from succeeding in other STEM fields. Research results do not support common assumptions about ability and motivation being the major causes of these gaps. Aggressively exploring strategies for making introductory physics courses part of a pathway to success in STEM fields is essential.

The content of courses and the structure of degree programs play an important role in recruitment and retention. Updating the curriculum while maintaining a strong focus on fundamental concepts, scientific practices, and reasoning skills can, in principle, better prepare students for the demands of further study, research, and the increasing variety of careers open to them.

The issue of recruitment is also linked to the high school physics experience. At all levels, physics instructors tend to teach in a manner consistent with how they were taught. For too many high school teachers, their last physics course was at the introductory level. The studies cited here indicate that it is essential that the undergraduate experience of future teachers reflect what is known from research on learning and teaching in general and on effective teacher education in particular. Changing high school physics requires transforming introductory undergraduate physics courses and creating mechanisms to ensure that future teachers are well prepared in both physics and physics-specific pedagogy.

The landscape of physics education is growing in complexity. An increasing number of nontraditional students (older, part-time) are enrolling, and increasing numbers of students from all backgrounds are taking physics courses in nontraditional venues, such as online or on high school campuses. A majority of students from groups that are traditionally underrepresented in science-based careers take their first (and too often their last) physics course at a 2-year college. It is clear that providing quality education in physics requires concerted and coordinated effort by faculty in 2- and 4-year colleges, research institutions, and high schools. Regardless of where and how instruction is offered, systematic and objective assessment of educational outcomes is needed to ensure continuous progress.

REFERENCES

AAMC-HHMI (Association of American Medical Colleges-Howard Hughes Medical Institute). 2009. *Scientific Foundations for Future Physicians.*

Abraham, N.B., Gerhart, J.B., Hobble, R.K., McDermott, L.C., Romer, R.H., and Thomas, B.R. 1991. The undergraduate physics major. *American Journal of Physics* 59:106-111.

Aud, S., Fox, M.A., and KewalRamani, A. 2010. *Status and Trends in the Education of Racial and Ethnic Groups, National Center for Education Statistics.* U.S. Department of Education, Washington, D.C.

Bandura, A. 1986. *Social Foundations of Thought and Action.* Prentice-Hall, Englewood Cliffs, N.J.

Beichner, R. 2008. The SCALE-UP Project: A student-centered active learning environment for undergraduate programs. A commissioned paper for the National Research Council's Evidence on Promising Practices in Undergraduate Science, Technology, Engineering, and Mathematics (STEM) Education Workshop 2, October 13-14, 2008. Available at http://sites.nationalacademies.org/DBASSE/BOSE/DBASSE_071087; accessed on April 23, 2013.

Beilock, S.L., and Ramirez, G. 2011. On the interplay of emotion and cognitive control: Implications for enhancing academic achievement. Pp. 137-169 in *Psychology of Learning and Motivation, Volume 55: Cognition in Education* (J. Mestre and B. Ross, eds.). Academic Press, San Diego, Calif.

Brahmia, S. 2008. Improving learning for underrepresented groups in physics for engineering majors. PER Conference Invited Paper. Pp. 7-10 in *2008 Physics Education Research Conference.* AIP Conference Proceedings 1064. Available at http://www.compadre.org/Repository/document/ServeFile.cfm?ID=7981&DocID=698; accessed on February 19, 2013.

Brahmia, S., and Etkina, E. 2001. "Emphasizing the Social Aspects of Learning to Foster Success of Students at Risk." Paper presented at the Research at the Interface, 2001 Physics Education Research Conference, Rochester, N.Y., July 25-26, 2001. Available at http://www.compadre.org/per/items/detail.cfm?ID=4382; accessed on April 23, 2013.

Brewe, E., Sawtelle V., Kramer, L.H., O'Brien, G.E., Rodriguez, I., and Pamela, P. 2010. Toward equity through participation in modeling instruction in introductory university physics. *Physical Review Special Topics—Physics Education Research* 6:010106.

Carnevale, A.P., and Strohl, J. 2010. How increasing college access is increasing inequality, and what to do about it. *Rewarding Strivers: Helping Low-Income Students Succeed in College.* Century Foundation Press, New York.

Chen, X., and Thomas, W. 2009. *Students Who Study Science, Technology, Engineering and Mathematics (STEM) in Post-Secondary Education.* NCES 2009-161. U.S. Department of Education, National Center for Education Statistics, Washington, D.C.

Etkina, E. 2010. Pedagogical content knowledge and preparation of high school physics teachers. *Physical Review Special Topics—Physics Education Research* 6:020110.

Etkina, E., and Van Heuvelen, A. 2007. Investigative science learning environment—A science process approach to learning physics. In *Reviews in Physics Education Research, Volume 1: Research-based Reform of University Physics.* American Association of Physics Teachers, Washington, D.C. Available at http://www.per-central.org/per_reviews/.

Etkina E., Gibbons, K., Holton, B.L., and Horton, G.K. 1999. Lessons learned: A case study of an integrated way of teaching introductory physics to at-risk students at Rutgers University. *American Journal of Physics* 67:810.

Goldberg, F., Otero, V., and Robinson, S. 2010. Design principles for effective physics instruction: A case from physics and everyday thinking. *American Journal of Physics* 78:1265.

Goldhaber, S., Pollock, S., Dubson, M., Beale, P., and Perkins, K. 2009. Transforming upper-division quantum mechanics: Learning goals and assessment. Pp. 145-148 in *AIP Conference Proceedings Vol. 1179: 2009 Physics Education Research Conference* (M. Sabella, C. Henderson, and C. Singh, eds.). American Institute of Physics, Melville, N.Y.

Greca, M., and Moreira, M.A. 2002. Mental, physical, and mathematical models in the teaching and learning of physics. *Science Education* 86:106-121.

Griffith, A.L. 2010. Persistence of women and minorities in STEM field majors: Is it the school that matters? *Economics of Education Review* 29:911-922.

Hake, R.R. 1998. Interactive-engagement versus traditional methods: A six-thousand-student survey of mechanics test data for introductory physics courses. *American Journal of Physics* 66:64-74.

Halloun, I.A., and Hestenes, D. 1985. The initial knowledge state of college physics students. *American Journal of Physics* 53: 1043-1055.

———. 1987. Modeling instruction in mechanics. *American Journal of Physics* 55:455.

Harlow, D.B. 2010. Structures and improvisation for inquiry-based science instruction: A teacher's adaptation of a model of magnetism activity. *Science Education* 94:142-163.

Hazari, Z., Sonnert, G., Sadler, P.M., and Shanahan, M.-C. 2010. Connecting high school physics experiences, outcome expectations, physics identity, and physics career choice: A gender study. *Journal of Research in Science Teaching* 47:978-1003, doi:10.1002/tea.20363.

Henderson, C. 2008. Promoting instructional change in new faculty: An evaluation of the physics and astronomy new faculty workshop. *American Journal of Physics* 76:179.

———. 2012. "Evaluation of the Physics and Astronomy New Faculty Workshop." White paper prepared for the Workshop on the Role of Scientific Societies in STEM Faculty Workshops, Washington, D.C., May 3. Available at http://ajp.aapt.org/resource/1/ajpias/v76/i2/p179_s1?isAuthorized=no; accessed on April 23, 2013.

Henderson, C., and Dancy, M. 2009. The impact of physics education research on the teaching of introductory quantitative physics in the United States. *Physical Review Special Topics—Physics Education Research* 5:020107.

Henderson, C., Dancy, M., and Niewiadomska-Bugaj, M. 2012. The use of research-based instructional strategies in introductory physics: Where do faculty leave the innovation-decision process? *Physical Review Special Topics—Physics Education Research* 8(2):020104.

Hestenes, D., Wells, M., and Swackhamer, G. 1992. Force concept inventory. *The Physics Teacher* 30:141-166.

Higher Education Funding Council for England. 2012. National Student Survey Data for the years 2005-2011. Available at http://www.hefce.ac.uk/whatwedo/lt/publicinfo/nationalstudentsurvey/nationalstudentsurveydata/; accessed on June 19, 2012.

Hilborn, R., R. Howes, and K. Krane, eds. 2003. *Strategic Programs for Innovations in Undergraduate Physics: Project Report.* Known as the SPIN-UP report. American Association of Physics Teachers, College Park, Md. Available at http://www.aapt.org/Programs/projects/ntfup.cfm.

Hodapp, T., Hehn, J., and Hein, W. 2009. Preparing high-school physics teachers. *Physics Today* 62:40-45.

Hoellwarth, C., Moelter, M.J., and Knight, R.D. 2005. A direct comparison of conceptual learning and problem solving ability in traditional and studio style classrooms. *American Journal of Physics* 73:459.

Huang, G., Taddese, N., and Walter, E. 2000. Entry and persistence of women and minorities in college science and engineering education. *Education Statistics Quarterly* 2:59-60.

Kost, L.E., Pollock, S.J., and Finkelstein, N.D. 2009. Characterizing the gender gap in introductory physics. *Physical Review Special Topics—Physics Education Research* 5:010101.

Lorenzo, M., Crouch, C.H., and Mazur, E., 2006. Reducing the gender gap in the physics classroom. *American Journal of Physics* 74:118.

Lovett, M., Meyer, O., and Thille, C. 2008. The open learning initiative: Measuring the effectiveness of the OLI statistics course in accelerating student learning. *Journal of Interactive Media in Education. Special Issue: Researching Open Content in Education*. Available at http://jime.open.ac.uk/2008/14; accessed on June 19, 2012.

Mann, C.R. 1912. *The Teaching of Physics for Purposes of General Education*. McMillan, New York, N.Y.

Mann, J. 1994. Bridging the gender gap: How girls learn. *Streamlined Seminar* 13:5.

Marder, M. 2012. Failure of U.S. public secondary schools in mathematics. *AASA Journal of Scholarship and Practice* 9:8-24.

Marx, J., and Cummings, K. 2007. Normalized change. *American Journal of Physics* 75:87-91.

May, G.S., and Chubin, D.E. 2003. A retrospective on undergraduate engineering success for underrepresented minority students. *Journal of Engineering Education* 92:27-40.

Mazur, E. 1997. *Peer Instruction.* Prentice Hall, Upper Saddle River, N.J.

McDermott, L.C. 1990. A perspective on teacher preparation in physics and other sciences: The need for special science courses for teachers. *American Journal of Physics* 58:734.

McDermott, L.C. 2006. Preparing K-12 teachers in physics: Insights from history, experience, and research. *American Journal of Physics* 74:758-762.

McDermott, L.C., and Shaffer, P.S. 1998. *Tutorials in Introductory Physics.* Prentice Hall, Upper Saddle River, N.J.

McDermott, L.C., Shaffer, P.S., and the Physics Education Group at the University of Washington. 2002. *Tutorials in Introductory Physics.* Prentice Hall, Upper Saddle River, N.J.

McDermott, L.C., Heron, P.R.L., Shaffer, P.S., and Stetzer, M.R. 2006. Improving the preparation of K-12 teachers through physics education research. *American Journal of Physics* 74:763-767.

McIntyre, D.H., Tate, J., and Manogue, C.A. 2008. Integrating computational activities into the upper-level Paradigms in Physics curriculum at Oregon State University. *American Journal of Physics* 76:340-346.

Meltzer, D., and Shaffer, P.S. 2011. *Teacher Education in Physics.* American Physical Society. Available at http://www.ptec.org/items/detail.cfm?id=11618; accessed on February 8, 2013.

Meltzer, D., and Thornton, R. 2012. Resource Letter ALIP-1: Active-Learning Instruction in Physics, *American Journal of Physics* 80(6):478-496.

Monroe, M.B., T.L. O'Kuma, and W. Hein. 2005. *Strategic Programs for Innovations in Undergraduate Physics at Two-Year Colleges: Best Practices of Physics Programs.* Known as the SPIN-UP/TYC report. American Association of Physics Teachers, College Park, Md. Available at http://www.aapt.org/projects/spinup-tyc.cfm.

Mulvey, P.J., and Nicholson, S. 2008. *Enrollments and Degrees Report, 2006.* AIP Statistical Research Center R-151.43. Available at http://www.aip.org/statistics/trends/reports/ed.pdf; accessed on April 23, 2013.

Mulvery, P., Tesfaye, C.L., and Neuschatz, M. 2007. *Initial Career Paths of Physics Bachelor's with a Focus on High School Teaching.* American Institute of Physics, College Park, Md.

NRC (National Research Council). 2003. *Bio 2010: Transforming Undergraduate Education for Future Research Biologists.* The National Academies Press, Washington, D.C.

National Science Board. 2007. *A National Action Plan For Addressing the Critical Needs of the U.S. Science, Technology, Engineering, and Mathematics Education System.* National Science Foundation, Arlington, Va. Available at http://www.nsf.gov/nsb/publications/pub_summ.jsp?ods_key=nsb07114; accessed on February 8, 2013.

National Survey of Student Engagement. 2008. *Promoting Engagement for All Students: The Imperative to Look Within: 2008 Results.* Available at http://nsse.iub.edu/NSSE_2008_Results/docs/withhold/NSSE2008_Results_revised_11-14-2008.pdf; accessed on June 19, 2012.

National Task Force on Teacher Education in Physics. 2010. *Report Synopsis.* American Physical Society. Available at www.aps.org/about/governance/task-force/upload/ttep-synposis10.pdf; accessed on April 23, 2013.

———. 2013. *Transforming the Preparation of Physics Teachers: A Call to Action.* American Physical Society. Available at http://www.ptec.org/webdocs/2013TTEP.pdf; accessed on April 23, 2013.

Neuschatz, M., Blake, G., Friesner, J., and McFarling, M.. 1998. *Physics in the Two Year Colleges.* Pub. No. R-425. American Institute of Physics, College Park, Md. October. Available at http://www.aip.org/statistics/trends/reports/twoyear.pdf.

Neuschatz, M., McFarling, M., White, S. 2008. *Reaching the Critical Mass: The Twenty Year Surge in High School Physics.* American Institute of Physics, College Park, Md.

Ost, B. 2010. The role of peers and grades in determining major persistence in the sciences. *Economics of Education Review* 29:923-934.

Otero, V., Finkelstein, N., McCray, R., and Pollock, S. 2006. Who is responsible for preparing science teachers? *Science* 313(5786):445-446.

Otero, V., Pollock, S., and Finkelstein, N. 2010. A physics department's role in preparing physics teachers: The Colorado Learning Assistant Model. *American Journal of Physics* 78:1218.

Palazzo, D.J., Lee, Y.-J., Warnakulasooriya, R., and Pritchard, D.E. 2010. Patterns, correlates, and reduction of homework copying. *Physical Review Special Topics—Physics Education Research* 6:010104. Available at http://prst-per.aps.org/abstract/PRSTPER/v6/i1/e010104; accessed on February 8, 2013.

PCAST (President's Council of Advisors on Science and Technology). 2012. *Engage to Excel: Producing One Million Additional College Graduates with Degrees in Science, Technology, Engineering, and Mathematics.* Executive Office of the President, Washington, D.C. Available at http://www.whitehouse.gov/ostp/pcast.

Pollock, S.J., Chasteen, S.V., Dubson, M., and Perkins, K.K. 2010. The use of concept tests and peer instruction in upper-division physics. Pp. 261-264 in *2010 Physics Education Research Conference* (C. Singh, M. Sabella, and S. Rebello, eds.). AIP Conference Proceedings Volume 1289. American Institute of Physics, Melville, N.Y.

Redish, E.F., Saul, J.M., and Steinberg, R.N. 1998. Student expectations in introductory physics. *American Journal of Physics* 66:212-224.

Rojstaczer, S., and March, C.H. 2010. Grading in American colleges and universities. *Teachers College Record.* ID Number 15928. Available at http://www.gradeinflation.com/tcr2010grading.pdf; accessed on February 8, 2013.

Sadler, P.M., and Tai, R.H. 2001. Success in introductory college physics: The role of high school preparation. *Science Education* 85:111-136.

Sawtelle, V. 2011. A Gender Study Investigating Physics Self-Efficacy. FIU Electronic Theses and Dissertations, Paper 512. Available at http://digitalcommons.fiu.edu/etd/512/; accessed on February 8, 2013.

Simpson, R.D., Koballa, T.R., Oliver, J.S., and Crawley, F.E. 1994. Research on the affective dimension of science learning. Pp. 211-234 in *Handbook of Research on Science Teaching and Learning.* Macmillan, New York.

Sloan Consortium. 2011. *Going the Distance: Online Education in the United States.* Babson Survey Research Group and Quahog Research Group, LLC. Available at http://sloanconsortium.org/publications/survey/going_distance_2011.

Steele C.M. 1997. A threat in the air: How stereotypes shape intellectual identity and performance. *American Psychologist* 52:613.

Tesfaye, C.L., and Mulvey, P. 2011. Physics Bachelor's Initial Employment—Data from the Degree Recipient Follow-Up Survey for the Classes of 2009 and 2010. *Focus On,* September. American Institute of Physics Statistical Research Center. Available at http://www.aip.org/statistics/trends/reports/empinibs0910.pdf; accessed on September 20, 2012.

———. 2012. Physics Bachelor's One Year Later. *Focus On,* June. American Institute of Physics Statistical Research Center. Available at http://www.aip.org/statistics/trends/reports/bach1yrlater0910.pdf; accessed on May 3, 2013.

Van Heuvelen, A. 1991. Learning to think like a physicist: A review of research-based instructional strategies. *American Journal of Physics* 59:891-897.

Watkins, J.E. 2010. "Examining Issues of Underrepresented Minority Students in Introductory Physics." Dissertation, Harvard University. Retrieved from ProQuest Dissertations and Theses. Accession Order No. AAT 3415393.

White, S., 2012. "Physics in Two-Year Colleges: A Closer Look." Presentation to the American Associate of Physics Teachers 2012 Summer Meeting, August. Available at http://www.aip.org/statistics/trends/undergradtrends.html.

White, S., and Tesfaye, C.L. 2010. High School Physics Courses and Enrollments—Results from the 2008-09 Nationwide Survey of High School Physics Teachers. *Focus On,* August. American Institute of Physics Statistical Research Center. Available at http://www.aip.org/statistics/trends/reports/highschool3.pdf.

———. 2011a. Female Students in High School Physics—Results from the 2008-09 Nationwide Survey of High School Physics Teachers. *Focus On,* July. American Institute of Physics Statistical Research Center. Available at http://www.aip.org/statistics/trends/reports/hsfemales.pdf.

———. 2011b. Under-represented Minorities in High School Physics—Results from the 2008-09 Nationwide Survey of High School Physics Teachers. *Focus On,* March. American Institute of Physics Statistical Research Center. Available at http://www.aip.org/statistics/trends/reports/hst5minorities.pdf.

3

Physics Education Research as a Foundation for Improving Education

Many of the advances in undergraduate physics education that are highlighted in Chapter 2 were the direct result of physics education research (PER). This chapter places the studies mentioned earlier into a broader context of scholarship. It must be emphasized that teaching is a complex process in which the intuition, experience, and enthusiasm of individual instructors play an important role that is not diminished by findings from research. Instead, systematic investigations of how students learn provide instructors with essential information and tools, much as fundamental research in the health sciences is a critical component of medical care but is not a replacement for clinical judgment, compassion, and dedication. PER can thus be thought of as one of the pillars that support physics education: not sufficient on its own, but necessary for promoting effectiveness.

Since the field of PER emerged in the 1970s, the PER community has made significant advances in understanding how students learn physics. Several hundred researchers are now tackling problems with both immediate and long-term implications for undergraduate physics education. As part of the preparation for the recent National Research Council (NRC) report *Discipline-Based Education Research: Understanding and Improving Learning in Undergraduate Science and Engineering* (2012), both a history of PER (Cummings, 2010) and an extensive synthesis of results (Docktor and Mestre, 2010) were prepared. The NRC report also discusses the role that PER has played in advancing education research as a scholarly pursuit for academic scientists in other disciplines.

The paper prepared by Docktor and Mestre (2010) includes 450 unique citations. A recent review by Meltzer and Thornton (2012) of findings related to active learning in undergraduate physics includes 173 unique citations. These reports are not replicated or summarized here. Below, a very brief overview of PER sets the stage for a discussion of key findings and current priorities in six major areas of research. Taken together, these items constitute a research agenda that responds to pressing needs in undergraduate physics education and also encourages foundational research that may drive improvements in courses and programs in the future.

A BRIEF OVERVIEW OF THE FIELD OF PHYSICS EDUCATION RESEARCH

As a field of investigation, PER has grown significantly since the 1970s, a decade in which the first Ph.D. degrees in physics in the United States were awarded for research on learning and teaching of physics. Since that time, PER has produced results that provide a foundation for improving both the efficiency and the effectiveness of student learning. Perhaps the most important finding of the past four decades of PER is that a variety of specific teaching methods can lead to improved student understanding, compared to the frequently used lecture method.

The effectiveness of different teaching methods has often been established by measuring what students are able to do at different points in instruction; for example, giving students pretests and post-tests before and after a specific intervention or an entire course. The pretests and post-tests typically consist of questions that require students to apply what they have been taught to situations that are not exactly the same as any they have seen before and that are not susceptible to formula manipulation.

Methods for assessing the degree to which changes to instruction bring about improvements in student understanding are part of a process of applied research that leads to the development of methods and materials that can be adopted by faculty at other institutions. Typically, initial design is based on a set of principles such as those listed in Chapter 2, including knowledge of common student ideas in the topic area. Successive refinements are suggested by post-test results, classroom observations, and further in-depth research (e.g., interviews). Eventually, testing takes place at other institutions to ensure that the methods or materials are transportable and to determine the conditions needed for effective implementation. While this is not by any means the only framework employed in PER, it is emphasized here because many of the innovative methods and materials mentioned in this document resulted from some variation on this procedure.

A broad range of student audiences have benefited from the improvements in instruction that have resulted from research-driven development so far. The majority have been students in introductory calculus and algebra-based courses. Research-based strategies for these courses are too numerous and too varied to summarize here; a brief discussion is presented in Chapter 2, and a good recent review can be found in Meltzer and Thornton (2012).

Similar methods have been used to achieve improvements in upper-division courses on electricity and magnetism (Chasteen et al., 2011; Pollock, 2009), classical mechanics (Ambrose, 2004), thermal physics (Cochran and Heron, 2006; Meltzer, 2004), and quantum mechanics (Singh, 2001; Cataloglu and Robinett, 2002; Zollman et al., 2002). Courses for elementary and secondary teachers have also been addressed (Etkina, 2010; McDermott et al., 2006, 1996; Goldberg et al., 2008; Zollman, 1990, 1996).

One of the difficulties of measuring improvements in instruction is that physics faculty and physics courses represent a variety of instructional goals that are rarely carefully articulated. Developing student understanding of physics concepts and developing student problem-solving abilities are often the top-stated goals for physics courses. Yet, the precise articulation and pursuit of these goals in terms of measurable student outcomes is rarely done.

Additional information on PER and research-based instructional methods can be found at PER Central (http://www.compadre.org/per/) and the PER User's Guide (http://perusersguide.org). Box 3.1 lists some short books that include additional information on using research-based methods in instruction. A series of articles published in the *American Journal of Physics* by winners of the AAPT's Oersted Medal and Millikan Award provides overviews of research and the development of research-based instructional materials and methods and includes articles by Lillian McDermott, Edward Redish, Priscilla Laws, Fred Goldberg, Frederick Reif, Carl Wieman, and Alan Van Heuvelen, among others.

KEY FINDINGS FROM PHYSICS EDUCATION RESEARCH

One of the most robust findings from PER is that traditional, lecture-style introductory courses have little long-lasting effect on students' erroneous notions about the physical world (McDermott, 1991; Hake, 1998). This can be assessed by asking students simple questions such as making a prediction or drawing an inference about a physical situation. Memorization of formulas or even a relatively high level of skill at solving traditional end-of-chapter problems is inadequate for reasoning in these situations. Further, research has determined that students' responses to such questions are typically not random and idiosyncratic. Instead, a small number of erroneous reasoning patterns are documented among a large variety of students. For example, when asked about the forces acting on a coin tossed straight up (and told to neglect air resistance), many students cite "a steadily decreasing upward force," possibly reasoning that upward motion implies an upward force and a decreasing velocity implies a decreasing force (Clement, 1982). Common student ideas such as this have been identified in almost all areas of physics.

Early research seeking to identify such ideas typically involved one-on-one interviews in which students were asked to apply the physics that they had learned

BOX 3.1
Important Initial Resources

Practical applications of physics education research (PER) are numerous in the literature. Authors of a few short books have collected a variety of research-based techniques and discussed how they can be used in the physics classroom. The books listed below provide applications of PER as well as references to many of the findings of the field.

Knight, R., 2002. *Five Easy Lessons: Strategies for Successful Physics Teaching.* Addison-Wesley, San Francisco, Calif.

Experienced physics instructor and textbook author Knight discusses some of the core findings of physics education research that directly apply to teaching an introductory quantitative physics course. After a brief overview of some general instructional principles, the rest of the book contains Knight's recommendations for teaching each of the core content areas of an introductory physics course. His recommendations are based both on the available research literature as well as his extensive teaching experience. Sample activities and homework and test problems are provided.

Mazur, E., 1997. *Peer Instruction: A User's Manual.* Prentice Hall, Upper Saddle River, N.J.

Peer Instruction and related techniques are widely known and use research-based instructional strategy for teaching introductory physics. In this book, peer instruction developer Mazur describes the philosophy behind the technique as well as detailed instructions for its implementation. Much of the book contains ConcepTests (multiple-choice conceptual questions to be used during lecture) and conceptually oriented exam questions that can be used by instructors. Mazur uses peer instruction with electronic student response systems (clickers); others have successfully used the strategy with flashcards (Meltzer and Manivannan, 1996).

Redish, E.F., 2003. *Teaching Physics with the Physics Suite.* John Wiley and Sons, Hoboken, N.J.

Experienced physics instructor and physics education researcher Redish discusses a variety of research-based tools for improving teaching and learning in introductory physics. After summarizing some of the relevant findings from cognitive science, the majority of the book is a discussion about what is involved in the implementation of 11 research-based instructional strategies. Assessing instructional effectiveness and assessing student learning are emphasized.

to a new situation, often supplemented with short written problems that require explanation. (See, for example, Goldberg and McDermott, 1987.) Researchers continue to use this method, along with videotaped group discussions among students or between students and a teacher, to draw inferences about how students are thinking about physics. However, the development of multiple-choice, research-validated conceptual evaluation instruments in the 1980s and 1990s allowed the rapid gathering of data from different colleges and universities, helping to establish the generality of earlier results. The most widely known multiple-choice instrument, the Force Concept Inventory (FCI), was developed based on students' answers to free-response questions (Hestenes et al., 1992). An example of the use of the FCI in assessment was presented in Chapter 2. Assessments have been developed in many other areas in physics, such as electricity and magnetism (Ding et al., 2006; Maloney et al., 2001), graphical interpretation (Beichner, 1994), and quantum mechanics (Zhu and Singh, 2012; McKagan et al., 2010; Cataloglu and Robinett, 2002).

Many physics instructors were (and still are) shocked to find that students can obtain high scores in their courses but, when faced with certain tasks (such as the coin-toss problem mentioned above), still express ideas that directly contradict what they have been taught. These results have been replicated in courses taught by experienced professors at a broad spectrum of institutions, including community colleges, large public research universities, and selective private colleges (McDermott and Redish, 1999; Duit, 2009) as well as at a range of universities outside the United States. (See, for example, Schecker and Gerdes, 1999; Duprez and Méheut, 2003; Hartmann and Niedderer, 2005; Bao et al., 2009a, 2009b; and Duit, 2009.) Moreover, similar results have been found in nearly every area of physics taught at the introductory level.

Taken together, the results of systematic research indicate that many students' success in introductory courses reflects the development of procedural skills with algorithmic methods without an understanding of the physics that is the foundation for those methods, the derivation of which they do not understand. Why do carefully prepared and delivered lectures, well-written textbooks, and experiments that validate the laws of physics lead to such disappointing results? The evidence suggests that in general the fault does not lie solely with poor mathematical preparation or poor study habits. Instead, the findings point to *an intrinsic weakness in the methods of instruction employed in typical physics courses.*

Significant improvement is possible. The second robust finding from PER highlighted here is that student understanding and performance can be greatly enhanced with approaches to learning that are more similar to the way scientists learn and do science: (1) students must be actively engaged in their own learning (an engagement that is often facilitated by classroom interactions with peers and instructors) and (2) instruction must attend to students' own reasoning (both their preexisting ideas about how the world works and those that develop as they try to integrate new ideas during instruction).

The validity of these two principles has been established in a variety of studies (see Meltzer and Thornton, 2012, for a comprehensive collection), and they are consistent with more general findings from cognitive science studies, as discussed in the NRC report *How People Learn* (2000). Redish and Steinberg's (1999) study also showed that students who completed courses using one of two different research-based curricula increased their scores on the FCI significantly more than students in traditional classes. (See Figure 3.1.) Classes that used *Tutorials in Introductory Physics* (McDermott et al., 1998, 2002) to supplement instruction in lecture and

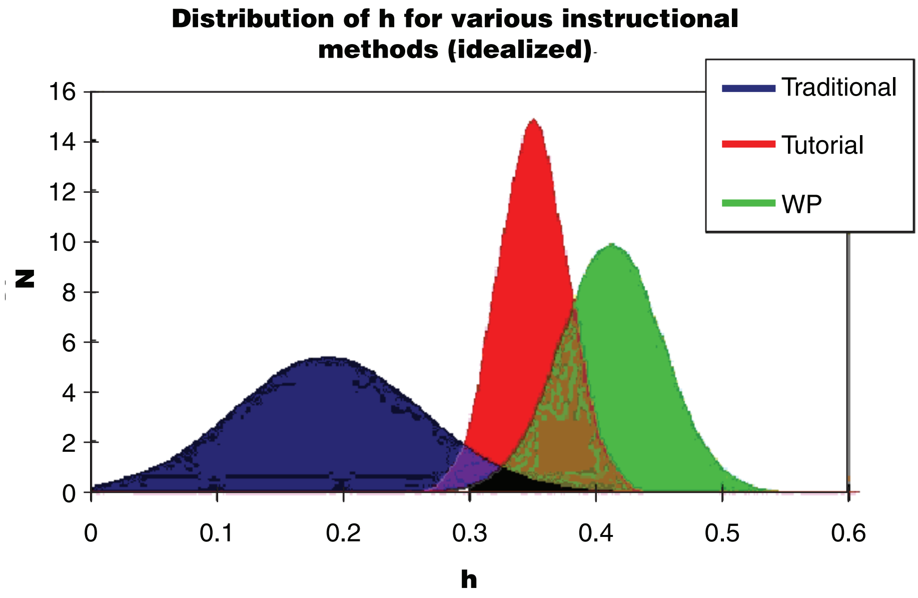

FIGURE 3.1 Gaussian fit to histograms of Force Concept Inventory gains in traditionally taught classes, in classes using UW *Tutorials* (McDermott et al., 1991, 2002; Redish and Steinberg, 1999) and cooperative group problem solving (GPS) techniques (Heller et al., 1992; Heller and Hollabaugh, 1992), and in classes using Workshop Physics (Laws, 1991, 1997). A total of eight institutions are represented. The horizontal axis represents normalized learning gains ("h" = [post-test score – pretest score]/[total possible score – pretest score]). The gain is higher in research-based learning environments than it is in traditional learning environments. SOURCE: Reprinted with permission from E.F. Redish and R.N. Steinberg, Teaching physics: Figuring out what works, *Physics Today* 52:24-30, 1999, Figure 4b, Copyright 1999, American Institute of Physics.

laboratories had greater learning gains than the traditionally taught course. Classes that used *Workshop Physics* (Laws, 1991, 1997), a studio-style course in which all instruction takes place in a laboratory-like setting, had still greater gains. Pollock (2012) reported learning gains from 8 years of introductory courses taught by a variety of instructors who used active engagement methods. Similar results have been found in a large study of introductory astronomy courses (Prather et al., 2009).

PER-based instructional methods have been tested extensively by faculty at institutions other than those where initial development took place. For example, Pollock and Finkelstein (2008) compared scores on conceptual questions on midterm exams for courses using *Tutorials in Introductory Physics* (McDermott et al., 1996, 2002) and replicated results from the University of Washington, where the materials were developed (Box 3.2). Francis et al. (1998) found that the same

BOX 3.2
Tutorials in Introductory Physics

Tutorials in Introductory Physics, developed at the University of Washington, is a set of research-based instructional materials that focus on active participation of students in the learning of physics in introductory classes (McDermott et al., 1998, 2002). In one study of the effectiveness of these instructional materials, student scores on conceptual questions in midterm exams of introductory physics classes at the University of Colorado (CU) and University of Washington (UW) were compared. Figure 3.2.1 shows the percentage of correct answers for students at the two universities who used the tutorials and those who did not. The students who used tutorials performed about equally well at both universities and significantly better than those students who had instruction that was not based on physics education research.

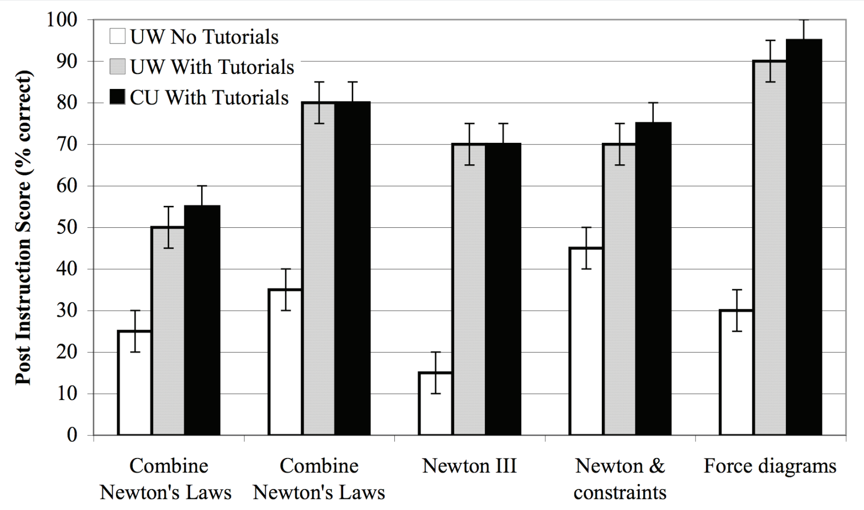

FIGURE 3.2.1 Post-test results on conceptual questions asked on midterm exams for students who used and did not use tutorials. Results from the University of Washington (UW) and University of Colorado (CU) are shown. SOURCE: Figure 4b from S.J. Pollock and N.D. Finkelstein, Sustaining educational reforms in introductory physics, *Physics Review Special Topics—Physics Education Research* 4:010110, 2008, Copyright 2008, The American Physical Society.

students can obtain high scores on the FCI several years after completion of a physics course that used interactive engagement methods.

Although active engagement and attending to students' reasoning is common among the methods used in the research discussed here, no single method stands out from this body of work as *the* definitive way to teach undergraduate physics.

Differing goals, resources, constraints, and student populations all may require subtle differences in approach. Nonetheless, taken together, the many studies that assess the effectiveness of different research-based instructional approaches demonstrate that there are general principles that work, and providing significantly more effective instruction is a realistic goal for all physics departments.

Conceptual understanding has been an important but not an exclusive focus in PER. Important findings address other aspects of education as well. As discussed in Chapter 2, studies have revealed that students form attitudes and expectations regarding knowledge and learning in physics courses that are at odds with those of physicists (Redish et al., 1998; Adams et al., 2006; Halloun, 1996). These studies have also found that introductory physics instruction generally exacerbates the problem: students who complete such a course almost invariably express attitudes that are less, rather than more, aligned with those of physicists, than when they began the course (Box 3.3). Improving this situation is a matter of current investigation, but seems to involve direct and explicit attention to students' views about learning science (Lindsey et al., 2012; Brewe et al., 2009; Redish and Hammer, 2009; Otero and Gray, 2008; Elby, 2001).

In addition to having positive impacts on student achievement, methods of interactive engagement have resulted in substantial improvements in the retention of underrepresented populations in physics. In particular, changes that have replaced the lecture with active learning have measured improved retention beyond the introductory course for both women and minority students (Brewe et al., 2010; Brahmia, 2008; Beichner, 2008). Other studies have come to conflicting conclusions about whether interactive methods alone can be responsible for a significant reduction of the gender gap (Lorenzo et al., 2006; Kost et al., 2009).

AREAS OF CURRENT AND EMERGING EMPHASIS IN RESEARCH

Many of the research themes that have been discussed in this report so far continue to be vital, with greater depth of understanding being achieved even in areas that have been under study for many years. At the same time, the field is diversifying, with researchers tackling increasingly interdisciplinary issues. The seven major areas of work in PER that are discussed below include applied research, with near-term practical implications for instruction, and basic research, aimed at developing a foundation of knowledge about the mechanisms of learning and reasoning. As in other areas of this report, this is not an attempt to include every topic that is or has been the subject of investigation. The choices reflect the report's overall emphasis on improving undergraduate physics education; thus, some areas that are more highly speculative are not discussed. (The committee also favors studies conducted in U.S. institutions because of their more immediate relevancy.) However, as in other areas of research, it is often difficult to tell at early stages whether

BOX 3.3
Improved Conceptual Understanding at What Cost?

As the discussion in this chapter makes clear, much of PER-based instruction emphasizes the development of conceptual understanding. In some (but not all) courses that use PER-based methods, the introduction of activities aimed at developing concepts came at the expense of class time devoted to quantitative problem solving. In some laboratories, time spent on careful experimental technique and calculating uncertainties gave way to time spent addressing misconceptions. The question naturally arises: Do the observed improvements in performance on conceptual assessments come at the expense of expertise in quantitative problem solving or other important course goals? The few studies that have addressed this issue directly suggest that the answer is no (Ambrose et al., 1999; Crouch and Mazur, 2001). That is, there is typically a *net gain* in ability. There is not, however, an automatic improvement in student ability to solve end-of-chapter problems, either. These findings suggest that the methods traditionally used to teach problem solving were not optimally effective (see Hsu et al., 2004 for more discussion) such that reduction in time spent on them does not necessarily have a detrimental effect on students. These findings also suggest that the reasoning involved in applying concepts in qualitative problem solving and in quantitative problem solving are not as tightly linked for students as they are for physicists. However, problem solving when taught using PER methods, such as cooperative group problem solving, has been shown to be effective for both conceptual learning and problem solving (Redish, 1998; Cummings et al., 1999; Heller et al., 1992). As discussed in Chapter 3, improving student ability to solve problems is an area of ongoing investigation.

For some physics faculty, another concern raised is that the introduction of PER-based instructional methods will be detrimental to the students who make up the current population of physics majors (and by extension, the future leaders in the field). It has been suggested that these students will be bored and/or alienated by the emphasis on basic concepts and collaboration during class. There is no evidence that capable students who are initially intending to pursue physics tend to change their minds as a result of exposure to PER-based methods, although this issue has not been studied systematically. A relevant study in the context of an upper-division physics course did not find students resistant to PER-based methods but found significant support for them (Perkins and Turpen, 2009). There is also evidence that the top students benefit from these methods as much as, or more than, any other group of students (Ding, 2011; Heller et al., 1992; Meltzer, 2002; Singh, 2005; Steinberg, 1996; Vokos et al., 2000).

certain lines of inquiry will prove to have practical implications. Therefore, this report emphasizes that fundamental research is important, even if applications are not immediately apparent.

Below are brief accounts of current priorities for the following areas:

- Student conceptual understanding, reasoning, and problem solving;
- How students learn how to learn—in other words, how they learn how to "think like physicists";
- The impact of the physical and social environment on learning in physics courses;

- Participation and achievement of students from groups traditionally underrepresented in physics;
- The preparation of future teachers of physics;
- The assessment of progress; and
- Scaling and sustaining research-supported instructional strategies.

Student Learning: Understanding, Reasoning, and Problem Solving

Student understanding of fundamental physics concepts has been, and continues to be, a major focus for PER. A considerable body of research that serves as a resource for instruction has been established (Docktor and Mestre, 2010; Duit, 2009; McDermott and Redish, 1999). The ability of students to do the reasoning necessary to develop, interpret, and apply concepts, especially in solving quantitative problems, is also a long-standing focus of investigation. Areas of current and emerging emphasis include the following:

- *The nature and origins of conceptual difficulties in learning physics.* Investigators are currently examining student understanding of physics topics at all levels of undergraduate instruction. Even in introductory physics, many topics have not been investigated as thoroughly as have the typical first-semester topics of kinematics and dynamics. The fundamental nature of difficulties themselves continues to be a topic of debate. In particular, the field has not yet reached consensus on the degree to which common conceptual errors stem from the application of "misconceptions" that are robust and stable or from the "in the moment" application of cognitive elements that exist at a much finer grain-size (Brown and Hammer, 2008; Minstrell, 1992; diSessa, 1993).
- *The promotion of reasoning abilities.* Since the earliest days of PER, reasoning skills have been an important focus (Reif, 1995; Renner and Lawson, 1973; McKinnon and Renner, 1971). Research has demonstrated that solving traditional end-of-chapter problems does not necessarily promote the ability to discuss or reason with underlying physics principles, although evidence suggests that these abilities are teachable (Leonard et al., 1996). Efforts to develop more effective strategies and problem sets include designing instructional approaches that promote the development of broadly applicable reasoning skills (e.g., Boudreaux et al., 2008) and nontraditional problem sets that emphasize conceptual reasoning in realistic scenarios. Such problem sets might be context-rich (Heller and Hollabaugh, 1992; Ogilvie, 2009), based on experiments (Van Heuvelen, 1995; Van Heuvelen et al., 1999), or related to real-world issues (http://relate.mit.edu/RwProblems/). The impact of students' initial basic reasoning abilities on their learning in physics courses is also emerging as an important area of investigation (Bao et al., 2009a; Coletta et al., 2007; Moore and Rubbo, 2012).

- *Factors affecting students' ability to solve problems.* A large body of research on students' solutions to traditional quantitative problems exists (see Hsu et al., 2004, for a comprehensive discussion of problem-solving research). These studies reveal a wide gulf between what most physicists consider to be appropriate approaches to solving problems and the approaches taken by many students. Moreover, as discussed in the previous section, solving many problems does not necessarily lead to enhanced conceptual understanding (Kim and Pak, 2002). The converse also appears to be true: an increased emphasis in instruction on conceptual understanding does not automatically lead to improved problem-solving ability (although it typically does not lead to a decrease). The University of Minnesota Cooperative Group Problem Solving instructional strategy, however, has demonstrated that a curriculum heavily based on having students solve problems can lead to improved problem-solving abilities as well as improved conceptual learning (Redish et al., 1998; Cummings et al., 1999; Heller et al., 1992). This work employs the use of context (context-rich problems) and social learning (cooperative groups) and is one of the most widespread pedagogies in physics, although it still spans only a small fraction of physics classes. Explicitly modeling an organized set of problem-solving steps and reinforcing this framework in the course itself has also shown to result in higher course performance (Huffman, 1997; Heller and Reif, 1984; Wright and Williams, 1986; van Weeren et al., 1982).

In upper-level courses, efforts to improve problem-solving capabilities include adding laboratory experiments, more strongly linking mathematics and physics in problems, and introducing computational examples and problems (McGrath et al., 2008). These have been shown not only to improve problem-solving abilities, but also to improve retention of physics majors in the program (Manogue et al., 2001).

One area of current emphasis is the role of context. Evidence indicates that the statement of a problem may strongly influence the reasoning students use to solve it. For example, students often display appropriate conceptual understanding when responding to one problem statement, yet a seemingly identical problem framed slightly differently can trigger erroneous reasoning patterns (Brookes et al., 2011; Dufresne et al., 2002; Steinberg and Sabella, 1997). Ability to apply knowledge flexibly across contexts (broadly known as transfer of learning) has been a goal in cognitive science and PER for decades but remains elusive (Mestre, 2003, 2005; Nguyen and Rebello, 2011).

A second area of current emphasis is the role that mathematics plays in problem solving and conceptual understanding. In physics courses, in contrast to mathematics courses, mathematical expressions and symbols have conceptual meaning and describe relationships among physical quantities. Studying how students interpret and use those mathematical constructs provides a window into understanding how students attempt to solve problems (Sherin, 1996, 2001) and how they learn, or fail to learn, the underlying physics (Hammer et al., 2005; Tuminaro and Redish, 2007).

- *A more precise understanding of the role of interactive engagement on learning.* As reported earlier, the available evidence supports the conclusion that interactive engagement methods lead to greater student learning. However, there are cases in which instructional strategies that at least superficially would be considered interactive have not led to significant conceptual learning gains (Cummings et al., 1999; Loverude et al., 2003). As a result, researchers are still pursuing a more precise understanding of the nature of interventions (and the critical elements of learning contexts) that result in improved learning. Moreover, most studies have taken place in actual classrooms with at least some uncontrolled variables.

There have not been many studies of the impact on students beyond the context of the reformed instruction itself. One was a study (Pollock, 2009) showing evidence of lasting benefits of conceptual understanding for students who took a reformed introductory physics course in electricity and magnetism using *Tutorials in Introductory Physics* (McDermott et al., 2002): In their junior year, students who had used the tutorials as freshmen scored significantly higher on a conceptual exam than students who had not. Another study (Etkina et al., 2010) showed evidence that students' work in ISLE design laboratories (Etkina and Van Heuvelen, 2007) helped them in subsequent, non-ISLE novel experimental tasks.

Learning to Learn Physics

While much progress has been made in the area of conceptual understanding, far less is known about the broad and less well defined objective of helping students learn to "think like physicists." That is, much more is known about how to help students develop an understanding of concepts than about how to help them address open-ended, novel, challenging questions in ways that build toward professional expertise. Many physics faculty would agree these are important goals, and AIP surveys indicate that they are for employers. Yet such goals are seldom primary targets of physics instruction until students conduct research in later undergraduate years or in graduate school.

Evidence suggests that even instructional approaches that produce conceptual gains may leave students reliant—and expecting to be reliant—on guidance from instructors (Redish et al., 1998). Students do not expect to be able to address situations they have not encountered before or to judge for themselves when an answer makes sense. Instead, students' principal method for assessing their understanding is to check that their answers to exercises align with the published solutions. In these respects, what students take away from physics courses systematically contradicts practices within the discipline. The enterprise of physics is learning about the physical world; physicists are professional learners. Physicists do their work without the benefit of an authority who can tell them when they have things right.

Abundant evidence from surveys, interviews, and observations of students in introductory courses shows that most students think of learning physics as a matter of remembering and rehearsing facts, formulas, and computational techniques (Adams et al., 2006; Halloun and Hestenes, 1998; Hammer, 1994; Kortemeyer, 2007; May and Etkina, 2002; Van Heuvelen, 1991). These findings are in contrast with research that extensively documents young children's abilities and inclinations to have and express their own ideas, to assess their ideas for consistency and fit with evidence, and, in general, to seek a coherent, mechanistic understanding of natural phenomena (Gopnik and Schulz, 2004; Koslowski, 1996; Lehrer, 2009; Metz, 2011; NRC, 2007).

Why would a pursuit of understanding that begins with such promise in young children all but disappear in students by the time they get to college physics courses? A likely conjecture is that science instruction guides students to focus on achieving fidelity to a canon of ideas specified by teachers and textbooks, but as yet no strong evidence supports that conjecture, such as might be provided by longitudinal studies. Accounts of science instruction have highlighted how goals of students learning to reason for themselves and goals of their arriving at particular conclusions may be in tension (Hodson, 1988), but little research provides guidance on how to improve the situation.

Increasing attention within PER is being paid to how students may learn to adopt and develop facility in disciplinary practices of learning—of having and articulating their own ideas; assessing the quality of those ideas for explanatory and predictive power; designing and conducting their own experimental tests; and identifying and reconciling theoretical inconsistencies (Elby, 2001; Hammer et al., 2005; Etkina, 2010).

The Role of Physical and Social Environments in Learning Physics

The recent emergence of new technologies, including newly pervasive social and informational media and online courses, as well as more specifically pedagogical online simulations, tutoring, homework, and interaction systems, are changing the environment for learning and instruction. Lectures can be recorded on video and published; texts can be interactive; classes can meet and interact in virtual spaces, and massive online open courses are finding a presence in the lives of students and teachers. The pace of this change is rapid. It affects both the design of instruction and the expectations of students with respect to how they obtain knowledge and skills. Yet little is known about its implications for learning complex material. One thing is clear: schools are no longer essential as *sources* of information. Many educators argue that their role needs to shift toward helping students learn how to assess and make use of the information they can access through the Internet (which is for many available on the mobile devices in their pockets).

Understanding how physical and social spaces for learning (both online and onsite) are best organized to meet the needs of today's students has become an important research priority. Research has been done on how physical classroom arrangements (e.g., seating arrangements, the use of clickers or dry erase whiteboards, and so on) can influence learning (Price et al., 2011; Beichner et al., 2007). This research connects closely with research on social arrangements, both designed and emergent, in which students speak with each other, for example, rather than only to the instructor; have the privilege (or obligation) to influence what questions and ideas the class will discuss; or participate in assessing their own learning or that of their classmates. Previous research shows how physical and social aspects of the environment interact with each other as well as with progress toward learning goals (Otero, 2004; Duit et al., 1998). For instance, some environments are more conducive to students engaging in scientific behaviors (such as making sense of physical phenomena, making inferences on the basis of evidence, argumentation, asking empirical questions, and so on) than others (Goldberg et al., 2010; Driver et al., 2000). Other studies have found that some environments are more inclusive than others (Ross and Otero, 2012; Brahmia and Etkina, 2001; Lee and Fradd, 1998) and suggest that some environments actually alienate a significant fraction of the students enrolled in the class (e.g., Lemke, 2001). Cooperative group-learning instructional environments have been shown to be capable of improving student learning for a broad range of students and are an important component of many PER-based instructional strategies.

A meta-analysis of studies that compared face-to-face and online instruction concluded that online environments are at least as effective as face-to-face classroom environments, but environments that combined face-to-face with online instruction showed statistically significant higher learning outcomes than those with only face-to-face instruction (see DOE, 2010, for meta-analysis). Less work has been done in combining what is known about effective active-engagement strategies with social aspects of online instructional environments.

Participation and Achievement of Students from Groups Traditionally Underrepresented in Physics

As an academic discipline, physics has a significant underrepresentation of women and ethnic/racial minorities as faculty, graduate students, undergraduate majors, and students in calculus-based courses (NCSES, 2011). Therefore, many of those entrusted with designing and teaching physics courses often have little or no experience in physics contexts involving a heterogeneous and diverse group of students. It is perhaps not surprising, then, that the largest participation and achievement gaps observed in science occur in introductory physics (http://www.aip.org/statistics/). Yet, as noted in Chapter 2, a growing number of students from diverse racial and ethnic backgrounds are enrolling in introductory physics, in part because populations in other disciplines that require a physics course are becoming increasingly diverse. Thus, the number of students from groups traditionally underrepresented in physics courses is greater than ever before and increasing.

A variety of studies have explored why achievement gaps continue to exist in science and why various groups of students continue to be underrepresented in physics (Kost et al., 2009; Hazari et al., 2007). Evidence shows that the achievement gap is not explained by student-specific characteristics, such as attitudes, motivation, or family support, nor is the achievement gap fully explained by poor academic preparation (Kost et al., 2009; McCullough, 2002).

Increasing evidence indicates that "self-efficacy," or the belief in one's own ability to succeed in a subject, is an important component to success in other science fields (Bandura, 1986; Zeldin and Pajares, 2000; Miyake et al., 2010). Specific activities, such as participating in learning communities and participating in undergraduate research, have been shown to greatly impact the retention of underrepresented students in science and engineering (Watkins and Mazur, 2013). Physics-specific research publications in these areas are few but are starting to appear. As mentioned earlier, evidence suggests that active learning environments increase performance for students from groups traditionally underrepresented in science (Brewe et al., 2010). Increasing attention in PER is being paid to studying how external characteristics, such as course format and participation in university-based activities, impact the performance and retention of students traditionally underrepresented in physics.

Preparation of Future Physics Teachers

Colleges and universities have long been the locus of physics teacher preparation. However, at a majority of U.S. universities, neither the college of education nor the physics department typically takes full responsibility for the preparation of physics teachers (National Task Force Report on Teacher Education in Physics, 2013; Buck et al., 2000). This lack of clarity concerning where physics teacher preparation should take place has led to a set of challenges both in the preparation of physics majors to teach physics and in the research associated with this preparation. Research on physics teacher preparation has proven to be challenging, due to the relatively small number of programs that prepare physics teachers specifically (National Task Force on Teacher Education in Physics, 2013); a lack of consensus on how to determine high-quality teaching and teacher preparation (NRC, 2010); and the great diversity of students, the variety of contexts, and the rapidly changing environments in which teachers work (NRC, 2010). Nonetheless, evidence from physics education research points to features of programs that are effective for preparing physics teachers (Meltzer, 2011). Current research emphasizes how classroom teaching is affected by the instruction and experiences of teacher candidates in their physics and teacher preparation programs (NRC, 2010). While more research is needed, key points for physics and other science teachers are that they need college-level study in the field that they will be teaching that is suitable to their students' age groups, an understanding of the objectives for students' learning science and developing science proficiency, and a command of the various instructional approaches designed to meet those objectives.

Related research concerns the preparation of teaching assistants (TAs) for their roles in instruction, both in their graduate programs and in their future roles as faculty. The development of TA attitudes toward teaching and their parallel development of expertise have been the focus of programs at several institutions, such as the University of Colorado and the University of Minnesota, and is the subject of current research by several groups.

Assessing Progress

As faculty and departments move more toward improving their courses, nationally normed assessment instruments for specific learning objectives provide convincing motivation for change as well as evidence that change is successful. Researchers also rely significantly on assessment instruments when developing new instructional methods. It is clear that assessment instruments like the FCI and FMCE—and more recently the MPEX and the Colorado Learning Attitudes about Science Survey—have brought conceptual knowledge and student attitudes into common discussion among physicists, revealing deficiencies in conceptual outcomes of traditional courses and motivating the adoption of many of the pedagogical innovations discussed throughout this report. Along with basic data on demographics (e.g., recruitment of majors, retention of underserved groups in an introductory course, and so on), these assessments provide the majority of the quantitative evidence cited in this report.

The tremendous impact of the few nationally normed assessment instruments currently available underscores the imperative for education researchers to develop and validate assessments that are easy for nonspecialists to administer and interpret. It is particularly important to develop ways to assess problem-solving ability, critical thinking in physics, scientific communication skills, student engagement, and so on, as well as developing assessments for other desirable objectives, such as predicting future learning or measuring teacher or TA preparation. In some of these areas there exists very little conclusive research on which to draw, implying the need for new basic research, some of which may involve novel approaches to assessment (e.g., Baker et al., 2011).

Scaling and Sustaining Research-Supported Instructional Strategies

To aid in the process of putting research results into practice, the PER community has engaged in substantial dissemination and implementation efforts. Curriculum developers frequently prepare publications—both for peer-reviewed journals and for classroom use—to make presentations and present at workshops. With respect to introductory algebra and calculus-based physics, currently almost all physics faculty (87 percent) say that they are familiar with one or more PER-based instructional strategy, and approximately half (48 percent) say that they currently use at least one PER-based strategy (Henderson and Dancy, 2009). The Workshop for New Physics and Astronomy Faculty, mentioned in Chapter 2, is a special effort to disseminate the results of PER to new physics faculty. Workshop participants report large increases in knowledge about and use of PER-based materials (Henderson, 2008; Henderson et al., 2012).

PER-based efforts have made significant headway into undergraduate physics education, but at the same time, they are not as broadly implemented as they could be. Research has shown that PER-based strategies are frequently not implemented as described by developers, and many faculty who try a PER-based strategy eventually discontinue use for a variety of reasons (Henderson and Dancy, 2009). Research is just beginning to shed light on the complex dynamics that are required for implementing, scaling and sustaining instructional changes (Yerushalmi et al., 2007; Henderson, 2007; and Henderson et al., 2012).

Establishing and maintaining effective practices and curricula in physics departments is currently a poorly understood challenge. Historically, change agents, usually curriculum developers, would work with individual faculty to support them in adopting various curricula with the expectation that the curricula would be adopted with minimal changes. However, factors that impede adoption of research-based materials seem to depend on a range of issues, including the type of institution and the orientation of the department. The size of classes, the support of colleagues, and the pressures to conduct research and obtain external funding for that research are all variables that affect the commitment to making changes in instruction. At some research-oriented institutions, tenure-track faculty might be discouraged from spending “too much time” in teaching innovations while establishing their research credentials. At others, innovative teaching could be part of the expectation for tenure. These issues increase the complexity of the models for development and dissemination of research-based instructional materials and practices. Thus, research aimed at the development of models of how to go from evidence-based knowledge in PER into practice is beginning to be recognized as important for the future.

CONCLUSION

While a few physicists may be naturally talented teachers who can reach a broad spectrum of students using instinct alone, most physics faculty can improve their teaching just as they improve other scholarly efforts, by incorporating practices based on scientific evidence. Over the past few decades, physics education research has provided a new perspective on issues related to the teaching and learning of physics. This research, which uses as a foundation the methods of physics and is conducted primarily by physicists, has collected data and built models to help us begin to understand what is happening in our classrooms, including why talented students turn away from physics. By incorporating research-based practices into teaching efforts, the physics community can reach a broader, more diverse audience and make the learning of physics a more productive and enjoyable experience for all students.

While research indicates that no easy or best teaching methods exists, it continually returns to one fundamental conclusion: *Faculty need to actively engage students in the learning process, paying attention to their spontaneous ways of thinking and the models of the natural world that they obtain from everyday life.* With this fundamental principle in mind, PER has developed a number of strategies that can help fix some of the problems that are faced. However, PER as a discipline is quite young. As it develops, and as students and society change, one can expect the need for research on issues that are only beginning to emerge as important or that are not yet anticipated.

The lines of research identified in this chapter have both short- and long-term implications for undergraduate physics education. The increasing availability of technological tools—ranging from systems for collecting high-quality classroom video to tracking eye movements and fMRI—are opening up previously unexplored areas for investigation. Talented faculty, graduate students and postdoctoral students are being attracted to the field of PER and are motivated by the discovery potential common to all fundamental research and by the prospect of conducting research that can have a powerful impact on people's lives. The successes outlined in this report demonstrate that PER has established a viable model for transforming insights about how people learn physics into significant improvements in classroom instruction. On this foundation the field is poised to help address the urgent problems facing physics education identified in this document. However, a number of practical challenges, some of them common to all research fields and others specific to discipline-based education research, threaten to hinder progress. Chapter 4 offers recommendations for promoting the vitality of the field of PER and thereby supporting advances in physics education.

REFERENCES

Adams, W., Perkins, K., Podolefsky, N., Dubson, M., Finkelstein, N., and Wieman, C. 2006. A new instrument for measuring student beliefs about physics and learning physics: The Colorado Learning Attitudes about Science Survey. *Physical Review Special Topics—Physics Education Research* 2:10101-1.

Ambrose, B.S. 2004. Investigating student understanding in intermediate mechanics: Identifying the need for a tutorial approach to instruction. *American Journal of Physics* 72**:**453.

Ambrose, B.S., Shaffer, P.S., Steinberg, R.N., and McDermott, L.C. 1999. An investigation of student understanding of single-slit diffraction and double-slit interference. *American Journal of Physics* 67:146.

Baker, R.S.J.D., Gowda, S., and Corbett, A. 2011. Automatically detecting a student's preparation for future learning: Help use is key. Pp. 179-188 in *Educational Data Mining Conference Proceedings 2011*. Available at http://educationaldatamining.org/EDM2011/wp-content/uploads/proc/edm11_proceedings.pdf, accessed on April 23, 2013.

Bandura, A. 1986. *Social Foundations of Thought and Action: A Social Cognitive Theory*. Prentice Hall, Englewood Cliffs, N.J.

Bao, L., Cai, T., Koenig, K., Fang, K., Han, J., Wang, J., Liu, Q., Lin, D., Cui, L., Luo, Y., Wang, Y., and Wu, N. 2009a. Learning and scientific reasoning. *Science* 323:586-587.

Bao, L., Fang, K., Cai, T., Wang, J., Yang, L., Cui, L., Han, J., Ding, L., and Luo, Y. 2009b. Learning of content knowledge and development of scientific reasoning ability: A cross culture comparison. *American Journal of Physics* 77:1118.

Beichner, R.J. 1994. Testing student interpretation of kinematics graphs. *American Journal of Physics* 62:750-762.

———. 2008. The SCALE-UP Project: A Student-Centered Active Learning Environment for Undergraduate Programs. A commissioned paper for the National Research Council's Evidence on Promising Practices in Undergraduate Science, Technology, Engineering, and Mathematics (STEM) Education Workshop 2, October 13-14, 2008. Available at http://sites.nationalacademies.org/DBASSE/BOSE/DBASSE_071087; accessed on April 23, 2013.

Beichner, R.J., Saul, J.M., Abbott, D.S., Morse, J.J., Deardorff, D.L., Allain, R.J., et al. 2007. The Student-Centered Activities for Large Enrollment Undergraduate Programs (SCALE-UP) project. In *Reviews in Physics Education Research, Volume 1: Research-based Reform of University Physics* (E.F. Redish and P.J. Cooney, eds.). American Association of Physics Teachers, Washington, D.C. Available at http://www.per-central.org/per_reviews/.

Boudreaux, A., Shaffer, P.S., Heron, P.R.L., and McDermott, L.C. 2008. Student understanding of control of variables: Deciding whether or not a variable influences the behavior of a system. *American Journal of Physics* 76:163.

Brahmia, S. 2008. Improving learning for underrepresented groups in physics for engineering majors. PER Conference Invited Paper. Pp. 7-10 in *2008 Physics Education Research Conference*. AIP Conference Proceedings 1064. Available at http://www.compadre.org/Repository/document/ServeFile.cfm?ID=7981&DocID=698; accessed on February 19, 2013.

Brahmia, S., and Etkina, E. 2001. Switching students on to science: An innovative course design for physics students. *Journal of College Science Teaching* 31:183-187.

Brewe, E., Kramer, L., and O'Brien, G. 2009. Modeling instruction: Positive attitudinal shifts in introductory physics measured with CLASS. *Physical Review Special Topics—Physics Education Research* 5:013102.

Brewe, E., Sawtelle, V., Kramer, L., O'Brien, G., Rodriguez, I., and Pamela, P. 2010. Toward equity through participation in modeling instruction in introductory university physics. *Physical Review Special Topics—Physics Education Research* 6:010106.

Brookes, D.T., Ross, B.H., and Mestre, J.P. 2011. Specificity, transfer, and the development of expertise. *Physical Review Special Topics—Physics Education Research* 7:010105.

Brown, D.E., and Hammer, D. 2008. Conceptual change in physics. Pp. 127-154 in *International Handbook of Research on Conceptual Change* (S. Vosniadou, ed.). Routledge, New York, N.Y.

Buck, G.A., Hehn, J.G., and Leslie-Pelecky, D.L., eds. 2000. *The Role of Physics Departments in Preparing K-12 Teachers*. American Institute of Physics, College Park, Md.

Cataloglu, E., and Robinett, R.W. 2002. Testing the development of student conceptual and visualization understanding in quantum mechanics through the undergraduate career. *American Journal of Physics* 70:238-251.

Chasteen, S.V., Pepper, R.E., Pollock, S.J., and Perkins, K.K. 2011. But does it last? Sustaining a research-based curriculum in upper-division electricity and magnetism. *2011 Physics Education Research Conference.* AIP Conference Proceedings 1413. Available at http://proceedings.aip.org/resource/2/apcpcs/1413/1/139_1?isAuthorized=no; accessed on April 23, 2013.

Clement, J.J. 1982. Students' preconceptions in introductory mechanics. *American Journal of Physics* 50:66-71.

Cochran, M.J., and Heron, P.R.L. 2006. Development and assessment of research-based tutorials on heat engines and the second law of thermodynamics. *American Journal of Physics* 74:734.

Coletta, V.P., Phillips, J.A., and Steinert, J.J. 2007. Why you should measure your students' reasoning ability. *The Physics Teacher* 45:235.

Crouch, C.H., and Mazur, E. 2001. Peer instruction: Ten years of experience and results. *American Journal of Physics* 69:970-977.

Cummings, K. 2010. A Developmental History of Physics Education Research. Commissioned paper for the National Research Council on Status, Contributions, and Future Direction of Discipline-Based Education Research; available at http://www7.nationalacademies.org/bose/DBER_Cummings_October_Paper.pdf, accessed March 27, 2012.

Cummings, K., Marx, J., Thornton, R.K., and Kuhl, D. 1999. Evaluating innovation in studio physics. *American Journal of Physics—Physics Education Research Supplement* 67:S38-S44.

Ding, L., Chabay, R., Sherwood, B., and Beichner, R. 2006. Evaluating an electricity and magnetism assessment tool: Brief electricity and magnetism assessment. *Physical Review Special Topics—Physics Education Research* 2:010105.

Ding, L., Reay, N., Lee, A., and Bao, L. 2011. Exploring the role of conceptual scaffolding in solving synthesis problems. *Physical Review Special Topics—Physics Education Research* 7:020109.

diSessa, A.A. 1993. Toward an epistemology of physics. *Cognition and Instruction* 10:105-225.

Docktor, J.L., and Mestre, J.P. 2010. A Synthesis of Discipline-Based Education Research in Physics. Commissioned paper for the National Research Council on Status, Contributions, and Future Direction of Discipline-Based Education Research; available at http://www7.nationalacademies.org/bose/DBER_Docktor_October_Paper.pdf, accessed October 8, 2011.

DOE (U.S. Department of Education). 2010. *Evaluation of Evidence-Based Practices in Online Learning: A Meta-Analysis and Review of Online Learning Studies.* Office of Planning, Evaluation, and Policy Development, Washington, D.C., available at http://www.ed.gov/about/offices/list/opepd/ppss/reports.html.

Driver, R., Newton, P., and Osborne, J. 2000. Establishing the norms of scientific argumentation in classrooms. *Science Education* 84:287-312.

Dufresne, R.J., Leonard, W.J., and Gerace, W.J. 2002. Making sense of students' answers to multiple choice questions. *The Physics Teacher* 40:174-180.

Duit, R. 2009. Bibliography—Students' and Teachers' Conceptions and Science Education. Available at http://www.ipn.uni-kiel.de/aktuell/stcse/stcse.html, accessed October 8, 2011.

Duit, R., Roth, W., Komorek, M., and Withers, J. 1998. Conceptual change cum discourse analysis to understand cognition in a unit on chaotic systems: Toward an integrative perspective on learning in science. *International Journal of Science Education* 20:1059-1073.

Duprez, C., and Méheut, M. 2003. About some of the difficulties in learning thermodynamics at the university level. Pp. 99-106 in *Science Education Research in the Knowledge-Based Society* (D. Psillos, P. Kariotoglou, V. Tselfes, E. Hatzikraniotis, G. Fassoulopoulos, and M. Kallery, eds.). Kluwer Academic Publishers, Dordrecht, The Netherlands.

Elby, A. 2001. Helping students learn how to learn. *American Journal of Physics, Physics Education Research Supplement* 69:S54-S64.

Etkina, E. 2010. Pedagogical content knowledge and preparation of high school physics teachers. *Physical Review Special Topics—Physics Education Research* 6:020110.

Etkina, E., and Van Heuvelen, A. 2007. Investigative science learning environment—A science process approach to learning physics. *Research-Based Reform of University Physics.* American Association of Physics Teachers, Washington, D.C.

Etkina, E., Karelina, A., Ruibal-Villasenor, M., Jordan, R., Rosengrant, D., and Hmelo-Silver, C. 2010. Design and reflection help students develop scientific abilities: Learning in introductory physics laboratories. *Journal of the Learning Sciences* 19(1):54-98.

Francis, G.E., Adams, J.P., and Noonan, E.J. 1998. Do they stay fixed? *The Physics Teacher* 36:488.

Goldberg, F.M., and McDermott, L.C. 1987. An investigation of student understanding of the real image formed by a converging lens or concave mirror. *American Journal of Physics* 55:108.

Goldberg, F., Robinson, S., and Otero, V. 2008. *Physics and Everyday Thinking*. It's About Time, Armonk, N.Y.

Goldberg, F., Otero, V., and Robinson, S. 2010. Design principles for effective physics instruction: A case from physics and everyday thinking. *American Journal of Physics* 78:1265.

Gopnik, A., and Schulz, L. 2004. Mechanisms of theory-formation in young children. *Trends in Cognitive Science* 8:8.

Hake, R.R. 1998. Interactive-engagement versus traditional methods: A six-thousand-student survey of mechanics test data for introductory physics courses. *American Journal of Physics* 66:64-74.

Halloun, I. 1996. Views about science and physics achievement: The VASS story. Pp. 605-613 in *Proceedings of the International Conference on Undergraduate Physics Education* (E.F. Redish and J.S. Rigden, eds.). American Institute of Physics, Washington D.C.

Halloun, I., and Hestenes, D. 1998. Interpreting VASS dimensions and profiles. *Science and Education* 7:553-577.

Hammer, D. 1994. Epistemological beliefs in introductory physics. *Cognition and Instruction* 12:151-183.

Hammer, D., Elby, A., Scherr, R.E., and Redish, E.F. 2005. Resources, framing, and transfer. Pp. 89-120 in *Transfer of Learning: Research and Perspectives* (J. Mestre, ed.). Information Age Publishing, Greenwich, Conn.

Hartmann, S., and Niedderer, H. 2005. Parallel conceptions in the domain of force and motion. Pp. 471-482 in *Research and the Quality of Science Education* (K. Boersma, M. Goedhart, O. De Jong, and H. Eijkelhof, eds.). Springer, Dordrecht, The Netherlands.

Hazari, Z., Tai, R.H., Sadler, P.M. 2007. Differences in introductory university physics performance: The influence of H.S. physics preparation and affective factors. *Science Education* 91(6):847-876.

Heller, P., and Hollabaugh, M. 1992. Teaching problem solving through cooperative grouping—2: Designing problems and structuring groups. *American Journal of Physics* 60:637-644.

Heller, P., Keith, R., and Anderson, S. 1992. Teaching problem solving through cooperative grouping—1: Group versus individual problem solving. *American Journal of Physics* 60:627-636.

Heller, T.L., and Reif, F. 1984. Prescribing effective human problem-solving processes: Problem solving in physics cognition and instruction. *Cognition and Instruction* 1(2):177.

Henderson, C. 2007. Evaluation of the Physics and Astronomy New Faculty Workshop. Contributed talk for the AAPT 2007 Summer Meeting, Greensboro, N.C., July 30, 2007. Available at http://homepages.wmich.edu/~chenders/Publications/HendersonAAPTSummer2007.pdf; accessed on May 7, 2013.

———. 2008. Promoting instructional change in new faculty: An evaluation of the physics and astronomy new faculty workshop. *American Journal of Physics* 76:179-187.

Henderson, C., and Dancy, M. 2009. The impact of physics education research on the teaching of introductory quantitative physics in the United States. *Physical Review Special Topics—Physics Education Research* 5:020107.

Henderson, C., Dancy, M., and Niewiadomska-Bugaj, M. 2012. Use of research-based instructional strategies in introductory physics: Where do faculty leave the innovation-decision process? *Physical Review Special Topics—Physics Education Research* 8:020104.

Hestenes, D., Wells, M., and Swackhamer, G. 1992. Force concept inventory. *The Physics Teacher* 30:141-166.

Hodson, D. 1988. Experiments in science and science teaching. *Educational Philosophy and Theory* 20:53-66.

Hsu, L., Brewe, E., Foster, T., and Harper, K., 2004. Resource Letter RPS-1: Research in problem solving. *American Journal of Physics* 72:1148-1156.

Huffman, D. 1997. Effect of explicit problem-solving instruction on high school students' problem-solving performance and conceptual understanding of physics. *Journal Research in Science Teaching* 36(6):337-379.

Kim, E., and Pak, S. 2002. Students do not overcome conceptual difficulties after solving 1000 traditional problems. *American Journal of Physics* 70:759.

Knight, R. 2002. *Five Easy Lessons: Strategies for Successful Physics Teaching*. Addison-Wesley, San Francisco, Calif.

Kortemeyer, G. 2007. The challenge of teaching introductory physics to premedical students. *The Physics Teacher* 45:552-557.

Koslowski, B. 1996. *Theory and Evidence: The Development of Scientific Reasoning*. MIT Press, Cambridge, Mass.

Kost, L.E., Pollock, S.J., and Finkelstein, N.D. 2009. Characterizing the gender gap in introductory physics. *Physical Review Special Topics—Physics Education Research* 5:010101.

Laws, P. 1991. Calculus-based physics without lectures. *Physics Today* 44:24-31.

———. 1997. *Workshop Physics Activity Guide*. John Wiley and Sons, New York, N.Y.

Lee, O., and Fradd, S. 1998. Science for all, including students from non-English-language backgrounds. *Educational Researcher* 27:12-21.

Lehrer, R. 2009. Designing to develop disciplinary dispositions: Modeling natural systems. *American Psychologist* 64:759-771.

Lemke, J. 2001. Articulating communities: Sociocultural perspectives on science education. *Journal of Research in Science Teaching* 38:296-316.

Leonard, W.J., Dufresne, R.J., and Mestre, J.P. 1996. Using qualitative problem-solving strategies to highlight the role of conceptual knowledge in solving problems. *American Journal of Physics* 64:1495-1503.

Lindsey, B., Hsu, L., Sadaghiani, H., Taylor, J.W., and Cummings, K. 2012. Positive attitudinal shifts with the Physics by Inquiry curriculum across multiple implementations. *Physical Review Special Topics—Physics Education Research* 8:010102.

Lorenzo, M., Crouch, C., and Mazur, E., 2006. Reducing the gender gap in the physics classroom. *American Journal of Physics* 74:118.

Loverude, M.E. 2003. "Measuring the Effectiveness of Research-Based Curriculum at a University Serving a Diverse Student Population." Presented at the 2003 Physics Education Research Conference, Madison, Wis.

Maloney, D., O'Kuma, T., Hieggelke, C., and Van Heuvelen, A. 2001. Surveying students' conceptual knowledge of electricity and magnetism. *American Journal of Physics* 69:S12.

Manogue, C.A., Siemens, P.J., Tate, J., Browne, K., Niess, M.L., and Wolfer, A.J. 2001. Paradigms in physics: A new upper-division curriculum. *American Journal of Physics* 69(9):978-990.

May, D.B., and Etkina, E. 2002. College physics students' epistemological self-reflection and its relationship to conceptual learning. *American Journal of Physics* 70:1249-1258.

Mazur, E. 1997. *Peer Instruction: A User's Manual*. Prentice-Hall, Upper Saddle River, N.J.

McCullough, L. 2002. Gender, math, and the FCI. In *Proceedings of the 2002 Physics Education Research Conference* (S. Franklin, J. Marx, and K. Cummings, eds.). AIP Press, Melville, N.Y.

McDermott, L.C. 1991. Millikan Lecture 1990: What we teach and what is learned—Closing the gap. *American Journal of Physics* 59:301-315.

McDermott, L.C., and Redish, E.F. 1999. Resource letter: PER-1: Physics Education Research. *American Journal of Physics* 67:755-767, and references cited therein.

McDermott, L.C., Shaffer, P.S., Rosenquist, M.L., and Washington, P.E.G.U. 1996. *Physics by Inquiry: An Introduction to Physics and the Physical Sciences (Volumes I and II)*. John Wiley and Sons, New York, N.Y.

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

———. 2002. *Tutorials in Introductory Physics*. Pearson Publishing, Upper Saddle River, N.J.

McDermott, L.C., Heron, P., Shaffer, P., and Stetzer, M. 2006. Improving the preparation of K-12 teachers through physics education research. *American Journal of Physics* 74:763-767.

McGrath, D., Savage, C., Williamson, M., Wegener, M., and McIntyre T. 2008. Teaching Special Relativity using Virtual Reality. *Proceedings of the UniServe Science Symposium on Visualisation and Concept Development, October 2008*. Available at http://www.anu.edu.au/Physics/Savage/papers/uniserve.pdf; accessed on May 6, 2013.

McKagan, S.B., Perkins, K.K., and Weiman, C.E. 2010. Design and validation of the quantum mechanics conceptual survey. *Physical Review Special Topics—Physics Education Research* 6:020121.

McKinnon, J.W., and Renner, J.W. 1971. Are colleges concerned with intellectual development? *American Journal of Physics* 39:1047-1052.

Meltzer, D. 2002. The relationship between mathematics preparation and conceptual learning gains in physics: A possible "hidden variable" in diagnostic pretest scores. *American Journal of Physics* 70:1259-1268.

———. 2004. Investigation of students' reasoning regarding heat, work, and the first law of thermodynamics in an introductory, calculus-based general physics course. *American Journal of Physics* 72:1432-1446.

———. 011. Research on the education of physics teachers. Pp. 3-14 in *Teacher Education in Physics: Research, Curriculum, and Practice* (D. Meltzer and P. Shaffer, eds.). American Physical Society, College Park, Md.

Meltzer, D., and Manivannan, K. 1996. Promoting interactivity in physics lecture classes. *The Physics Teacher* 34:72-76.

Meltzer, D., and Thornton, R. 2012. Resource letter ALIP-1: Active-Learning Instruction in Physics. *American Journal of Physics* 80:478.

Mestre, J. 2003. *Transfer of Learning: Issues and Research Agenda*. National Science Foundation, Washington, D.C. Available at www.nsf.gov/pubs/2003/nsf03212/nsf03212.pdf.

Mestre, J.P., ed., 2005. *Transfer of Learning from a Modern Multidisciplinary Perspective*. Information Age Publishing, Greenwich, Conn.

Metz, K.E. 2011. Young children can be sophisticated scientists. *Phi Delta Kappan* 92:68-71.

Minstrell, J. 1992. Facets of students' knowledge and relevant instruction. Pp. 110-128 in *The Proceedings of the International Workshop on Research in Physics Education: Theoretical Issues and Empirical Studies* (Bremen, Germany, March 5-8, 1991) (R. Duit, F. Goldberg, and H. Niedderer, eds.). IPN (Institut für die Pädagogik der Naturwissenschaften), Kiel, Germany.

Miyake, A., Kost-Smith, L.E., Finkelstein, N.D., Pollock, S.J., Cohen, G.L., and Ito, T.A. 2010. Reducing the gender achievement gap in college science: A classroom study of values affirmation. *Science* 330:1234-1237.

Moore, J.C., and Rubbo, L.J. 2012. Scientific reasoning abilities of nonscience majors in physics-based courses. *Physical Review Special Topics—Physics Education Research* 8:010106.

National Task Force on Teacher Education in Physics. 2013. *Transforming the Preparation of Physics Teachers: A Call to Action.* American Physical Society. Available at http://www.ptec.org/webdocs/2013TTEP.pdf; accessed on April 23, 2013.

NCSES (National Center for Science and Engineering Statistics). 2011. *Characteristics of Scientists and Engineers in the United States: 2006.* National Science Foundation, Arlington, Va.

Nguyen, D.-H., and Rebello, N.S. 2011. Students' understanding and application of the area under the curve concept in physics problems. *Physical Review Special Topics—Physics Education Research* 7:010112.

NRC (National Research Council). 2000. *How People Learn: Brain, Mind, Experience, and School.* The National Academies Press, Washington, D.C.

———. 2007. *Taking Science to School: Learning and Teaching Science in Grades K-8.* The National Academies Press, Washington, D.C.

———. 2010. *Preparing Teachers: Building Evidence for Sound Policy.* The National Academies Press, Washington, D.C.

———. 2012. *Discipline-Based Education Research: Understanding and Improving Learning in Undergraduate Science and Engineering.* The National Academies Press, Washington, D.C.

Ogilvie, C.A. 2009. Changes in students' problem-solving strategies in a course that includes context-rich, multifaceted problems. *Physical Review Special Topics—Physics Education Research* 5: 020102.

Otero, V. 2004. Cognitive processes and the learning of physics, Part II: Mediated action. *Proceedings of the 2003 International School of Physics "Enrico Fermi"* (M. Vicentini and E.F. Redish, eds). IOS Press, Amsterdam, The Netherlands.

Otero, V., and Gray, K. 2008. Attitudinal gains across multiple universities using the Physics and Everyday Thinking curriculum. *Physical Review Special Topics—Physics Education Research* 4:020104.

Perkins, K.K., and C. Turpen. 2009. Student perspectives on using clickers in upper-division physics courses. Pp. 225-228 in *2009 Physics Education Research Conference.* AIP Conference Proceedings 1179. AIP Press, Melville, N.Y.

Pollock, S.J. 2009. Longitudinal study of student conceptual understanding in electricity and magnetism. *Physical Review Special Topics—Physics Education Research* 5:020110.

———. 2012. Impacts of curricular change: 8 years of conceptual survey data from introductory physics. In *2012 Physics Education Research Conference* (S. Rebello, P. Engelhardt, and A. Churukian, eds.). AIP Press, Melville, N.Y.

Pollock, S.J., and Finkelstein, N.D. 2008. Sustaining educational reforms in introductory physics. *Physical Review Special Topics—Physics Education Research* 4:010110.

Prather, E.E., Rudolph, A.L., Brissenden, G., and Schlingman, W.M. 2009. A national study assessing the teaching and learning of introductory astronomy. Part I. The effect of interactive instruction. *American Journal of Physics* 77:320-330.

Price, E., Tsui, S., Hart, A., and Saucedo, L. 2011. Don't erase that whiteboard! Archiving student work on a photo sharing website. *The Physics Teacher* 49:334-336.

Redish, E., and Hammer, D. 2009. Reinventing college physics for biologists: Explicating an epistemological curriculum. *American Journal of Physics* 77:629-642.

Redish, E.F., and Steinberg, R.N. 1999. Teaching physics: Figuring out what works. *Physics Today* 52:24-30.

Redish, E.F., Saul, J.M., and Steinberg, R.N. 1998. Student expectations in introductory physics. *American Journal of Physics* 66: 212-224.

Reif, F. 1995. Millikan Lecture 1994: Understanding and teaching important scientific thought processes. *American Journal of Physics* 63:17-32.

Renner, J.W., and Lawson, A.E. 1973. Promoting intellectual development through science teaching. *The Physics Teacher* 11:273.

Ross, M.J., and Otero, V.K. 2012. Challenging traditional assumptions about secondary science through the PET curriculum. *2012 Physics Education Research Conference Proceedings* (S. Rebello, P. Engelhardt, and A. Churukian, eds.). AIP Press, Melville, N.Y.

Schecker, H., and Gerdes, J. 1999. Messung von Kozeptualisierungsfaehigkeit in der Mechanik zur Aussagekraft des Force Concept Inventory. *Zeitschrift für Didaktik der Naturwissenschaften* 5:75-89.

Sherin, B.L. 1996. The Symbolic Basis of Physical Intuition: A Study of Two Symbol Systems in Physics Instruction. Dissertation. Available at http://www.sesp.northwestern.edu/docs/dissertation/386770764374ec34c2565.pdf; accessed on May 7, 2013.

———. 2001. How students understand physics equations. *Cognition and Instruction* 19(4):479-541.

Singh, C. 2001. Student understanding of quantum mechanics. *American Journal of Physics* 69:885.

———. 2005. Impact of peer interaction on conceptual test performance. *American Journal of Physics* 73:446-451.

Steinberg, R.N., and Sabella, M.S. 1997. Performance on multiple-choice diagnostics and complementary exam problems. *The Physics Teacher* 35:150-155.

Steinberg, R.N., Oberem, G.E., and McDermott, L.C. 1996. Development of a computer-based tutorial on the photoelectric effect. *American Journal of Physics* 64:1370.

Tuminaro, J., and Redish, E.F. 2007. Elements of a cognitive model of physics problem solving: Epistemic games. *Physical Review Special Topics—Physics Education Research* 3:020101.

Van Heuvelen, A. 1991. Learning to think like a physicist: A review of research-based instructional strategies. *American Journal of Physics* 59:891-897.

———. 1995. Experiment problems for mechanics. *The Physics Teacher* 33:176.

Van Heuvelen, A., Allen, L., and Mihas, P. 1999. Experiment problems for electricity and magnetism. *The Physics Teacher* 37(8):482.

van Weeren, J.H.P., de Mul, F.F.M., Peters, M.J., Kramers Pals, H., and Roossink, H.J. 1982. Teaching problem-solving in physics: A course in electromagnetism. *American Journal of Physics* 50(8):725-732.

Vokos, S., Shaffer, P.S., Ambrose, B.S., and McDermott, L.C. 2000. Student understanding of the wave nature of matter: Diffraction and interference of particles. *American Journal of Physics* 68:S42-S51.

Watkins, J., and Mazur, E. 2013. Retaining students in science, technology, engineering, and mathematics (STEM) majors. *Journal of College Science Teaching* 42(5).

Wright, D., and Williams, C.D. 1986. A WISE strategy for introductory physics. *The Physics Teacher* 24:211-216.

Yerushalmi, E., Henderson, C., Heller, K., and Heller, P., and Kuo, V. 2007. Physics faculty beliefs and values about the teaching and learning of problem solving, Part I: Mapping the common core. *Physical Review Special Topics—Physics Education Research* 3(2):020109.

Zeldin, A.L., and Pajares, F. 2000. Against the odds: Self-efficacy beliefs of women in mathematical, scientific, and technological careers. *American Educational Research Journal* 37:215-246.

Zollman, D.A. 1990. Learning cycles for a large-enrollment class. *The Physics Teacher* 28:20-25.

———. 1996. Millikan Lecture 1995: Do they just sit there? Reflections on helping students learn physics. *American Journal of Physics* 64:114-119.

Zollman, D.A., Rebello, N.S., and Hogg, K. 2002. Quantum mechanics for everyone: Hands-on activities integrated with technology. *American Journal of Physics* 70:252-529.

Zhu, G., and Singh, C. 2012. Surveying students' understanding of quantum mechanics in one spatial dimension. *American Journal of Physics* 80(3):252-259.

4

Recommendations

In spite of the numerous challenges facing undergraduate physics education, a realistic future includes introductory physics courses that students view as an opportunity to exercise their thinking rather than their memory; learn approaches to solving problems that transfer to other science, technology, engineering, and mathematics (STEM) courses; improve their expertise in and attitudes toward learning science; and see the relevance of physics to their future lives and to the world around them. In this future, more students, especially women and minorities underrepresented in physics, will decide to major in physics and teach others about it.

The major result of this committee's deliberations, expressed in more detail in the recommendations below, is that the physics community pursue this vision by making significant changes in undergraduate physics education that are grounded in scientific evidence. To achieve this transformation at scale, the community must undertake a systematic process that draws on discipline-based research on student learning and on rigorous assessment of the degree to which students are acquiring the knowledge, skills, and attitudes that are needed to solve 21st-century problems. Change in the academic culture is required in order to encourage, enact, spread, and sustain these improvements.

Achieving the necessary rate and scope of change will require coherent, coordinated action among many different groups at different levels—both inside and outside educational institutions. In this chapter each group is offered specific suggestions, based on research, where possible, and on successful practice, or on the judgment of the committee where it is not. To augment the specific examples and sources of organized research findings given in the preceding chapters, several general sources for materials and ideas, as well as summaries of related national reports, are included. Broadly speaking, the key recommendations for each of the major audiences, whose active and concerted engagement is essential to building a successful future for undergraduate physics education, are as follows:

- Individual physics faculty should improve their courses, using objective evidence to judge success.
- Departmental leadership should create a culture of continuous improvement in which educational innovation is encouraged, sustained when it succeeds, and tolerated when it fails.
- Academic leadership should encourage faculty groups to seek improvement and should reward faculty and departments that are successful at implementing positive changes.
- Funding agencies should support change at all levels and should support fundamental educational research, development, adoption, and dissemination.
- Physics (and other) education researchers should focus some of their efforts on critical areas, including improving fundamental understanding of learning and instruction and developing and disseminating improved assessment tools and instructional methods and materials.
- Professional societies should emphasize the importance of education research and play a major role in the dissemination of its results, recognizing those who successfully improve instruction.

Change in undergraduate physics education is long overdue. Advances in research on learning and in technology have given us new insights and opportunities to change the way students learn physics. The committee's suggestions can be used as a launching point to increased awareness of developing findings through publications, workshops, and seminars produced by the growing corps of education researchers and instructors who are discovering and developing more effective ways for students to learn. The detailed recommendations presented below for each major audience group identified in the key recommendations provide a guide to each of the constituent groups on ways that they can contribute to the important task ahead.

PHYSICS FACULTY

Key Recommendation A. Individual physics faculty should improve their courses, using objective evidence to judge success.

Physics faculty can improve learning, prepare students for further work in science and engineering, broaden participation of students from groups underrepresented in physics, increase the numbers of majors, minors, and high school physics teachers, and augment the stature of their departments via innovative teaching and creative use of resources. However, priorities and challenges vary tremendously in institutions of different sizes, overall objectives, and student demographics. Therefore, the committee is not giving prescriptions but is urging faculty to adopt the very approach that the physics community employs in conducting experiments or developing theories: know the underlying principles that have been established by systematic research, apply what seems relevant to the problems at hand, observe and quantify the results, and repeat this process if further improvement is desired. Sustainable improvement results from incremental changes, continual renewal, and long-term commitment.

Educational change has historically begun with the dedicated efforts of a single faculty member who realizes the status quo is inadequate and decides to take action. Frequently, it is a motivated individual who realizes that students are not learning as intended and has heard about novel physics pedagogies or assessment instruments or has attended a workshop or meeting on physics education research. Such an individual can be a catalyst for change, motivating others to get involved.

Detailed Recommendations for Individual Physics Faculty

Recommendation A1. Faculty should become knowledgeable about educational innovation in physics and the importance of active engagement of students in the learning process.

Box 3-1 summarizes several useful resources that provide accessible introductions to educational innovations in physics. Attending a talk or workshop about a new instructional strategies (e.g., as at an American Physical Society [APS] or American Association of Physics Teachers [AAPT] meeting) can be a very efficient way to learn enough about a new strategy to judge if it is worth investigating in more depth. Attending intensive workshops, when available, visiting other institutions to see interesting advances, or inviting individuals whose knowledge can assist in this learning process may also be useful steps.

Recommendation A2. Faculty should engage colleagues in discussions of learning goals, measures of outcomes, and strategies for a scientific approach to teaching and evaluating students' learning and observe successful approaches to engagement in classroom settings.

Faculty members can share ideas and class materials and help each other solve problems that arise as they redesign their instructional activities. They could consider including in these discussions interested colleagues from neighboring units or departments, including education departments, and encourage feedback. Many commonalities exist between STEM disciplines in terms of effective teaching.

Recommendation A3. Faculty should review and modify courses to reflect the needs of different segments of the student community, including those who might succeed in physics with some additional or different types of help.

All students can benefit from attention to general learning goals, including developing a better understanding of physics topics, solving quantitative problems, communicating effectively orally and in writing, designing experiments to answer specific questions, working effectively in groups, solving problems where the path is not clear, building models, learning how to learn, and so on. However, many students have additional specific needs that should be accommodated. Some are interested in eventually participating in scientific research. Others are interested in activities related to physics, for example, in technology, chemistry, medicine, engineering, environmental science, or businesses dependent on science. A significant number are interested in becoming teachers, science writers, or other professionals for whom a physics background can be useful. Courses and programs should be designed to reflect these diverse outcomes rather than being focused on only preparing students for graduate school.

Recommendation A4. Faculty should assess the knowledge, skills, and attitudes of students by using research-based instruments and methods.

Many research-based assessment instruments are readily accessible. Commonly used instruments for measuring conceptual understanding in an introductory physics course include the Force Concept Inventory and the Conceptual Survey of Electricity and Magnetism. Other instruments, such as the Colorado Learning About Science Survey, exist for measuring student attitudes and expectations. These are just a few of the research-developed assessment instruments that can be used by instructors to gain an understanding of what is actually happening as a result of instruction. For a more complete list, see the collection at http://www.ncsu.edu/PER/TestInfo.html. The results of these instruments should be treated as a starting point for discussions, not the definitive measure of learning. Recommended practices for using these assessment instruments can be found in many places (see, for example, Redish, 2003, Chapter 5).

Recommendation A5. Faculty should engage students in a discussion of why and how evidence-based methods that engender effective learning require changing the teaching and learning process.

Students are frequently resistant to new teaching ideas because of uncertainty and the perception that they will have to do more work. Some are wary of group work or of methods in which they may not be told the answers but are expected to determine them by themselves. By focusing on the scientific basis for the pedagogy being used, faculty can show students that the same type of reasoning was applied to the way they are learning as is applied to the science concepts that they are learning. Thus, an instructor can clearly explain to students what is expected from them and how evidence shows that this type of instruction improves learning.

DEPARTMENTAL LEADERSHIP[1]

> Any useful discussion of undergraduate education must begin by making it clear what it is that colleges are trying to achieve.
>
> —Bok (2006, p. 57)

Key Recommendation B. Department leadership should create a culture of continuous improvement in which educational innovation is encouraged, sustained when it succeeds, and tolerated when it fails.

In order for any changes in a department's educational program to benefit the department and its students—and indeed for these changes to be more than ephemeral—department leadership should support and enable this as an ongoing process. Research indicates that leadership that emphasizes teaching and manages it collaboratively with faculty correlates positively with teaching that is focused on students and their understanding (Ramsden et al., 2007).

Department leadership should act to foster a culture that encourages evidence-based instructional changes and a collective approach toward improving the overall physics program. Creating this culture requires facilitating an ongoing discussion among key players in the department that acknowledges the mission of the institution, academic unit, and department.

Detailed Recommendations for Physics Department Leadership

Recommendation B1. Departmental leadership should review and implement appropriate ideas from relevant reports.

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[1] Note that "department leadership" is used in this section to indicate the chair or head of the physics department, or of the physics and astronomy department, the head of the science faculty unit, and so on.

A number of studies have outlined issues facing departments. Several are given below for various sizes of departments and departmental contexts. These reports clarify, and in some cases codify, actions that can be taken at the departmental level.

- *Strategic Programs for Innovations in Undergraduate Physics: Project Report* (Hilborn et al., 2003; see Box 2.2), known as the SPIN-UP report, was the result of an intensive study of how some undergraduate programs thrived in a period of falling enrollments nationally.
- *Strategic Programs for Innovations in Undergraduate Physics at Two-Year Colleges: Best Practices of Physics Program* (Monroe et al., 2005), known as the SPIN-UP/TYC report, is a complementary effort to SPIN-UP that focuses on 2-year colleges.
- *Gender Equity: Strengthening the Physics Enterprise in Universities and National Laboratories* (APS, 2007) relates information gathered from Ph.D.-granting departments on techniques to improve climate and promote gender equity at research universities and national laboratories.
- *Engage to Excel: Producing One Million Additional College Graduates with Degrees in Science, Technology, Engineering, and Mathematics* (PCAST, 2012), issued by the President's Council of Advisors on Science and Technology, provides a national perspective on and recommends significantly increasing the number of high-quality STEM graduates in the United States.
- *Transforming the Preparation of Physics Teachers: A Call to Action* (National Task Force on Teacher Education in Physics, 2013; see Box 2.3), from APS, AAPT, and AIP, documents successful programs of high school teacher education in physics and provides an analysis and recommendations for building and improving such programs.

Recommendation B2. Departmental leadership should discuss and consider how to implement physics-specific learning goals, recognizing the needs of varying student constituencies, the needs of future employers and teachers of these students, and the views of alumni.

Physics departments need to be aware of and respond to the needs of the many different groups of students who enroll in introductory courses. For all students, physics education should help develop skill sets that prepare the student for further learning, for future employment, and for participation in the broader scientific enterprise.

Important goals for physics majors include the following:

- Participating in an undergraduate research experience. Programs should encourage students to apply for Research Experiences for Undergraduates and other off-campus undergraduate research experiences (see Box 4.1),

BOX 4.1
Professional Society Statements on Undergraduate Research

- American Physical Society:[1]

  The Committee on Education of the American Physical Society calls upon this nation's physics and astronomy departments to provide, as an element of best practice, all undergraduate physics and astronomy majors a significant research experience.

- American Association of Physics Teachers:[2]

  American Association of Physics Teachers urges that every physics and astronomy department provide its majors and potential physics majors with the opportunities and encouragement to engage in a meaningful and appropriate undergraduate research experience.

- Society of Physics Students:[3]

  We advocate that every student majoring in physics and/or astronomy engage in a meaningful undergraduate research experience.

- Council on Undergraduate Research Statement, Physics and Astronomy Division:[4]

  We call upon this Nation's physics and astronomy departments to provide, as an element of best practice, all undergraduate physics and astronomy majors a significant research experience.

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[1] American Physical Society, "Statement on Undergraduate Research," 2008, available at http://www.aps.org/programs/education/undergrad/faculty/ug-research.cfm.

[2] American Association of Physics Teachers, "AAPT Statement on Research Experiences for Undergraduates," adopted by the AAPT Executive Board on November 1, 2009, available at http://www.aapt.org/Resources/policy/ugresearch.cfm.

[3] Society of Physics Students, "SPS Statement Regarding Undergraduate Research," approved on December 1, 2008, available at http://www.spsnational.org/governance/statements/2008undergraduate_research.htm.

[4] Council on Undergraduate Research, Physics and Astronomy Division, Letter from Vijendra Agarwal, Chair, CUR Division of Physics and Astronomy, to the Chairs of Physics/Astronomy Departments, dated May 19, 2009, available at http://www.spsnational.org/governance/statements/cur_undergrad_research.pdf.

- Becoming effective in oral and written communication of scientific ideas,
- Achieving a basic understanding of statistical methods,
- Learning about numerical simulations, and
- Becoming familiar with current physics research.

Recommendation B3. Departmental leadership should recognize in the overall program the role of activities outside the classroom.

One of the key findings of the SPIN-UP report (Hilborn et al., 2003) is that thriving physics departments do more than just offer a series of high-quality courses. Thriving physics departments create an environment with significant out-of-class interactions among students as well as between students and faculty. Examples of ways to promote out-of-class interactions include:

- Offer active and personalized advising and career guidance.
- Sponsor and support a campus chapter of the Society of Physics Students and encourage students to participate.
- Create a comfortable student lounge or common room.
- Work with students to develop community outreach activities.
- Maintain a tutoring program matching upper-division students with introductory students needing help.
- Involve students in existing invited speakers programs with opportunities to interact and dine with these and other visitors.

Recommendation B4. Departmental leadership should establish collective responsibility and a commitment to incremental improvement, based on research on programs and courses.

Establish a faculty working group to formulate a set of realistic goals for the overall program and especially the introductory courses, consider how to reach these goals, and decide on what evidence will be used to assess progress. The resulting plans will need to consider the structure of courses and programs, the processes of teaching and assessment, and the structures that affect cohesion and motivation of students (such as advising and informal interactions between students and faculty). This group should utilize education research findings in their deliberations. Plans should include the following:

- *Identify specific evidence to help assess learning objectives for each course.*
- *Consider pedagogies that can help to realize these objectives.* As discussed throughout this report, the specific pedagogies that are appropriate will vary from one department to another. There exists a vast array of publications and websites that can help faculty select appropriate strategies, materials, and methods.
- *Work with interested department faculty members and groups of faculty to implement the agreed-upon changes.* This is one of the most difficult aspects of successful improvement programs. Faculty members who welcome experienced observers into their classes, and who consider their advice, can be more successful in implementing change. Conversations and resources should be extended to all interested faculty, including fulltime, adjunct, and

individuals who have special roles within the department (e.g., lecturers, laboratory preparation, and so on).

- *Involve students in the process of improvement.* New techniques often confuse students when they challenge them to think or act in ways different from their established patterns. Engage students from the beginning to help them understand the reasons for change and how the newly defined roles of instructor and student interact within the course. Regularly solicit student input to understand their concerns and assess how the innovations are working.
- *Assess the results of these efforts regularly.* Use the results to update the plan for continued reform and work to maintain successes when reforms are successful. Assessments that have been developed through research methods are helpful.
- *Document and share successes and instructional materials.* Organizing the concepts and writing about the results provides a focus and critical analysis of goals, methods, and outcomes that can lead to incremental improvements and lasting changes to departmental culture, particularly if the resulting publications are valued in the faculty rewards system.

Recommendation B5. Departmental leadership should provide and participate in professional development opportunities for faculty.

Ideas and methods for improving undergraduate education are being refined continuously. In just the same way that scientific research requires continual renewal, faculty and staff members must be exposed to new ideas in order to implement incremental changes to the department's programs. Examples of professional development include the following:

- Send all new faculty members to the APS/AAPT/AAS new faculty workshops and have existing faculty members attend these or similar faculty workshops;
- Take advantage of research-based online resources for individual faculty (e.g., ComPADRE.org, which is described in Box 4.2 and the PER Users' Guide, http://perusersguide.org/);
- Establish regular physics education seminars or colloquia (speakers are available on the APS PER speakers database; see http://aps.org/programs/education/speakers); and
- Implement professional development programs for all educators, including adjunct faculty, lecturers, lecture-demonstration staff, teaching assistants, and learning assistants, and including travel support for professional development workshops and seminars.

BOX 4.2
ComPADRE

The National Science Digital Library project of the National Science Foundation (NSF) began as an ambitious effort to bring together and enhance electronic resources to benefit science, technology, engineering, and mathematics (STEM) education. From the beginning, it became obvious that larger thematic collections would provide an advantage over individual projects by assembling and evaluating related resources, providing specialized tools for searches and content management, and interacting with broader audiences. A number of "pathways" projects emerged under the second round of NSF funding, among them ComPADRE (Communities of Physics and Astronomy Digital Resources for Education) for physics and astronomy educators.

ComPADRE, like other discipline-based collections, was sponsored by leading professional societies (in this case, the American Association of Physics Teachers [AAPT], the American Physical Society [APS], and Society of Physics Students [SPS]). The combined ComPADRE collections now index more than 12,000 items from high school physics to undergraduate quantum mechanics and include portals (websites) covering introductory courses, computational physics, relativity, advanced laboratories, and statistical physics, among others. In the 2010-2011 academic year ComPADRE hosted visits from about 2 million faculty and students from colleges and universities and about 6 million high school teachers and students. Today, it has become a centralized and recommended repository for outcomes of NSF-sponsored physics educational resources, collections of materials from joint society projects like the Physics Teacher Education Coalition, and indexed databases of items with topics ranging from summer research opportunities for undergraduate students to results from physics education research groups.

The most popular of ComPADRE's assets is its online physics tutorial/textbook that averages more than 1.8 million visits each month during the school year. Popularity aside, important niche audiences, like those seeking information on how to teach quantum mechanics, can find resources specifically vetted and indexed. An educator can locate materials specifically relevant to narrowly defined topics within physics and astronomy education and tailored to a specific course and grade level.

SOURCE: ComPADRE, available at http://www.compadre.org.

Recommendation B6. Departmental leadership should provide leadership to implement and support reforms.

The SPIN-UP report (Hilborn et al., 2003) found that sustained departmental leadership was critical to establishing and maintaining departmental improvements. Changes can be encouraged and sustained in a variety of ways, including the following:

- Encourage individual faculty and staff to use research-based assessments and techniques to adapt, reject, or adopt pedagogical changes;

- Establish a system for propagating and improving successful changes in courses and/or the curriculum;
- Encourage experimentation that includes well-defined assessment of progress;
- Provide support for faculty willing to experiment and practice new techniques and ideas, including letters of support for tenure/promotion files, discussions within the department, and explanations to administration, other faculty, and students;
- Consider and discuss with faculty the role that PER faculty might have in the department;
- Keep administration, faculty, and staff informed about the value of research-based educational improvements and the role played by discipline-based educational research in developing and validating these changes; and
- Implement regular classroom visits by colleagues to promote discussions of pedagogy among faculty members in a framework analogous to visiting laboratories or group seminars of colleagues engaged in similar research.

ACADEMIC ADMINISTRATORS

Key Recommendation C. Academic administrators should encourage faculty groups to seek improvement and should reward faculty and departments that are successful at implementing positive changes.

General university support for improvements in the teaching and learning of physics is essential both for departmental programs and for maintaining or improving an institution's educational reputation. As emphasized in the previous section, leadership for and implementation of change tend to come from individuals or small groups within the faculty, but making those changes systematic and persistent is a social process in which departmental and college or university-wide administration plays an important part. Grassroots reform is unlikely to be successful in the long term if the administrative structures are not in place to nurture and support it. At the same time, top-down efforts at reform will rarely work unless they are adopted and led by the faculty doing the teaching. This requires incentives for change that include powerful motivational ideas and resources that provide incentives and support.

Setting the tone from the top does not suggest that the leader give detailed prescriptions for change, but instead communicate the urgency for change and the broad directions. However, the results of research in physics education and other work in cognitive sciences, as discussed elsewhere in this report, provide ample evidence that improvement is both urgently needed, and also possible, in undergraduate physics education. Leadership needs to create an environment that nurtures, recognizes, and institutionalizes change.

Detailed Recommendations for Higher-Level Academic Administrators

Recommendation C1. Administrators should set the tone at the top.

Important first steps are to

- Empower and fund the physics department to perform an in-depth self-assessment based on the contents of this report, commit to carefully reviewing those findings, and work to implement the changes that this assessment might motivate.
- Declare publicly and consistently to other administrators and faculty within and beyond the walls of the college or university why changes are needed and how they will improve student learning and in turn the quality of the college or university.
- Emphasize that undergraduate student learning is part of the core academic mission and devote adequate resources to educational models shown by research to improve student outcomes, even if these models are not the least expensive available. Also assume an appropriate share of responsibility for the improvement of K-12 science and mathematics education, for example, by supporting disciplinary faculty in the preparation of high school teachers or the science and mathematics education of elementary school teachers.
- Finally, provide campus recognition for faculty and programs that have demonstrated an evidence-based approach to undergraduate teaching and learning. Recognition should identify and value the individuals and organizational structures that have made these improvements—especially those that implement changes that address paradigm shifts within the academic culture.

Recommendation C2. Administrators should establish a teaching and learning group or unit to advise and support faculty engaged in pedagogical improvements.

Dedicated organizational units can advise and assist faculty with pedagogical improvements, techniques, and structures. These organizational structures (often called Centers for Teaching and Learning) can also provide interdepartmental opportunities such as education-oriented colloquia for faculty to learn about and discuss pedagogy and educational change. One strategy that some institutions have found to be successful is to establish "teaching and learning seminars" to provide a mechanism for regular discussion groups about educational change.

Recommendation C3. Administrators should provide incentive funding to faculty who wish to implement evidence-based pedagogical improvements.

Incentives should

- Offer financial resources to faculty who wish to implement evidence-based improvements and couple those grants with assistance in seeking external funding and outreach to other colleagues.
- Reward a faculty member's obtaining external grants for educational activities in the same way as that faculty member is rewarded for obtaining funding for research.

Recommendation C4. Administrators should support faculty who conduct discipline-based education research and the establishment of faculty lines and/or interdisciplinary units to help develop the growth of education research in university science, technology, engineering, and mathematics departments.

As with all scholarly endeavors, engagement in PER, and discipline-based education research in general, can benefit a university by attracting top scholars who lend prestige to the institution and secure external research funds. These activities can also invigorate educational efforts on campus: A PER group can support a department's efforts to adopt new approaches by providing initial impetus, helping to fine-tune the implementation, and helping to assess the outcomes. It can similarly support local community colleges and K-12 schools. Administrators must work with the relevant departments and discipline-based educational research faculty to determine the best way to integrate them into the institution. A common route is a direct appointment in the relevant academic department, or a joint appointment involving both the relevant academic department and an education department, center, or institute focused on education research. (See Box 4.3 for

BOX 4.3
Where Does Physics Education Research Belong?

While most physics education researchers are faculty in physics departments, some debate continues about whether this is the proper home for physics education research (PER). The issues surrounding the optimal conditions for promoting the quality of scholarship and the likelihood that findings have an impact on teaching are complex. There remain robust institu-

continued

BOX 4.3 Continued

tional and societal impediments to establishing PER, and discipline-based education research in general, as sustainable fields.

In several respects the prevailing culture is built into the institutional structures of research-oriented institutions of higher education in which research and teaching are distinct categories of criteria for promotion and tenure. To the extent that education research has a home in most universities, it is almost always entirely located within schools of education, institutionally sequestered from the disciplines, and focused on pre-college education. The situation hinders PER specialists who are in colleges of education and may have specific research interests that only tangentially connect to those of their colleagues. PER specialists in a physics department may lack colleagues who share their expertise in education. A lack of a "critical mass" in a research group may limit its ability to build a national and international reputation.

Progress in PER depends on interdisciplinarity. It depends first on the participation of physicists in physics departments, who represent the core community and possess a deep, nuanced understanding of physics content. It also draws on methods and frameworks developed in other fields, historically primarily cognitive psychology and, more recently, an expanded range of scholarship—the "learning sciences" concerned with knowledge, reasoning, learning, and development.

Thus, intellectually and institutionally, PER is a hybrid crossing the discipline of physics with research on learning and instruction. Intellectually, this hybridization has allowed for significant progress, introducing new ways of thinking about how undergraduate physics education can be organized, implemented, and advanced. Institutionally, however, it presents challenges.

As the statement on PER by the APS[1] emphasizes, the continued involvement of physicists in physics departments is essential for making further progress in PER. Faculty with the necessary understanding of the subject matter, with the motivation to investigate it and with access to students studying it, are naturally located in physics departments. The significant influence of PER on physics teaching can be attributed to the fact that many of the findings, approaches, and materials have been developed by physicists working in physics departments, addressing problems important to physics faculty, and using methods familiar (or immediately graspable) by researchers in more traditional fields. Affirming and strengthening this tradition, while expanding our notion of what PER is, where it is done, and who does it, is critical for fostering the further development of fundamental insights into learning and for promoting future impact on students.

At the same time, the larger community and research universities in particular must support PER that has connections to related work conducted outside of physics departments. A number of universities have begun programs in the learning sciences. Faculty in these programs, while having homes in their respective discipline departments, enjoy enhanced opportunities for collaboration and community among scholars from various intellectual traditions that inform research on knowledge, learning, and instruction—including education, psychology, cognitive science, computer science, sociology, anthropology, and, recently, neuroscience.

The question, Where does PER belong? does not have a single answer. Much like biological physics, the diversity of research programs suggests a range of departmental contexts is necessary for fostering high-quality, influential work. Although researchers are not always directly tied to specific course improvements, effectiveness in implementing changes will typically benefit from close interactions with other physics faculty and physics instruction.

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[1] APS (American Physical Society), APS Statement on Research in Physics Education, available at http://www.aps.org/publications/apsnews/199908/statements.cfm, 1999.

a discussion of the issues surrounding PER appointments.) However, it is crucial that when such faculty are appointed, they should be rewarded for their scholarly activities in educational research as well as their contributions to the university's teaching mission.

The potential is great: research universities are natural laboratories for research on learning and teaching. The committee does not suggest that there is one model that will fit all institutions, but it is time to move past ad hoc solutions. PER and, more generally, discipline-based education research need systemic support to flourish at the university.

Recommendation C5. Administrators should include, for all faculty who teach, education research and development among the factors considered in reward structures, not just for those faculty who conduct discipline-based education research.

Reward structures should

- Recognize that major course improvements, assessment, and educational publications require creativity and systematic effort and should be considered a part of the record of achievement along with excellent teaching, research, and service.
- Recognize further that for discipline-based educational researchers, a simple division of activities into teaching, research, and service cannot always be made. An excellent treatment of how to consider the broad inclusion of scholarship of teaching is given by Boyer (1990).

Thus, institutional guidelines should acknowledge these issues and include multiple measures for all components of a faculty member's productivity. While this recommendation is not unique to physics, it is an important part of what is needed to set the appropriate tone that will allow substantive improvements in undergraduate physics education.

FUNDING AGENCIES

Key Recommendation D. Funding agencies should support positive change at all levels and should support fundamental educational research, development, adoption, and dissemination.

Funding agencies play a critical role in supporting research, development, and dissemination of innovations in undergraduate physics education. They also set an authoritative tone for the improvement of educational practice, including new emphasis for research physicists on the professional importance of effective educational practice. Current support from the National Science Foundation (NSF), the Department of Education, and private foundations, while limited, provides an important incentive for faculty and administrators to improve the learning environment in colleges and universities in the United States.

NSF's significant funding for undergraduate physics education (Henderson et al., 2012) has provided leadership through the design of its solicitations, selection of awards, and promotion of discipline-based research, research-based assessments, and innovations in undergraduate education. NSF's Broader Impacts criterion in award selection has opened an opportunity to address education issues as a component of all funded scientific research projects, but its potential to promote the adoption of research-based educational improvements has not been fully realized.

Availability of adequate funding is also essential in light of Recommendation C4, which calls for faculty appointments. For these faculty to be successful they would need to have adequate funding from both local and national sources to support their research as well as to support work of other faculty who are making changes to their undergraduate courses as recommended.

Detailed Recommendations for Funding Agencies

Recommendation D1. Agencies should support a balanced portfolio that includes dissemination of good practices and both applied and foundational education research.

Physics education research remains critical to advancing our understanding of the learning processes necessary for advances in undergraduate physics education. This research should continue to be supported by NSF Directorates of Math and Physical Sciences (MPS) as well as Education and Human Resources (EHR). The Divisions of Physics (PHY) and Materials Research (DMR) play an important role in supporting and promoting these efforts in conjunction with EHR, as this research impacts the future generations of scientists, engineers, and others involved in science-based business activities.

As in all areas of research, adequate funding is an ongoing concern for PER. However, the challenges facing physics education research, and discipline-based education research (DBER) in general, go beyond the total level of support available. A recent study of PER funding indicates that about 75 percent of the direct or indirect support for PER over the period 2006-2010 came from NSF, primarily through programs in the Directorate for Education and Human Resources (Henderson et al., 2011). Some of these programs fund basic research in science teaching and learning. However, many have the primary goal of supporting improvements in educational practice, rather than basic research. The projects funded by these programs often contain research components, but the research tends to be tightly linked to the assessment of particular classroom innovations. Moreover, in contrast to some programs that support traditional research in physics, grants funded through these programs are almost always awarded on a project-by-project basis, and no renewal mechanisms are available to support productive research programs over an extended period of time.

The current funding opportunities thus constrain PER by focusing on applied projects that can show classroom impact over short time scales. Sustained effort over long time periods is needed to establish that the results of educational innovations are robust and replicable beyond their original setting and to ensure that these innovations spread. Likewise, sustained effort is required to develop the sorts of deep insights into fundamental issues of learning that have the potential for significant impact in the long term. Thus, funding programs are needed that are adequate in size to support large multi-institutional collaborations where appropriate, flexible enough in scope to support both "classroom ready" projects and foundational research, and designed to allow productive programs to survive over long time scales.

Recommendation D2. Agencies should educate principal investigators in all areas of physics research about how physics education research (PER) methods and PER-based materials can help them build a relevant educational component for their research projects so that they have a broader impact on the formal or informal education of broad and diverse populations of learners.

NSF's Broader Impacts criterion for evaluating proposals provides a unique opportunity to influence how researchers work to improve undergraduate physics education. NSF should consider more direct ways of educating potential principal investigators about research-based educational advances that could support better the broader impacts of their projects.

Recommendation D3. Agencies should support development, validation, and implementation of new assessment instruments and provide standards for their interpretation.

Improvement of education is impossible without relevant assessments. Assessment drives innovation by identifying where and what type of change is needed and by allowing progress to be monitored. Assessment informs students about what is required (and can guide their study if used formatively) and allows instructors to determine how their students are progressing. Current widely used assessments, such as the Force Concept Inventory (FCI), the Force and Motion Conceptual Evaluation (FMCE), the Conceptual Survey of Electro-Magnetism (CSEM), and the Colorado Learning Attitudes about Science Survey, are examples of instruments that inform faculty of student learning and provide evidence to help departments evaluate the impact of instruction.[2] However, no user-friendly assessments exist to gauge progress toward the many other desired outcomes, such as problem solving, sense making, learning to learn, self-reliance, and facility in disciplinary practices (e.g., argumentation and experimental design).

Recommendation D4. Agencies should promote dissemination strategies and research on such strategies that more effectively help faculty and departments incorporate the results of education research into their courses.

A high priority for funding agencies should be to support the development of more effective methods for spreading and sustaining existing and emerging innovations. Although some limited research findings can inform sustained adoption of programs, much remains to be understood. Electronic distribution of educational resources and ideas offers new opportunities and challenges. Funding agencies should support experimentation with novel methods of dissemination and adoption and sustaining good practices. As an example, they might encourage collaboration between education researchers and open educational resource organizations such as the Community College Consortium for Open Educational Resources.[3] National and regional workshops, such as the Workshop for New Physics and Astronomy Faculty (see Chapter 2 and Henderson, 2008), are also key and should be supported and possibly expanded to include senior faculty and instructors at all levels of undergraduate education. In all cases, an increased awareness of the role that academic departments play in sustaining successful innovations should arise.

Recommendation D5. Agencies should support research into the impact of instructional improvements on students from groups underrepresented in physics and the impact on capable students who choose not to pursue physics.

Considerably more needs to be known about the differential impact of educational practices in physics on groups that are underrepresented in physics. Likewise, little physics-specific knowledge exists about why students who are capable of completing study in physics choose to leave the field. Research on these issues can improve our understanding and help guide implementation of alternative practices based on this research.

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[2] See http://www.ncsu.edu/per/TestInfo.html for links to each of these assessments.

[3] See http://oerconsortium.org/.

EDUCATION RESEARCHERS

Key Recommendation E. Physics (and other) education researchers should focus some of their efforts on critical areas, including improving fundamental understanding of learning and instruction and developing and disseminating improved assessment tools and instructional methods and materials.

Physics education researchers must continue to engage in foundational and applied research, develop new research-based pedagogies and resources, and spearhead their effective dissemination and adoption. This section concentrates on recommendations for applied research and dissemination that are likely to have the most significant near-term impact on undergraduate physics education.

The committee views as especially important aligning the development and interpretation of assessment instruments with the community's goals for developing 21st-century skills like problem solving, reasoning, and learning to learn. This alignment will enable the development of curricula and learning tools that enhance these skills. Finally, these improvements must be undertaken with an eye to improving recruitment and retention of underrepresented groups and prospective high school teachers.

Detailed Recommendations for Education Researchers

Recommendation E1. Researchers should develop instruments to include all components of expert physics learning, including physics reasoning, problem solving, experimental practices, effective study habits and attitudes, and other capabilities important for a good education.

Targeted assessment instruments are an important driver of scientifically based course change. Easily implemented multiple-choice tests can drive a series of changes and new developments, first by surprising even the relatively "in touch" instructors with the extent of student difficulties and then by providing motivation and standards for new pedagogies and instructional material that address these difficulties. Thus, the research community needs to make assessment tools easier for faculty to find and use and provide guidance in interpreting results. Priority should be given to the development of tools to assess valued student skills, such as problem solving, critical thinking, and experimental design. Existing instruments that focus on conceptual understanding were built on a research base established through detailed, in-depth investigations of the nature of this understanding and how it develops. Similar fundamental research is needed to inform the development of easily accessible assessment tools in other areas of student learning.

Recommendation E2. Researchers should develop and disseminate homework and exam problems that require and assess desirable skills.

Most homework problems available to physics instructors and students are "plug and chug" problems (Harper et al., 2007) featured in popular textbooks. These types of problems encourage poor student attitudes toward learning science (Adams et al., 2006). Alternative problem types have been developed that are shown to help improve student learning. Thus, efforts to develop and disseminate high-quality alternative problems are needed. Ideally these problems would be available and assignable through learning management systems as well as other means.

Recommendation E3. Researchers should study what makes effective teaching assistants and learning assistants and provide guidance for those preparing and training them.

Graduate and undergraduate students assist with instruction in many colleges and universities. Some research has investigated how to best prepare and train these students in a way that benefits them personally and professionally and also results in good instruction, but much additional research is needed in this area.

Recommendation E4. Researchers should apply physics education research more extensively to upper division courses.

Much of PER to date has been done on introductory-level physics courses. More recently, some researchers have been applying these ideas productively to upper-level courses. (See, for example, Thompson et al., 2011; Ambrose, 2004; Chasteen et al., 2011; and Baily et al., 2013.) The initial results from this work suggest that similar models for curriculum development are fruitful in these courses and should be encouraged. Work to re-envision and update the content of the upper division physics courses is also needed.

Recommendation E5. Researchers should continue and expand research on the impact of research-based instructional improvements on underrepresented groups and on students who are capable but now drop out of physics.

This important issue was discussed under Recommendation D5 to funding agencies.

Recommendation E6. Researchers should continue research efforts that develop a foundational knowledge base for physics education.

While research and development are needed to address the immediate issues in undergraduate physics education, the PER community must also build for the future through fundamental research on learning processes and knowledge structures. Much of this is likely to involve collaboration between physics education researchers, cognitive scientists, and neuroscientists.

Recommendation E7. Researchers should work collaboratively with federal research agencies to identify additional sources of support for research and dissemination of results.

The PER community should work with federal agencies, especially NSF, to identify new and existing mechanisms for supporting discipline-based research. The PER community should establish better ties with the Department of Education and other potential funding sources to raise awareness of existing programs and provide information about discipline-based education research that could influence the design of future funding programs.

PROFESSIONAL SOCIETIES

Key Recommendation F. Professional societies should emphasize the importance of education research and play a major role in the dissemination of its results, recognizing those who successfully improve instruction.

Professional societies play an increasingly important role as catalysts for change in undergraduate education. In physics, three organizations have invested significantly in improving undergraduate education: the American Physical Society (APS); the American Association of Physics Teachers (AAPT); and the American Institute of Physics (AIP). Professional societies have several avenues for promoting progress: convening conferences, workshops, and meetings; producing peer-reviewed journals and more generic publications like newsletters, websites, magazines, blogs, and other “general” audience formats; awarding prizes and honors to recognize and support the actions of individuals or groups; and providing general advocacy from an informed viewpoint.

Educational innovations and advances are often unfamiliar to, and even distrusted by, the physics research community and the teaching community at large. Professional societies can provide a forum and an implicit or explicit endorsement of such improvements.

Detailed Recommendations for Professional Societies

Recommendation F1. Professional societies should publicize the results and endorse the importance of educational developments.

Improving physics education requires a much more active approach than "if you build it, they will come." Bringing effectual innovations successfully and sustainably into classroom settings is perhaps the greatest challenge facing undergraduate physics education. Professional societies bring together physics professionals, many of whom teach, in an environment in which they are receptive to new ideas. Highlighting educational developments and tools is an essential component in realizing widespread usage. In addition to the New Faculty Workshop, examples include dedicated columns in electronic and print newsletters or magazines, regular articles on educational innovations and associated research results, and opinion pieces solicited from noted physicists on their use of these materials.

Recommendation F2. Professional societies should collect, review, and make available Web-based resources for individual faculty.

To encourage dissemination of innovations, professional societies need to build on the example of ComPADRE (see Box 4.2) and collect, review, and make available Web-based materials informed by education research. Providing a community-based structure to vet physics-specific materials and ideas furthers society goals and provides services that broad science organizations (e.g., all of STEM) are unable to fulfill in one-size-fits-all organizational structures.

Recommendation F3. Professional societies should convene community leaders and practitioners on a regular basis to discuss and share implementation of better practices.

Regular gatherings of departmental leaders and faculty are needed to discuss our changing understanding of undergraduate physics education and to help faculty understand how to effectively implement improvements. These efforts should include department chairs and directors of undergraduate education, new faculty, and faculty who are working to improve courses or components of a physics curriculum. Gatherings should include direct engagement with new learning techniques to model good learning practice, as well as interactive discussions on implementation, assessment, and retention.

Recommendation F4. Professional societies should publish physics education research in the general physics journals (e.g., *Physical Review Letters* and *Reviews*

***of Modern Physics*) and review in society journals other types of teaching and learning applications in addition to textbooks.**

Peer-reviewed publication venues to disseminate knowledge are necessary for recognizing the significance of physics education research among academic physicists. Beyond the traditional publications, such as *Physical Review Special Topics—Physics Education Research* and the *American Journal of Physics*, appropriate education research articles should be published in journals, such as *Physical Review Letters* and *Reviews of Modern Physics,* that are read by the community at large, as well as in "magazine-style" publications like *The Physics Teacher* and *Physics Today*, where several important articles have appeared. Encouraging publication of articles in these widely respected research journals and popular publications both legitimizes the results among a broader community and shows that publishable scholarship is what academic physicists do. These venues also offer a broader dissemination of research-based pedagogies among the international community.

Recommendation F5. Professional societies should expand at meetings the presence of sessions on educational innovations and practices.

National, topical, and regional physics meetings should host and highlight sessions that feature innovations in pedagogy, understanding and assessing student learning and tools available to explore and document theses issues. APS division, topical group, and section meetings should offer sessions during their annual meetings on these topics. APS and AAPT should link and strongly promote meetings, when possible, to allow crossover between constituencies and help faculty who are primarily engaged in research to understand how pedagogy affects their effectiveness in advancing the next generation of scientists. Societies should make education-related sessions available electronically to enhance dissemination.

Recommendation F6. Professional societies should help guide student expectations and improve students' understanding of pedagogical improvements.

While faculty and departments are primary agents in implementing change, students are the direct consumers of these changes. SPS and other physics student groups can and should play important roles in advocacy, feedback, and encouraging curricular changes. Since pedagogical changes will often be looked on with trepidation by students who have obtained good grades under traditional instruction, enlisting students and student organizations can help allay fears and actively engage them in implementing improvements.

CONCLUSIONS

These recommendations represent the committee's consensus on adaptable solutions for problems that face undergraduate physics education. They also represent a set of actions that can be taken to work toward a better understanding of these problems and solutions for the future. In developing these recommendations, the committee acted as scientists. It looked carefully at current practices in undergraduate physics education, noting a number of concerns and sources for optimism.

As the physics community works to improve undergraduate physics education, it needs to be aware that the job will never be finished. A statement frequently attributed to Melba Phillips makes the point well: "The trouble with problems in physics education is that they don't stay solved." In making this assertion, Dr. Phillips was noting that students, faculty, society, and physics are all changing continuously. While instructional methods found to be effective today must be applied, the community must also be aware of changes that will necessitate further modifications tomorrow. In this way physics teaching can be kept up-to-date just as the fundamentals of physics are kept up-to-date.

REFERENCES

AAPT (American Association of Physics Teachers). 2009. "AAPT Statement on Research Experiences for Undergraduates." Adopted by the AAPT Executive Board on November 1, 2009. Available at http://www.aapt.org/Resources/policy/ugresearch.cfm.

Adams, W.K., Perkins, K.K., Podolefsky, N.S., Dubson, M., Finkelstein, N.D., and Wieman, C.E. 2006. A new instrument for measuring student beliefs about physics and learning physics: The Colorado Learning Attitudes about Science Survey. *Physical Review Special Topics—Physics Education Research* 2(1):010101-1.

Ambrose, B.S. 2004. Investigating student understanding in intermediate mechanics: Identifying the need for a tutorial approach to instruction. *American Journal of Physics* 72**:**453.

APS (American Physical Society). 1999. APS Statement on Research in Physics Education. Available at http://www.aps.org/publications/apsnews/199908/statements.cfm.

———. 2007. *Gender Equity: Strengthening the Physics Enterprise in Universities and National Laboratories. May 6-8, 2007.* Conference Report. Available at http://www.aps.org/programs/women/workshops/gender-equity/upload/genderequity.pdf; last accessed on April 23, 2013.

———. 2008. "Statement on Undergraduate Research." Available at http://www.aps.org/programs/education/undergrad/faculty/ug-research.cfm.

Baily, C., Dubson, M., and Pollock, S.J. 2013. Research-based course materials and assessments for upper division electrodynamics (E&M II). Pp. 54-57 in *2012 Physics Education Research Conference.* AIP Conference Proceedings 1513. AIP Press, Melville, N.Y.

Bok, D. 2006. *Our Underachieving Colleges: A Candid Look at How Much Students Learn and Why They Should Be Learning More.* Princeton University Press, Princeton, N.J.

Boyer, E. 1990. *Scholarship Reconsidered: Priorities of the Professoriate.* Jossey-Bass Publishers, San Francisco, Calif.

Chasteen, S.V., Pepper, R.E., Pollock, S.J., and Perkins, K.K. 2011. But does it last? Sustaining a research-based curriculum in upper-division electricity and magnetism. Pp. 139-142 in *2011 Physics Education Research Conference.* AIP Conference Proceedings 1413. AIP Press, Melville, N.Y.

Council on Undergraduate Research, Physics and Astronomy Division. 2009. Letter from Vijendra Agarwal, Chair, CUR Division of Physics and Astronomy, to the Chairs of Physics/Astronomy Departments, dated May 19, 2009. Available at http://www.spsnational.org/governance/statements/cur_undergrad_research.pdf.

Harper, K.A., Freuler, R.J., and Demel, J.T. 2007. Cultivating problem solving skills via a new problem categorization scheme. Pp. 141-144 in *2006 Physics Education Research Conference*. AIP Conference Proceedings 883. AIP Press, Melville, N.Y.

Henderson, C. 2008. Promoting instructional change in new faculty: An evaluation of the physics and astronomy new faculty workshop. *American Journal of Physics* 76:179.

Henderson, C., Beach, A., and Finkelstein, N. 2011. Facilitating change in undergraduate STEM instructional practices: An analytic review of the literature. *Journal of Research in Science Teaching* 48(8):952-984.

Henderson, C., Barthelemy, R., Finkelstein, N., and Mestre, J. 2012. Physics education research funding census. Pp. 211-214 in *2011 Physics Education Research Conference*. AIP Conference Proceedings 1413. AIP Press, Melville, N.Y.

Hilborn, R., Howes, R., and Krane, K., eds. 2003. *Strategic Programs for Innovations in Undergraduate Physics: Project Report*. Known as the SPIN-UP report. American Association of Physics Teachers, College Park, Md. Available at http://www.aapt.org/Programs/projects/ntfup.cfm.

Monroe, M.B., O'Kuma, T.L., and Hein, W. 2005. *Strategic Programs for Innovations in Undergraduate Physics at Two-Year Colleges: Best Practices of Physics Programs*. Known as the SPIN-UP/TYC report. American Association of Physics Teachers, College Park, Md. Available at http://www.aapt.org/projects/spinup-tyc.cfm.

National Task Force on Teacher Education in Physics. 2013. *Transforming the Preparation of Physics Teachers: A Call to Action*. American Physical Society. Available at http://www.ptec.org/webdocs/2013TTEP.pdf; accessed on April 23, 2013.

PCAST (President's Council of Advisors on Science and Technology). 2012. *Engage to Excel: Producing One Million Additional College Graduates with Degrees in Science, Technology, Engineering, and Mathematics*. Executive Office of the President, Washington, D.C. Available at http://www.whitehouse.gov/ostp/pcast.

Ramsden P., Prosser, M., Trigwell, K., and Martin, E. 2007. University teachers' experiences of academic leadership and their approaches to teaching. *Learning and Instruction* 17:140-155.

Redish, E.F. 2003. *Teaching Physics with the Physics Suite*. John Wiley and Sons, New York, N.Y.

Society of Physics Students. 2008. "SPS Statement Regarding Undergraduate Research." Approved on December 1, 2008. Available at http://www.spsnational.org/governance/statements/2008undergraduate_research.htm.

Thompson, J.R., Christensen, W.M., and Wittmann, M.C. 2011. Preparing future teachers to anticipate student difficulties in physics in a graduate-level course in physics, pedagogy, and education research. *Physical Review Special Topics—Physics Education Research* 7:010108-1-11.

Appendixes

A

Statement of Task

The committee will produce a report that identifies the goals and challenges facing undergraduate physics education and identifies how best practices for undergraduate physics education can be implemented on a widespread and sustained basis. In so doing, the committee will assess the status of physics education research (PER) and will discuss how PER can assist in accomplishing the goal of improving undergraduate physics education best practices and education policy. As part of this task, the committee will:

1. Assess the current status of Physics Education and PER by:

    a. Describing the current landscape of undergraduate physics education with a focus on its ability to recruit and retain undergraduate students in physics, to prepare and support teachers of physics and physical science from K-12, and to provide meaningful physics education to other science and technology professionals;
    b. Discussing progress and issues in the PER field, including preparation of a synthesis of findings from this body of research; and
    c. Identifying and examining the efficacy of current assessment methods.

2. Address the future of undergraduate physics education and PER by:

    a. Identifying best practices in undergraduate physics education for majors and non-majors alike;

b. Identifying those practices and programs in physics that effectively engage, recruit, prepare, and support current and future pre-college teachers;
c. Considering mechanisms to deploy assessment tools by which best practices and research-based findings in physics education can be scaled to make them more widespread and sustained;
d. Identifying the future directions of PER;
e. Recommending strategies for academic institutions and policymakers to implement those mechanisms to improve undergraduate physics education.

B

Meeting Agendas

MEETING 1: MARCH 18-19, 2011
WASHINGTON, D.C.

March 18, 2011

Closed Session

8:00 am	Committee Discussions

Open Session

1:45 pm	Welcome from Chair
1:50 pm	Perspectives from Sponsor: NSF-Physics and NSF-Education
2:10 pm	Question and Answer with the Sponsors

Closed Session

2:45 pm	Committee Discussions
8:00 pm	Adjourn for the Day

March 19, 2011

Closed Session

8:30 am	Committee Discussions
2:30 pm	Meeting Adjourns

MEETING 2: MAY 31-JUNE 1, 2011
IRVINE, CALIFORNIA

May 31, 2011

Closed Session

12:00 pm	Committee Discussion
8:00 pm	Adjourn for the Day

June 1, 2011

Open Session

8:15 am	Open Committee Discussions
10:10 am	Topic: Preparation for K-12 Speakers, Joe Wise, New Roads School
10:50 am	Overview and Highlights of the Forthcoming UDPER Report, Michael Loverude
11:30 am	General Discussion of Morning Talks with Speakers
12:15 pm	Working Lunch

Closed Session

12:45 pm	Committee Discussion
5:30 pm	Meeting Adjourns

MEETING 3: JULY 25-26, 2011
IRVINE, CALIFORNIA

July 25, 2011

Closed Session—12:00 pm to 6:00 pm

July 26, 2011

Closed Session—7:45 am to 12:00 pm

Open Session

12:00 pm	Working Lunch
1:00 pm	Open Session Welcome and Introductions
1:10 pm	Digital PER User's Guide, Sam McKagan
1:55 pm	Open Discussion

Closed Session—2:15 pm to 5:30 pm

MEETINGS 4 AND 5

The committee's two final meetings, on September 22-24, 2011, in Woods Hole, Massachusetts, and January 13-14, 2012, in Washington D.C., were held entirely in closed session.

C

Biographies of Committee Members

DONALD N. LANGENBERG, *Chair,* is the chancellor and professor emeritus in the Department of Physics at the University of Maryland. He earned his B.S. at Iowa State University, his M.S. at the University of California, Los Angeles, and his Ph.D. at the University of California, Berkeley. Dr. Langenberg has served as chancellor of the University System of Maryland and the University of Illinois, Chicago. He has received numerous honorary awards and degrees and has served on a number of boards. He served as chairman of the board of directors of the American Association for the Advancement of Science (AAAS) and the executive board of the National Association of the State Universities and Land Grant Colleges. He has also served on the board of directors of the Alfred P. Sloan Foundation and the board of trustees of the University of Pennsylvania, as well as president of the American Physical Society (APS).

SUZANNE BRAHMIA is director of the extended physics program and associate director of the Math and Science Learning Center at Rutgers—The State University of New Jersey. Dr. Brahmia has taught physics at the middle school through university levels since 1987. Prior to attending graduate school at Cornell University where she conducted research in solid-state physics, she was a Peace Corps volunteer teaching physical science in a rural French-speaking African high school (grades 7-12). She brings expertise in the areas of bridging the gender and ethnicity gap in science, technology, engineering, and mathematics and in developing curriculum for grades 6-13. Dr. Brahmia designed and runs an innovative two-semester introductory physics course for freshman engineering majors who are underprepared in mathematics. She has published several papers on bridging the ethnicity and gender gaps in engineering based on the success of the Extended Physics program. She is also the associate director for physics at the Math and Science Learning Center, which provides academic support for undergraduates in math, physics, chemistry and biology through coordination of the student support services, and provides outreach to regional K-12 students and teachers. In this capacity, she works with physics faculty to integrate research-based teaching activities into their courses and conducts summer workshops for middle and high school science teachers. Dr. Brahmia is the co-principal investigator (co-PI) on two National Science Foundation (NSF)-funded curriculum development projects. One is for college students, the Investigative Science Learning Environment project, which she developed with Alan Van Heuvelen and Eugenia Etkina. The other curricular project is for precollege students, Physics Union Mathematics, where she develops innovative materials that promote mathematical reasoning for the middle school/early high school levels of physics. She is the co-author with Peter Lindenfeld of a textbook for college science majors titled *Physics, the First Science.*

JERRY P. GOLLUB (NAS) is professor of natural sciences (physics) at Haverford College and an adjunct professor at University of Pennsylvania. He is a member of the National Academy of Sciences (NAS), a fellow of the American Academy of Arts and Sciences, and a recipient of the Fluid Dynamics Prize and the Award for Research in Undergraduate Institutions of the APS. A past member of the NAS Governing Council, Dr. Gollub was co-chair of the National Research Council (NRC) study for the report *Learning and Understanding: Improving Advanced Study of Mathematics and Science in U.S. High Schools.* He currently serves on the NRC Board on Science Education. His research is concerned with nonlinear phenomena and fluid dynamics. He is coauthor of *Chaotic Dynamics: An Introduction*, an undergraduate textbook. Dr. Gollub teaches science courses designed for a broad audience, including "Fluids in Nature," "Predictability in Science," and "Energy Options and Science Policy." He has been provost of Haverford College and chair of its Educational Policy Committee. He served as chair of the Division of Fluid Dynamics of the APS and as a member of its executive board. In 2008-2009 he was the Leverhulme Visiting Professor at University of Cambridge and an overseas fellow of Churchill College. He has served on the editorial boards of *Physical Review Letters* and *Physics of Fluids* and has been an invited columnist for *Physics Today*. Dr. Gollub received his Ph.D. in experimental condensed matter physics at Harvard University in 1971.

DAVID HAMMER is a professor in education and physics and astronomy and co-director of the Center for Engineering Education and Outreach at Tufts University. Previously, he was a professor in physics and curriculum and instruction, a member of the Physics Education Research Group, and the coordinator of the Science Teaching Center at the University of Maryland. Dr. Hammer received his B.A. in physics from Princeton University, an M.A. in physics and a Ph.D. in science and mathematics education from the University of California, Berkeley. His principal focus is studying how science, mainly physics, is learned and taught across ages from young children through adults.

CHARLES HENDERSON is an associate professor at Western Michigan University (WMU), with a joint appointment between the Physics Department and the WMU Mallinson Institute for Science Education. His research within the field of physics education focuses on scaling and sustaining the use of teaching and learning ideas developed by the physics education research (PER) community. This work has involved both assessments of the current use of PER ideas by traditional physics faculty as well as the development and testing of strategies for increasing this use. Dr. Henderson is the physics education research editor for the *American Journal of Physics*. He has held several leadership positions within the PER community including chair of the American Association of Physics Teachers (AAPT) Committee on Research in Physics Education, president of the Michigan Section of AAPT, editor of the *Proceedings of the Physics Education Research Conference,* and member of Physics Education Research Leadership and Organizing Council. In spring 2010, he was a Fulbright Scholar working with the Finnish Institute for Educational Research at the University of Jyväskylä, Finland.

PAULA HERON is a professor of physics at the University of Washington. She received a B.Sc. and M.Sc. in physics from the University of Ottawa and a Ph.D. in theoretical condensed matter physics from the University of Western Ontario. She has broad expertise in physics education research, undergraduate education, teaching assistant preparation, and K-12 teacher education. Dr. Heron has given invited talks at conferences and in university physics departments in the United States, Canada, and Europe. She is frequently consulted by national organizations devoted to improving teacher education, such as the Physics Teacher Education Coalition and the National Task Force on Physics Teacher Education. She has served on numerous NSF review committees and on advisory boards to NSF-funded projects. She has been elected to the executive committee of the Forum on Education of the APS and has served as chair of the Committee on Research in Physics Education of AAPT. Dr. Heron is the co-founder and co-chair of the biannual conference series "Foundations and Frontiers in Physics Education Research," which began in 2005 and has become the leading conference devoted to PER in North America. She was editor of the proceedings of the annual 2-day Physics Education Research Conference in 2005 and conference co-chair in 2010. In 2007 Dr. Heron was elected fellow of the APS. In 2008 she shared the APS Physics Education Award with Lillian C. McDermott, Peter S. Shaffer, and the Physics Education Group at the University of Washington.

THEODORE HODAPP is the director of education and diversity for the APS and project director and PI of the Physics Teacher Education Coalition (PhysTEC) project. He served as a program director for NSF's Division of Undergraduate Education (DUE), working with programs including teacher education, curriculum development, assessment, and digital libraries. Prior to this he was a professor of physics and chair of the Hamline University Physics Department. He is currently a research professor at Hamline. He served as chair of the Council on Undergraduate Research's Division of Physics and Astronomy and served on its executive committee. He worked as a visiting scientist at the 3M corporate research laboratories and holds several patents in optical devices. He is a fellow of the APS and has published work in atomic, molecular, and optical physics, physics teacher education, and diversity issues.

MICHAEL P. MARDER is a professor of physics and associate dean for science and mathematics education at the University of Texas, Austin. He received his A.B., summa cum laude, from Cornell University in 1982 and his Ph.D. in physics from the University of California, Santa Barbara, in 1986. His research interests are in nonlinear dynamics, and he also serves as co-director of UTeach, a program at University of Texas, Austin, for the preparation of secondary math and science teachers. UTeach serves as a model for expanding opportunities for developing science and mathematics in K-12 and is being replicated at an increasing number of universities—currently more than 20 nationwide. Dr. Marder also directs programs to help improve undergraduate instruction at the university and to increase access of underrepresented K-12 students to careers involving science and mathematics. Among his honors are the Elizabeth Shatto Massey Award for Excellence in Teach Education and Fellowships of the APS, the Exxon Education Foundation, and the Sloan Foundation.

JOSÉ P. MESTRE is professor of physics and educational psychology and associate dean for research at the University of Illinois, Urbana-Champaign. Since earning his Ph.D. in theoretical nuclear physics in 1979, his research has focused on the learning of physics, making many pioneering contributions in areas such as the acquisition and use of knowledge by experts and novices, transfer of learning, and problem solving. He was among the first to publish scholarly articles on the use of classroom polling technologies to promote active learning in large classes and is a co-developer of Minds-On Physics, an activity-based high school physics curriculum that is heavily informed by learning research. Most recently, his research has focused on applications of methodologies common in cognitive science (e.g., eye-tracking) to study learning and information processing by physics novices and experts. In 2001 he offered congressional testimony before the U.S. House of Representatives Science Committee's Subcommittee on Research at a hearing titled "Classrooms as Laboratories: The Science of Learning Meets the Practice of Teaching." His past and present service includes the NRC's Mathematical Sciences Education Board and the Committee on Developments in the Science of Learning; the College Board's Sciences Advisory Committee, SAT Committee, and Council on Academic Affairs; the Educational Testing Service's Visiting Committee and Graduate Research Examination Technical Advisory Committee; the editorial boards of *The Physics Teacher* and the *Journal of the Learning Sciences*; the Committee on Education of the APS; the Physics Education Research Leadership Organizing Council of AAPT; and the Expert Panel of the Federal Coordinating Council for Science, Engineering and Technology. He has published numerous research and review articles on science learning and teaching and has co-authored or co-edited 18 books.

MARY BETH MONROE is a professor of physics and the department chair in the Department of Physical Science at Southwest Texas Junior College. Ms. Monroe received her B.S. degree in physics from Sam Houston State University and her M.S. in physics with a double minor in junior college teaching and math. Ms. Monroe is a fellow of the APS and a member of AAPT, AAAS, Texas Section AAPT, Texas Section APS, Society of Physics Students, and the Texas Community College Teachers Association. She has served 12 years as a member of the AAPT Executive Board (two terms as the TYC representative to the board and a 6-year term as AAPT secretary), and she is currently on the presidential track of the AAPT (vice president, president elect, president, and past president), serving as vice president in 2012. She served as PI for "The Two Year College in the Twenty First Century (TYC21)," an NSF/DUE award to AAPT (1995-2000) and as co-PI and project director for "Strategic Programs for Innovations in Undergraduate Physics at Two Year Colleges (SPIN-UP/TYC)," an NSF/DUE-ATE award to AAPT (2002-2004). From 1991-2004, Ms. Monroe was a staff member for the Physics Enhancement Program for Two Year Colleges, funded by Texas A&M University, Lee College, and NSF. From 2000-2005, she served on the NSF National Visiting Committee for the Pennsylvania Collaborative for Excellence in Teacher Preparation. She has played a leading role in developing networks among physicists teaching in 2-year colleges that have led both to their increasing involvement in AAPT and to better teaching for the students who study physics in these schools. In 2009 Ms. Monroe was awarded the Melba Newell Phillips Medal from the AAPT in recognition of her creative leadership and dedicated service that have resulted in exceptional contributions within AAPT.

VALERIE OTERO is an associate professor of science education and is involved in several large projects throughout the University of Colorado, Boulder, and throughout the United States. She is the director of the Colorado Learning Assistant Program, the Colorado Noyce Fellowship program, and the CU-Teach program. Dr. Otero has been involved with the PER community since 1995, when she began her doctoral work in PER. She has served on the Physics Education Research Leadership Organizing Council, on the Research in Physics Education Committee for AAPT, and she currently serves on the National Task Force for Teacher Education in Physics. Her research spans from studies of physics teacher knowledge to studies of how both majors and non-majors learn various concepts in physics and the nature of science. Dr. Otero has published broadly from *Science* magazine to *Science and Children* magazine. She is co-author of the popular Physics and Everyday Thinking curriculum, used in physics departments throughout the United States. She has been invited to give hundreds of talks about physics education and physics teacher education throughout the United States and in Italy, Saudi Arabia, and Korea. Dr. Otero is the PI for more than $14 million in grants to improve mathematics and science education. As a first generation college student from a Hispanic grocery store family, she is committed to increasing access and opportunities for students of all ages to get the most out of their science education.

DAVID E. PRITCHARD attended the California Institute of Technology (B.S., 1962) and Harvard University (Ph.D., 1968), and has been with Massachusetts Institute of Technology (MIT) since 1968, where he is now the Cecil and Ida Green Professor of Physics. His research accomplishments span modern atomic physics, including laser spectroscopy, atom-atom and atom-molecule collisions, atomic line broadening, van der Waals molecules, atom optics, atom trapping, atom interferometry, precision mass measurement, atom interferometry with Bose Einstein Condensates, and condensed matter physics using ultracold bosons and fermions. His group invented the MOT, a laser trap for cold atoms, as well as the Ioffe-Pritchard trap, both workhorses in the study of ultracold atoms and molecules. Dr. Pritchard has mentored four winners of national thesis awards and three Nobel Prize winners. He is a member of the NAS and a fellow of the American Academy for Arts and Sciences, AAAS, the APS, and the Optical Society of America (OSA). Dr. Pritchard has won the Broida and Schawlow prizes from the APS, the Max Born Award from OSA, and the IUPAP Senior Scientist Medal in Fundamental Metrology. Dr. Pritchard has a lifelong interest in teaching problem solving and is the author of *A Mechanics Workbook* and founded Effective Educational Technologies, which developed myCyberTutor—now sold by Pearson Education as MasteringPhysics.com, MasteringChemistry.com, etc. He was the first major coordinator in the MIT Physics Department and won a Dean's Teaching and Advising Award and the Ethyl Murman Award for Advising at MIT (2010). His education research group is developing new pedagogy for teaching problem solving.

JAMES SCHAFER is a physics instructor at the Science, Mathematics and Computer Science Magnet Program at Montgomery Blair High School in Silver Spring, Maryland. He teaches a variety of courses related to the study of physics, including thermodynamics, quantum physics, advanced placement physics, mathematical physics, and other introductory physics courses. He was the recipient of the 2011 Montgomery County Teacher of the Year award and was chosen as a finalist for the 2011 Maryland State Teacher of the Year. As an educator, his focus outside of the classroom has been on community outreach for physics and engineering. He is an event coordinator and judge for Final Frontiers, an engineering competition sponsored by the Maryland Space Business Roundtable. He has participated in a number of professional development groups focusing on physics education, including the NASA Teachers Advanced Study Institute and the University of Maryland Physics Education Research Group. He is an active member of AAPT and has served as a field tester for educational materials developed by that group. In his role as sponsor and coach for the Montgomery Blair Physics Club, he has had two students earn places on the International Physics Team, where those students earned gold and silver medals. He is the recipient of the 2010 Marian Greenblatt Excellence in Teaching Award, he is nationally board certified in physics for adolescence and young adults, and he is a multiyear recipient of the Intel Science Talent Search Teacher of Merit Award.

JACK M. WILSON is currently the president emeritus of the University of Massachusetts. Prior to that, he served as vice president for academic affairs of the University of Massachusetts System and held several positions at Rensselaer Polytechnic Institute, including professor of physics, dean of undergraduate education, interim provost, and founding director of the Anderson Center for Innovation in Undergraduate Education. He has served on the boards of several national organizations, including the board of directors of the American Public and Land Grant Universities, the board of directors of the Alliance for Research in Science and Technology for America, and the U.S. Council on Competitiveness. Dr. Wilson is a fellow of the APS, was awarded the Distinguished Service Citation from AAPT, and served as chair of the APS Forum on Education during 2001-2002.

HUNG-HSI WU is an emeritus professor of mathematics at the University of California, Berkeley, where he taught from 1965 to 2009. He is a differential geometer by profession and has authored research papers and research monographs. He has also written three graduate-level math textbooks in Chinese. In 1992, he was moved by what he witnessed in mathematics education reform and was determined to initiate change in mathematics education. After 1996, he started to participate in the education process full-time, first as a critic and then as a member of various state and national committees. He probably played a role in changing the practices of professional development in California and the attitude of textbook publishers toward textbook writing. His latest project is the improvement of the professional development of math teachers, both pre-service and in-service. He has been engaged in in-service work since 2000, and starting with 2006, he has begun working on the pre-service professional development of high school teachers.

DEAN ZOLLMAN is the William and Joan Porter University Distinguished Professor and head of the Department of Physics at Kansas State University. He also holds the title of Distinguished University Teaching Scholar. He has focused his scholarly activities on research and development in physics education since 1972. He has received three major awards—the NSF Director's Award for Distinguished Teacher Scholars (2004), the Carnegie Foundation for the Advancement of Teaching Doctoral University Professor of the Year (1996), and the AAPT Robert A. Millikan Medal (1995). His present research concentrates on investigating the mental models and operations that students develop as they learn physics and how students transfer knowledge in the learning process. He also applies cutting-edge technology to the teaching physics and to providing instructional and pedagogical materials to physics teachers, particularly those teachers whose background does not include a significant amount of physics. He has twice been a Fulbright Fellow in Germany—in 1989 at Ludwig-Maximilians University, Munich, and in 1998 at the Institute for Science Education at the University in Kiel. In addition to numerous papers in refereed journals, Dr. Zollman is co-author of six video discs for physics teaching, the Physics InfoMall database, a textbook and Visual Quantum Mechanics project that developed interactive materials for teaching quantum physics to three different groups of students, including non-science students, science and engineering students, and students interested in biology and medicine.

D

Additional Suggested Reading Material

CHAPTER 2

Adams, W.K., K.K. Perkins, N.S. Podolefsky, M. Dubson, N.D. Finkelstein, and C.E. Wieman, 2006. A new instrument for measuring student beliefs about physics and learning physics: The Colorado Learning Attitudes about Science Survey. *Physical Review Special Topics—Physics Education Research* 2(1):010101-1.

American Institute of Physics. 2001. What's important? *Physics Trends,* Fall. AIP Statistical Research Center. Available at http://www.aip.org/statistics/trends/reports/fall01a.pdf.

Beichner, R.J., Saul, J.M., Allain, R.J., Deardorff, D.L., and Abbott, D.S. 2000. Introduction to SCALE UP: Student-Centered Activities for Large Enrollment University Physics. *Proceedings of the 2000 Annual Meeting of the American Society for Engineering Education.* Session 2380. Available at http://www.ncsu.edu/PER/Articles/01ASEE_paper_S-UP.pdf.

Belcher, J.W. 2003. Improving Student Understanding with TEAL. *The MIT Faculty Newsletter* 16(2):1 and 8-11.

Breslow, L. 2010. Wrestling with Pedagogical Change: The TEAL Initiative at MIT. *Change: The Magazine of Higher Learning* 42(5):23-29.

Carrell, S., and J. West. 2010. Does professor quality matter? Evidence from random assignment of students to professors. *Journal of Political Economy* 118:409-432.

Etkina, E., Van Heuvelen, A., White-Brahmia, S., Brookes, D.T., Gentile, M., Murthy, S., Rosengrant, D., and Warren, A. 2006. Scientific abilities and their assessment. *Physical Review Special Topics—Physics Education Research* 2:020103.

Franz, J.R. 1995. *Improving the Climate for Women in Physics.* American Physical Society. Available at http://www.aps.org/programs/education/conferences/chairs/1995/upload/climate.pdf; accessed on June 19, 2012.

Halloun, I., and Hestenes, D. 1985. The initial knowledge state of college physics students. *American Journal of Physics* 53:1043-1055.

Kohlmyer, M.A., Caballero, M.D., Catrambone, R., Chabay, R.W., Ding, L., Haugan, M.P., Jackson Marr, M., Sherwood, B.A., and Schatz, M.F. 2009. A tale of two curricula: The performance of two thousand students in introductory electromagnetism. *Physical Review Special Topics—Physics Education Research* 5:020105.

Laws, P. 1991. Calculus-based physics without lectures. *Physics Today* 44(12):24-31.

———. 1997. *Workshop Physics Activity Guide.*John Wiley and Sons, New York, N.Y.

Laws, P.W., Teese, R.B., Willis, M.C., and Cooney, P.J. 2009. *Physics with Video Analysis.* Vernier, Portland, Ore.

Miyake, A., Kost-Smith, L.E., Finkelstein, N.D., Pollock, S.J., Cohen, G.L., and Ito, T.A. 2010. Reducing the gender achievement gap in college science: A classroom study of values affirmation. *Science* 330:1234.

Monroe, M.B., O'Kuma, T.L., and Hein, W. 2005. *Strategic Programs for Innovations in Undergraduate Physics at Two-Year Colleges: Best Practices of Physics Programs.* Known as the SPIN-UP/TYC report. American Association of Physics Teachers, College Park, Md. Available at http://www.aapt.org/projects/spinup-tyc.cfm.

Mulvey, P., and Shindel, B. 2010. Physics Bachelor's Initial Employment Data from the Degree Recipient Follow-Up Survey for the Classes of 2006 and 2007. *Focus On,* June. AIP Statistical Research Center. Available at http://www.aip.org/statistics/trends/reports/emp2010.pdf.

———. 2010. Physics Bachelor's One Year Later—Data from the Degree Recipient Follow-Up Survey for the Classes of 2006 and 2007. *Focus On,* May. AIP Statistical Research Center. Available at http://panda.unm.edu/pandaweb/undergraduate/careerinfo.pdf.

Mulvey, P.J., and Nicholson, S. 2011. Physics Enrollment—Results from the 2008 Survey of Enrollments and Degrees. *Focus On,* February. AIP Statistical Research Center. Available at http://www.aip.org/statistics/trends/reports/physenroll2008.pdf, accessed on April 23, 2013.

———. 2011. Physics Undergraduate Degrees—Results from the 2008 Survey of Enrollments and Degrees. *Focus On,* May. AIP Statistical Research Center. Available at http://www.aip.org/statistics/trends/reports/physund08.pdf.

———. 2011. Physics Undergraduate Enrollments and Degrees—Results from the 2007 Survey of Enrollments and Degrees. *Focus On,* January. AIP Statistical Research Center. Available at http://www.aip.org/statistics/trends/reports/EDphysund07.pdf.

National Center for Education Statistics. 2012. Fast Facts web page. Available at http://nces.ed.gov/fastfacts/display.asp?id=98; accessed on June 19, 2012.

Neuschatz, M., and McFarling, M. 2003. Physics in the Two-Year Colleges: 2001-02. *AIP Report,* June. AIP Pub. Number R-436. AIP Statistical Research Center. Available at http://www.aip.org/statistics/trends/reports/tycreport.pdf.

Otero, V., and Gray, K. 2008. Attitudinal gains across multiple universities using the Physics and Everyday Thinking curriculum. *Physics Review Special Topics—Physics Education Research* 4:020104.

Perkins, K.K., and Wieman, C.E. 2005. Free on-line resource connects real-life phenomena to science. *Physics Education* January: 93-95.

———. 2005. The surprising impact of seat location on student performance. *The Physics Teacher* 43(1):30-33.

Pollock, S. 2007. A longitudinal study of the impact of curriculum on conceptual understanding in E&M. In *2007 Physics Education Research Conference Proceedings* (L. McCullough, L. Hsu, and P. Heron, eds.). AIP Press, Melville, N.Y.

Rutgers Physics and Astronomy Education Research Group. 2012. Scientific Abilities Rubrics. Available at http://paer.rutgers.edu/ScientificAbilities/default.aspx.

Sonnert, G., and Holton, G. 1995. *Who Succeeds in Science? The Gender Dimension.* Rutgers University Press, New Brunswick, N.J.

Tesfaye, C.L., and White, S. 2012. High School Physics Teacher Preparation. *Focus On,* February. AIP Statistical Research Center. Available at http://www.aip.org/statistics/trends/reports/hsteachprep.pdf.

White, S., and Tesfaye, C.L. 2010. Who Teaches High School Physics? Results from the 2008-09 Nationwide Survey of High School Physics Teachers. *Focus On,* November. AIP Statistical Research Center. Available at http://www.aip.org/statistics/trends/reports/hsteachers.pdf.

Zollman, D., and Fuller, R. 1994. Teaching and learning physics with interactive video. *Physics Today* 47(4):41-47.

CHAPTER 3

American Physical Society. 1999. APS Statement on Research in Physics Education. Available at http://www.aps.org/publications/apsnews/199908/statements.cfm.

Arons, A.B. 1997. *Teaching Introductory Physics.* John Wiley and Sons, New York, N.Y.

Atkinson, R.K., Derry, S.J., Renkl, A., and Wortham, D.W. 2000. Learning from examples: Instructional principles from the worked examples research. *Review of Educational Research* 70(2):181-214.

Baily, C., and Finkelstein, N. 2011. Refined characterization of student perspectives on quantum physics. *Physical Review Special Topics—Physics Education Research* 6:020113.

Baily, C., Dubson, M., and Pollock, S.J. In review. Research-based course materials and assessments for upper division electrodynamics (E&M II). In *2012 Physics Education Research Conference Proceedings* (S. Rebello, P. Engelhardt, and A. Churukian, eds.). AIP Press, Melville, N.Y.

Burnstein, R., and Lederman, L.M. 1996. Report on progress in using a wireless keypad response system. In *Proceedings of the ICUPE.* Available at http://proceedings.aip.org/resource/2/apcpcs/399/1/531_1?isAuthorized=no; accessed on April 23, 2013.

———. 2001.Using wireless keypads in lecture classes. *The Physics Teacher* 39:8.

Campbell, D.K., Gladding, G.E., and Elliott, C.M. 1997. Parallel-parking an aircraft carrier: Revising the introductory physics sequence at Illinois. *Forum on Education of the American Physical Society* Summer:8-11.

Collea, F.P., Fuller, R., Karplus, R., Paldy, L.G., and Renner, J.W. 1975. *Physics Teaching and the Development of Reasoning Workshop*. American Association of Physics Teachers, Stony Brook, N.Y.

Cross, J.B., Dodge, J.H., Walter, J.A., and Haber-Schaim, U. 1960. *PSSC. Physics*, 1st ed. D.C. Heath, Boston, Mass.

De Ambrosis, A., and Levrini, O. 2010. How physics teachers approach innovation: An empirical study for reconstructing the appropriation path in the case of special relativity. *Physical Review Special Topics—Physics Education Research* 6:020107-1-11.

Dori, Y.J., Belcher, J., Bessette, M., Danziger, M., McKinney, A., and Hult, E. 2003. Technology for active learning. *Materials Today* 44-49.

Dunning, D., Johnson, K., Ehrlinger, J., and Kruger, J. 2003. Why people fail to recognize their own incompetence. *Current Directions in Psychological Science* 12:83-87.

Eylon, B.S., and Bagno, E. 2006. Research-design model for professional development of teachers: Designing lessons with physics education research. *Physical Review Special Topics—Physics Education Research* 2:020106-1-14.

Finkelstein, N.D. 2004. Teaching and learning physics: A model for coordinating physics instruction, outreach, and research. Journal of Scholarship of Teaching and Learning 4(2):1-17.

Francis, G.E., Adams, J.P., and Noonan, E.J. 1998. Do they stay fixed? *The Physics Teacher* 36:488.

Gordon Research Conference. 2006. Physics Research and Education: Electromagnetism. June 11-16. Available at http://www.grc.org/programs.aspx?year=2006&program=physres; accessed October 8, 2011.

Gray, K., Webb, D., and Otero, V. 2011. Effects of the learning assistant experience on in-service teachers' practices. In *2011 Physics Education Research Conference Proceedings.* AIP Press, Melville, N.Y.

Hammer, D., and Elby, A. 2003. Tapping epistemological resources for learning physics. *Journal of the Learning Sciences* 12:53-90.

Harlow, D.B. 2010. Structures and improvisation for inquiry-based science instruction: A teacher's adaptation of a model of magnetism activity. *Science Education* 94(1):142-163.

Henderson, C., Barthelemy, R., Finkelstein, N., and Mestre, J. 2011. Physics Education Research Funding Census. Paper presented at the 2011 Physics Education Research conference, Omaha, Neb. Available at http://homepages.wmich.edu/~chenders/Publications/2011HendersonPERCPaper.pdf; accessed on April 23, 2013.

Hestenes, D. 1987. Toward a modeling theory of physics instruction. *American Journal of Physics* 55:440-454.

Hodapp, T., Hehn, J., and Hein, W. 2009. Preparing high-school physics teachers. *Physics Today* 62(2):40-45.

Holland, D.C., and Eisenhart, M.A. 1990. *Educated in Romance.* University of Chicago Press, Chicago, Ill.

Institute of Education Sciences. What Works Clearinghouse. Available at http://ies.ed.gov/ncee/wwc/; accessed on June 20, 2012.

Jasien, P.G., and Oberem, G.E. 2002. Understanding of elementary concepts in heat and temperature among college students and K-12 teachers. *Journal of Chemical Education* 79:889-895.

Karplus, R. 1964. The science curriculum improvement study. *Journal of Research in Science Teaching* 2:293-303.

Karplus, E.F., and Karplus, R. 1970. Intellectual development beyond elementary school 1: Deductive logic. *School Science and Mathematics* 70:392-406.

Keller, C., Finkelstein, N., Perkins, K., Pollock, S., Turpen, C., and Dubson, M. 2007. Research-based Practices For Effective Clicker Use. Paper presented at the 2007 Physics Education Research Conference. Available at http://www.colorado.edu/physics/EducationIssues/papers/Turpen_etal/Effective_Clicker_Use.pdf; accessed on April 23, 2013.

Kortemeyer, G. 2009. LON-CAPA—An Open-Source Learning Content Management and Assessment System. Paper presented at the EdMedia 2009 Conference. Available at http://ajp.aapt.org/resource/1/ajpias/v76/i4/p438_s1?isAuthorized=no; accessed on April 23, 2013.

Kruger, J., and Dunning, D. 1999. Unskilled and unaware of it: How difficulties in recognizing one's own incompetence lead to inflated self-assessments. *Journal of Personality and Social Psychology* 7:1121-1134.

Lattuca, L.R., and Stark, J.S. 2009. *Shaping the College Curriculum: Academic Plans in Context.* John Wiley and Sons, San Francisco, Calif..

Laws, P.W., Teese, R.B., Willis, M.C., and Cooney, P.J. 2009. *Physics with Video Analysis.* Vernier, Portland, Ore.

Lippert, R.C., Heller, P.A., Jones, R.S., and Hobbie, R.K. 1988. An evaluation of classroom teaching practices one year after a workshop for high-school physics teachers. American Journal of Physics 56:505-509.

Loverude, M.E., Gonzalez, B.L., and Nanes, R. 2011. Inquiry based course in physics and chemistry for preservice K-8 teachers. *Physical Review Special Topics—Physics Education Research* 7:010106-1-18.

MacIsaac, D., and Falconer, K. 2002. Reforming physics instruction via RTOP. *The Physics Teacher* 40:479-485.

Malone, K.L. 2008. Correlations among knowledge structures, force concept inventory, and problem-solving behaviors. *Physical Review Special Topics—Physics Education Research* 4:020107-1-15.

Mann, C.R. 1912. *Teaching of Physics.* The Macmillan Company, New York, N.Y.

McDermott, L.C. 1990. A perspective on teacher preparation in physics and other sciences: The need for special science courses for teachers. American Journal of Physics 58:734-742.

McDermott, L.C., Shaffer, P.S., and Somers, M.D. 1994. Research as a guide for teaching introductory mechanics: An illustration in the context of the Atwood's machine. *American Journal of Physics* 62:46.

Mulvery, P., Tesfaye, C.L., Neuschatz, M. 2007. *Initial Career Paths of Physics Bachelor's with a Focus on High School Teaching.* American Institute of Physics, College Park, Md.

National Academy of Sciences, National Academy of Engineering, Institute of Medicine. 2007. *Rising Above the Gathering Storm Two Years Later: Energizing and Employing America for a Brighter Economic Future.* The National Academies Press, Washington, D.C.

———. 2009. *Rising Above the Gathering Storm Two Years Later: Accelerating Progress Toward a Brighter Economic Future.* The National Academies Press, Washington, D.C.

Neuschatz, M., McFarling, M., White, S. 2008. *Reaching the Critical Mass: The Twenty Year Surge in High School Physics.* American Institute of Physics, College Park, Md.

Oberem, G.E., and Jasien, P.G. 2004. Measuring the effectiveness of an inquiry-oriented physics course for in-service teachers. *Journal of Physics Teacher Education Online* 2(2):17-23.

Otero, V., Finkelstein, N., McCray, R., and Pollock, S. 2006. Who is responsible for preparing science teachers? *Science* 313(5786):445-446.

Otero, V., Pollock, S., and Finkelstein, N. 2010. A physics department's role in preparing physics teachers: The Colorado Learning Assistant Model. *American Journal of Physics* 78(11):1218.

Paas, F. 1992. Training strategies for attaining transfer of problem-solving skill in statistics: A cognitive-load approach. *Journal of Educational Psychology* 84:429-434.

Pollock, S.J., Finkelstein, N.D., and Kost, L.E. 2007. **Reducing the gender gap in the physics classroom: How sufficient is interactive engagement?** *Physical Review Special Topics—Physics Education Research* 3(1):010107.

Pollock, S.J., Pepper, R., Chasteen, S., and Perkins, K. 2011. Multiple roles of assessment in upper-division physics course reforms. In *2011 Physics Education Research Conference Proceedings* (S. Rabelo, C. Singh, and P. Engelhardt, eds.). AIP Press, Melville, N.Y.

Powell, K. 2003. Spare me the lecture. *Nature* 425:234-236, doi:10.1038/425234a.

Presidential Council of Advisors on Science and Technology. 2010. Prepare and Inspire: K-12 Education in Science, Technology, Engineering, and Math (STEM) for America's Future. Available at http://www.whitehouse.gov/sites/default/files/microsites/ostp/pcast-stemed-report.pdf; accessed on April 23, 2013.

———. 2012 *Engage to Excel: Producing One Million Additional College Graduates with Degrees in Science, Technology, Engineering, and Mathematics.* Executive Office of the President, Washington, D.C. Available at http://www.whitehouse.gov/ostp/pcast.

Roediger, H.L., and Karpicke, J.D. 2006. Test enhanced learning: Taking memory tests improves long-term retention. *Psychological Science* 17:249-255.

———. 2006. The power of testing memory: Basic research and implications for educational practice. *Perspectives on Psychological Science* 1:181-210.

Roediger, H.L., Putnam, A.L., and Smith, M.A. 2011. Ten benefits of testing and their applications to educational practice. Pp. 1-36 in *The Psychology of Learning and Motivation: Cognition in Education* (J.P. Mestre and B.H. Ross, eds.). Volume 55. Academic Press, San Diego, Calif.

Ross, B.H. 1989. Distinguishing types of superficial similarities: Different effects on the access and use of earlier problems. *Journal of Experimental Psychology: Learning, Memory, and Cognition* 15(3):456-468.

Rutherford, F.J., Holton, G. and Watson, F.G. 1964. *Harvard Project Physics.* Holt, Rinehart, and Winston, New York, N.Y.

Sahin, M. 2010. Effects of problem-based learning on university students' epistemological beliefs about physics and physics learning and conceptual understanding of Newtonian mechanics. *Journal of Scholarship of Teaching and Learning* 19(3):266-275, doi:10.1007/s10956-009-9198-7.

Sawtelle, V., Brewe, E., and Kramer, L. 2012. Exploring the relationship between self-efficacy and retention in introductory physics. *Journal of Research in Science Teaching* 49(9):1096-1121.

Seymour, E., and Hewett, N.M. 1997. *Talking about Leaving.* Westview Press, Boulder, Colo.

Sokoloff, D.R., and Thornton, R.K. 2004. *Interactive Lecture Demonstrations: Active Learning in Introductory Physics.* John Wiley and Sons, Hoboken, N.J.

Sokoloff, D.R., Thornton, R.K., and Laws, P.W. 2004. *RealTime Physics Active Learning Laboratories Module 1: Mechanics,* 2nd ed. John Wiley and Sons, Hoboken, N.J.

———. 2004. *RealTime Physics Active Learning Laboratories Module 2: Heat and Thermodynamics,* 2nd Ed. Hoboken, N.J.: John Wiley and Sons, Hoboken, N.J.

———. 2004. *RealTime Physics Active Learning Laboratories Module 3: Electric Circuits,* 2nd ed. Hoboken, N.J.: John Wiley and Sons, Hoboken, N.J.

———. 2004. *RealTime Physics Active Learning Laboratories Module 4: Light and Optics,* 2nd ed. Hoboken, N.J.: John Wiley and Sons, Hoboken, N.J.

Sorensen, C.M., Churukian, A.D., Maleki, S., and Zollman, D. 2004. The new studio format for instruction of introductory physics. *American Journal of Physics* 74(12):1077-1082.

Steele, C.M. 1988. The psychology of self-affirmation: Sustaining the integrity of the self. Pp. 261-302 in *Advances in Experimental Social Psychology* (L. Berkowitz, ed.), Volume 21. Academic Press, New York, N.Y.

Stelzer, T., Brookes, D.T., Gladding, G., and Mestre, J. 2010. Impact of multimedia learning modules on an introductory course on electricity and magnetism. *American Journal of Physics* 78(7):755-759.

Stelzer, T., Gladding, G., Mestre, J. and Brookes, D.T. 2009. Comparing the efficacy of multimedia modules with traditional textbooks for learning introductory physics content. *American Journal of Physics* 77(2):184-190.

Sweller, J. 2011. Cognitive load theory. Pp. 38-76 in *The Psychology of Learning and Motivation: Cognition in Education* (J.P. Mestre and B.H. Ross, eds.), Volume 55. Academic Press, San Diego, Calif.

Thacker, B.A. 2003. Recent advances in classroom physics. *Reports on Progress in Physics* 66:1833-1866.

Thompson, J.R., Christensen, W.M., and Wittmann, M.C. 2011. Preparing future teachers to anticipate student difficulties in physics in a graduate-level course in physics, pedagogy, and education research. *Physical Review Special Topics—Physics Education Research* 7:010108-1-11.

Titus, A., Martin, L., and Beichner, R. 1998. Web-based testing in physics education: Methods and opportunities. *Computers in Physics* 12:117-123.

Warnakulasooriya, R., Palazzo, D.J., and Pritchard, D.E. 2005. Evidence of Problem-Solving Transfer in Web-based Socratic Tutor. Paper presented at the 2005 Physics Education Research Conference. Available at http://www.masteringphysics.com/assets/site/res/pdf/Evidence_problem_transfer_2005.pdf; accessed on April 23, 2013.

Watkins, J., Coffey, J.E., Redish, E.F., and Cooke, T.J. Submitted in 2012. Disciplinary authenticity: Enriching the reforms of introductory physics courses for life-science students. *Physical Review Special Topics—Physics Education Research.* Available at http://arxiv.org/abs/1109.4983; accessed on April 23, 2013.

Wilson, J.M. 1994. The CUPLE Physics Studio. *The Physics Teacher* 32:518-523.

Wilson, S., Floden, R., and Ferini-Mundy, J. 2001. *Teacher Preparation Research: Current Knowledge, Gaps, and Recommendations.* Document R-01-3. Center for the Study of Teaching and Policy. University of Washington, Seattle, Wash. Available at https://www.stcloudstate.edu/tpi/initiative/documents/preparation/Teacher%20Preparation%20Research-Current%20Knowledge,%20Gaps,%20and%20Recommendations.pdf; accessed on April 23, 2013.

Zollman, D.A., Fuller, R.G. 1994. Teaching and learning physics with interactive video. *Robert G. Fuller Publications and Presentations.* Paper 35. Available at http://digitalcommons.unl.edu/physicsfuller/35.

CHAPTER 4

Hutchinson, J.R., and Huberman, M. 1994. Knowledge dissemination and use in science and mathematics education: A literature review. *Journal of Science Education and Technology* 3(1):27-47.

Miyake, A., Kost-Smith, L.E., Finkelstein, N.D., Pollock, S.J., Cohen, G.L., and Ito, T.A. 2010. Reducing the gender achievement gap in college science: A classroom study of values affirmation. *Science* 330:1234.

North Carolina State University. Assessment Instrument Information Page, available at http://www.ncsu.edu/PER/TestInfo.html; accessed on June 21, 2012.

Seymour, E. 2001. Tracking the process of change in U.S. undergraduate education in science, mathematics, engineering, and technology. *Science Education* 86:79-105.