The future of physics education research: Intellectual challenges and practical concerns

During the World Year of Physics, much effort is being made to celebrate the unprecedented advances in our understanding of the physical world made during the past century. However, we have not yet seen comparable advances in our understanding of student learning of our discipline. One possible explanation is that learning is inherently more complex than most physical processes. Although this explanation is plausible, we have not made similar systematic efforts to understand student learning. The enormous effort expended by many physics instructors over the past century was not harnessed in a way that made cumulative progress likely. As Lillian McDermott has observed, ''Unless we are willing to apply the same rigorous standards of scholarship to issues related to learning and teaching that we regularly apply in more traditional research, the present situation in physics education is unlikely to change.''[1]

In the past few decades, an increasing number of physicists have taken up this challenge by applying methods of research based on those that have been employed successfully in investigations of the physical world. This endeavor is broadly known as ''physics education research'' (PER). Systematic studies of student learning have revealed a wide gap between the objectives of most physics instructors engaged in traditional forms of instruction and the actual level of conceptual understanding attained by most of their students.[2] But PER has gone beyond documenting shortcomings in student learning and traditional instruction. Researchers have developed instructional materials and methods that have been subjected to repeated testing, evaluation, and redesign. Numerous reports have documented significant and reproducible learning gains from the use of these materials and methods in courses ranging from large-enrollment classes at major public universities to small classes in two-year colleges and high schools.[1–3] Still, there remain inadequacies in even the most recent instructional approaches and many unanswered questions. In this Guest Editorial we will identify some of the current and emerging research directions that we consider promising. We also argue for the importance of doing research on the learning and teaching of physics in physics departments. We do not mean to suggest that PER should not be conducted in schools of education, but, as we argue later, we do not believe that the field is viable without a critical mass of faculty in physics departments. Finally, we identify some practical and political challenges and propose some steps that could be taken to help ensure the stability, growth, and productivity of PER.

Current and future research directions. We first briefly mention some of the research directions that have potential for deepening our understanding of how students learn physics. This understanding should lead to more effective instructional tools, techniques, and materials. We highlight those directions that address intellectual issues that are specific, but not necessarily unique, to the subject matter and reasoning patterns of physics. Therefore we omit important work on investigating gender-equity issues, for example. Moreover, we focus on the college and university level, although some issues we mention have implications for K-12 instruction. We do not wish to neglect the large and vigorous PER community outside the U.S. However, although many fundamental issues of student learning are largely invariant across cultures, the diversity of approaches to education and, consequently, of research goals is too broad to be addressed satisfactorily here.

Most early PER work focused on student ability to apply the concepts covered in typical introductory university physics courses. The results of these studies have proven invaluable in guiding improvements in instruction. The breadth of topics covered, their importance as a foundation for future study, and the many students involved ensure that the introductory course will continue to be a major emphasis for the foreseeable future. Current research efforts range from extensions of earlier studies of student ability to interpret and apply kinematical concepts[4] to investigations of student understanding of basic electromagnetism and modern physics.

In recent years, there has been an increasing focus on student learning in upper-level courses such as quantum mechanics,[5] thermal physics,[6] relativity,[7] and advanced mechanics.[8] This research should lead to learning gains for physics majors similar to those found for research-based instruction at the introductory level.

We also expect to see a greater emphasis on tracing students' intellectual development as they progress through the undergraduate curriculum, both in physics and in related disciplines such as engineering. Although a few relevant studies have been conducted[9] (the results of which are consistent), most are unpublished. It is important that these studies be conducted and the results be widely disseminated. These investigations should lead to the development of strategies that help students apply the knowledge and skills developed in their physics courses to their subsequent studies or nonacademic pursuits.

Helping students to approach novel problems in a systematic fashion is a major goal of physics instruction. It also is one of the most difficult goals to achieve, although significant success has been reported.[10] However, much remains unknown. Efforts to understand the interrelationships among conceptual knowledge, mathematical skills, and logical reasoning ability should significantly enhance our progress toward helping students become better problem solvers.[11]

The rapid proliferation of computer-based technologies represents both an opportunity and a challenge. Technically sophisticated simulations, animations, and multimedia representations of physics concepts are being developed and implemented by many instructors and curriculum designers, but research into the effectiveness of these technologies lags far behind development.[12] It will be a major challenge to assess the effects of these technologies on student understanding of abstract physics concepts, the nature of scientific models, and the relation of both to the natural world. Such research is crucial for informing the implementation and further development of computer-based instructional tools.

In recent years, students' beliefs about the nature of knowledge in physics and how it is acquired have become a major focus of interest.[13] There is reason to suspect that such epistemological beliefs can influence students' learning of physics and their development of more generalized reasoning skills. Future directions will include efforts to understand these relationships and to incorporate the results in practical instructional strategies and materials.[14]

Although it has long been recognized that student knowledge is complex, there is now an increasing amount of research that focuses on the organization of this knowledge, the elements that it comprises, and the mechanisms by which it evolves.[15] In particular, the dynamics of learning are being investigated in studies that range from the construction of statistical and/or qualitative models of the knowledge states of students[16,17] to qualitative analyses of student thinking over the course of a single interview. The systematic analysis of student behavior during instruction will be an increasing focus for many workers.[18] The identification of common learning ''trajectories'' and strategies for promoting those that are productive would provide valuable assistance in the design of instructional methods and materials.

The findings of empirical investigations of student learning are usually accompanied by some speculation as to the underlying causes of common student errors or the nature of the learning process. In many cases this speculation is situation specific and is not tightly linked to an over-arching structure or theory. In this frequently successful approach, one attempts to affect *what* students do without being able to explain fully *why*. However, even this minimal-interpretation approach is carried out within a framework of specific ideas regarding the nature of the processes involved in learning physics.[19]

The refinement of such frameworks, with the ultimate goal of elucidating a few fundamental principles from which broad explanatory if not predictive power can be derived, is the focus of some PER workers.[20] Although this effort is potentially fruitful, it is important that theoretical descriptions remain firmly linked to empirically observable phenomena. The relationship between experiment and theory in PER will continue to be very different from that in traditional areas of physics from the standpoint of providing precise operational definitions and predictive power. In fact, in the context of PER we prefer to use the phrases ''models'' or ''theoretical frameworks'' to clearly differentiate generalizations about learning from the physical theories with which physicists are familiar. We expect that additional data from detailed studies of the dynamics of student learning will enhance efforts to establish useful theoretical frameworks. At the same time, we believe that empirical studies that are not necessarily closely identified with a specific theoretical framework will continue to lead to significant advances in instruction.

Whereas PER tends to focus on problems associated with the teaching of physics, cognitive science considers the nature of knowledge and learning in general. There is rough agreement on general principles between the two fields, but there has been relatively little cross fertilization, in part because differing goals have led to studies that have little detailed overlap. However, some PER researchers are working to build stronger connections between these two disciplines.[21] As more is learned about memory and learning, it will be a challenge to incorporate those findings into new lines of investigation within PER. An even greater challenge will be to incorporate these findings in practical classroom applications. Collaboration between members of the PER and cognitive science communities in designing and conducting experiments relevant to physics education could be useful and productive.

Physics is at the forefront, but discipline-based education research is growing in the other sciences and engineering. We believe that the PER community should actively cultivate connections with these related fields. Moreover, as we will discuss, lobbying for increased funding is more likely to be successful when broadly based.

Necessity for PER physicists within physics departments. Research on education in general, and on science teaching in particular, has been carried out for nearly a century. However, the impact of this research on undergraduate physics instruction is small compared to that from PER. The explanation is simple: education research conducted by physicists in physics departments is more credible, more accessible, and, in general, more relevant to physics faculty than that conducted in colleges of education or departments of psychology (although the conclusions are typically consistent). Thus for PER to be influential, it is essential that its researchers maintain close ties with the traditional physics community.

For PER to be both valid and useful, it is important that researchers have close, sustained, and day-to-day contact with physics students. Graduate students who work in this field need advanced training in physics and physics research methods, in addition to specialized training in PER. It is difficult to imagine that this training could occur without a firm base in a college or university physics department, for which undergraduate (and graduate) education is a central mission. In contrast, the mission of colleges of education is focused almost exclusively on K-12 instruction, with much less attention to discipline-specific instruction at the undergraduate level.

The close links to the rest of the physics community have enabled PER to make a contribution to education research that is unique.[22] Physicists have deep knowledge about physics concepts as well as familiarity with the methods and culture of the physics research community and the goals of physics instructors. These conditions have helped workers in PER to gain insights about physics learning and to develop instructional materials and methods that, although informed by work in related fields, have gone beyond those fields in terms of their direct impact on instructional practice. It is worth noting that ''the research-based development of tools and processes for use by practitioners''[23]—long the primary goal of most PER workers—is a relative rarity in traditional educational research. One of the strengths of PER is that it is not simply traditional education research conducted by individuals with a strong subject matter background, but rather it is a unique enterprise in which the techniques are strongly colored by the discipline in which it is embedded.

Practical and political issues facing the PER community. In the past seven years, more than 50 people who were trained in PER through Ph.D. or postdoctoral studies have obtained new tenure-track faculty positions in institutions ranging from four-year liberal arts colleges to research-oriented universities. At the same time, a number of physicists who had already achieved tenure through research in traditional areas have ''converted'' to PER. The pace of such conversions has increased in recent years, and such individuals form a significant fraction of PER workers. This dual-track expansion has allowed the field to grow rapidly. Although the numbers suggest that the field is thriving, there are several serious hurdles that must be overcome for PER to become a viable subfield of physics.

The fact that a significant fraction of PER faculty are tenure-track assistant professors is a concern. Although all tenure-track faculty have uncertain futures, there is an additional potential danger in PER. That is, there is a tendency in some departments for PER faculty to be viewed as resource people whose major responsibility is to provide local support for instruction rather than to conduct scholarly research. The responsibilities of PER faculty should be consistent with those of the other faculty in their departments, and they should have the same opportunities for promotion and tenure as faculty in other areas of physics. Although standards for teaching and service are primarily locally determined, criteria regarding publication can be set relative to national norms for PER, just as in other subfields of physics. These conditions are necessary for ensuring that the quality of PER is high and for ensuring that talented people continue to enter the field.

The current level of activity in PER requires a stable source of support to be sustained. Work in PER is primarily funded by the National Science Foundation (NSF) but the research aspect of funded projects is typically secondary to curriculum development, teacher education courses and workshops, and other applications of interest to the various funding programs. There is no source of funding for physics education research *per se*. When the research phase of a project is subservient to teacher education workshops or the production of curricular materials, the overall research and development endeavor is weakened. There are NSF programs that support science education research, but many PER projects are not competitive because they are perceived by the reviewers to be too narrowly focused. (Reviewers in these programs are drawn primarily from the traditional science education and cognitive science communities, instead of the physics community.) The traditional models of physics research funding, such as the renewable three-year grants provided to individual researchers by the NSF Divisions of Physics and of Materials Research, are virtually unknown in PER. However, the NSF Directorate for Mathematical and Physical Sciences (MPS) has recently taken tentative steps to support a small number of PER projects. If this initiative leads to increased and sustained support, it could have a significant impact.

We would like to see the Directorate for Mathematical and Physical Sciences support fundamental research on the learning and teaching of physics through competitive proposals submitted through standard procedures and peer-reviewed by experts in PER. A new program is not necessary—an explicit expansion of the types of projects considered suitable for submission would suffice. We recognize that the suggestion that MPS spread its limited funds over a larger number of areas is unlikely to find favor with much of the physics community. However, the lack of a funding base within NSF for discipline-based education research, despite the documented successes of this research, is a problem not just for physics but also for the other sciences and engineering. We would like to see physicists at NSF take the lead in establishing mechanisms for funding discipline-based education research within NSF. These programs could be jointly administered by the Division of Undergraduate Education and the appropriate divisions within the traditional research directorates.

A research field must have mechanisms to support the documentation, peer review, and dissemination of findings. For more than 25 years, the American Journal of Physics has served this function for PER, and also has served as the principal link between the PER community and the broader community of physics educators. (There are other journals in which research on physics teaching and learning is reported, but most have a limited readership in the U.S. among physics instructors at the postsecondary level.) There are now frequent special sections in AJP, overseen by an editor with expertise in PER, that provide a venue for PER articles that are more technically oriented than those in the main body of the journal. This development is an important acknowledgment of the role that AJP plays in the PER community. The proceedings of the annual Physics Education Research Conference provides a useful forum for the publication of short, preliminary accounts of investigations. The publication of the proceedings by the American Institute of Physics (starting with the 2003 conference) will make them much more widely accessible. An additional on-line archival journal with the tentative title *Physical Review Special Topics—Physics Education Research* is planned in partnership with the American Physical Society. Although a secure, long-term funding mechanism has not yet been established, we are hopeful that this new journal will greatly enhance the ability of members of the PER community to publish new and important results with a minimum of delay. Because it is critical that this new journal establish credibility in the physics community, we believe that the review criteria should resemble as closely as possible those in place for Physical Review as a whole.

While growing in size, the PER community also has diversified in terms of research themes, with both positive and negative future implications. The complex problem of improving physics learning requires that many and varied approaches be investigated and tested; not all will be fruitful, but that is the nature of research. However, the community is still relatively small and resources are limited. Too broad a dispersion of effort may result in research areas that fall below the critical mass needed to sustain a viable, self-critical, and productive research field. Collaborations could increase the impact of individual efforts and ensure that important issues receive adequate attention.

The growing number of faculty positions indicates that PER is increasingly viewed as a legitimate field for scholarly research by physicists in physics departments. However, many physicists still question whether effective teaching, long considered a skill or even an art, is amenable to scientific study. The large number of variables involved in student learning in the classroom is usually assumed to render the scientific study of physics education more difficult than most investigations of the physical world. We do not dispute this assumption, but we note that research in traditional areas of physics also is characterized by difficulties in identifying and controlling variables and by the necessity of making and assessing assumptions, approximations, and models. Physicists deal with these issues on a regular basis. Resolution comes only through the continual testing of models and assumptions by many research groups over the long term. In practice, the situation may well be significantly more challenging in PER, but it does not differ in principle.

As in traditional areas of physics, there are many careful experiments in PER and some that are not. Critical review of evidence by expert peers, the open debate of alternative interpretations, and experimental challenges to reported findings are the only way to ensure legitimacy. Therefore, it is especially crucial for members of the PER community to document their findings in sufficient detail to permit replication, to consider alternate interpretations explicitly, to cite the work of others, and to draw conclusions that are only as general as the scope of the given study warrants. A relatively new field such as PER has a special responsibility in these matters. At the same time, it is reasonable to expect that respectful consideration by the broader community of physicists will be given to well-executed PER investigations, just as would be given to such investigations in other areas of physics.

There are numerous examples of PER results that are highly robust and reproducible across diverse student populations, institutions, instructors, and nations. It is tempting to believe that the growing weight of such evidence will eventually overcome lingering doubts about the validity of PER within the larger physics community. These doubts reflect intellectual concerns and perhaps a generally conservative attitude about what and how we teach. However, efforts to convince skeptics by ''drowning them in data'' can engender further resistance. A backlash effect is created when the message heard by physics instructors is that *they* are ineffective and that *we*, the PER community, are the only ones who know how to teach. Results from a pilot study of attitudes toward PER held by mainstream physics faculty suggest that this type of miscommunication may be a significant issue.[24] There is a clear lesson here for physics education researchers. When communicating with the physics community, we must pay attention to the message received as much as the message that we intend to transmit. We must increase our efforts to assure our colleagues that PER results do not imply either that they are wasting their efforts in the classroom, or that their ideas are without merit. We also must try to correct the common inference that research-based instruction has no room for the creativity, intuition, or experience of individual instructors. And we must be careful not to over-generalize or over-simplify our results. Instead we should try to convey the simple premise on which PER rests: systematic research is an appropriate way to learn as much as possible about what students are learning and to guide improvements in instruction where indicated.

Conclusions. We have argued that it is important for PER to preserve and cultivate close connections with the traditional physics community, both to further the unique contributions made by physicists to the understanding of the learning of physics and to strengthen and widen the impact of PER on physics instruction in colleges and universities.

The regular inclusion of PER in AAPT and APS meetings and the growth in attendance at the annual Physics Education Research Conference are among the many signs of vigorous activity in this field. Physics education researchers are frequently invited to give colloquia in physics departments and PER is highlighted at AAPT-sponsored conferences including the New Faculty Workshop and the Conference of Physics Department Chairs. Prominent physics education researchers have been awarded the Oersted and Millikan awards, the highest honors of the AAPT. The Executive Committee of the APS Forum on Education is working to create stronger links between the AAPT, which is the traditional home of PER, and the APS. By maintaining high standards for PER and reaching out to the general physics community, we are optimistic that PER can become a firmly established and productive subfield of physics. The APS Council explicitly endorsed this outlook in its 1999 statement supporting PER in physics departments.[25] However, the differences in outlook between PER faculty and faculty in traditional areas of physics cannot be bridged solely by efforts from the PER community. Physicists in traditional areas need to acknowledge that the specialist knowledge of the PER community on instructional issues merits special consideration when physics pedagogy is the subject of discussion.

ACKNOWLEDGMENTS

We are grateful to Professor L. C. McDermott and Professor E. L. Jossem, and a number of other colleagues who read and commented on an earlier version of this Guest Editorial.

[1]L. C. McDermott, ''Research in physics education,'' APS News **7**(1), (1998); Education Outreach, p. 8.

[2]L. C. McDermott, ''Millikan Lecture 1990: What we teach and what is learned—Closing the gap,'' Am. J. Phys. **59**, 301–315 (1991); ''Guest Comment: How we teach and how students learn—A mismatch?,'' *ibid.* **61**, 295–298 (1993); R. R. Hake, ''Interactive-engagement versus traditional methods: A six-thousand-student survey of mechanics test data for introductory physics courses,'' *ibid.* **66**, 64–74 (1998).

[3]L. C. McDermott and E. F. Redish, ''Resource Letter: PER-1: Physics Education Research,'' Am. J. Phys. **67**, 755–767 (1999); L. C. McDermott, ''Oersted Medal lecture 2001: 'Physics Education Research—The key to student learning',' *ibid.* **69**, 1127–1137 (2001).

[4]These were first published in AJP in the 1980s; see D. E. Trowbridge and L. C. McDermott, ''Investigation of student understanding of the concept of velocity in one dimension,'' Am. J. Phys. **48**, 1020–1028 (1980); ''Investigation of student understanding of the concept of acceleration in one dimension,'' *ibid.* **49**, 242–253 (1981). Also see F. Reif and S. Allen, ''Cognition for interpreting scientific concepts: a study of acceleration,'' Cognit. Instruct. **9**, 1–44 (1992).

[5]C. Singh, ''Student understanding of quantum mechanics,'' Am. J. Phys. **69**, 885–895 (2001); M. C. Wittmann, R. N. Steinberg, and E. F. Redish, ''Investigating student understanding of quantum physics: Spontaneous models of conductivity,'' *ibid.* **70**, 218–226 (2002); E. Cataloglu and R. W. Robinett, ''Testing the development of student conceptual and visualization understanding in quantum mechanics through the undergraduate career,'' *ibid.* **70**, 238–251 (2002).

[6]M. E. Loverude, C. H. Kautz, and P. R. L. Heron, ''Student understanding of the first law of thermodynamics: Relating work to the adiabatic compression of an ideal gas,'' Am. J. Phys. **70**, 137–148 (2002).

[7]R. E. Scherr, P. S. Shaffer, and S. Vokos, ''Student understanding of time in special relativity: Simultaneity and reference frames,'' Am. J. Phys. **69**, S24–S35 (2001).

[8]B. S. Ambrose, ''Investigating student understanding in intermediate mechanics: Identifying the need for a tutorial approach to instruction,'' Am. J. Phys. **72**, 453–459 (2004).

[9]See, for example, G. E. Francis, J. P. Adams, and E. J. Noonan, ''Do they stay fixed?,'' Phys. Teach. **36**, 488–490 (1998).

[10]A. Van Heuvelen, ''Learning to think like a physicist: A review of research-based instructional strategies,'' Am. J. Phys. **59**, 891–897 (1991); ''Overview, Case Study Physics,'' **59**, 898–907 (1991); P. Heller, R. Keith, and S. Anderson, ''Teaching problem solving through cooperative grouping. Part 1: Group versus individual problem solving,'' *ibid.* **60**, 627–636 (1992); P. Heller and M. Hollabaugh, ''Teaching problem solving through cooperative grouping. Part 2: Designing problems and structuring groups,'' *ibid.* **60**, 637–644 (1992); F. Reif and L. A. Scott, ''Teaching scientific thinking skills: Students and computers coaching each other,'' *ibid.* **67**, 819–831 (1999); A. Van Heuvelen and Xueli Zou, ''Multiple representations of work-energy processes,'' *ibid.* **69**, 184–194 (2001).

[11]W. J. Leonard, R. J. Dufresne, and J. P. Mestre, ''Using qualitative problem-solving strategies to highlight the role of conceptual knowledge in solving problems,'' Am. J. Phys. **64**, 1495–1503 (1996); F. Reif and L. A. Scott, Ref. 10; C. Henderson, E. Yerushalmi, V. H. Kuo, P. Heller, and K. Heller, ''Grading student problem solutions: The challenge of sending a consistent message,'' Am. J. Phys. **72**, 164–169 (2004).

[12]D. J. Grayson and L. C. McDermott, ''Use of the computer for research on student thinking in physics,'' Am. J. Phys. **64**, 557–565 (1996); R. J. Beichner, ''The impact of video motion analysis on kinematics graph interpretation skills,'' *ibid.* **64**, 1272–1277 (1996); R. N. Steinberg, G. E. Oberem, and L. C. McDermott, ''Development of a computer-based tutorial on the photoelectric effect,'' *ibid.* **64**, 1370–1379 (1996); E. F. Redish, J. M. Saul, and R. N. Steinberg, ''On the effectiveness of active-

engagement microcomputer-based laboratories,'' *ibid.* **65**, 45–54 (1997); R. K. Thornton and D. R. Sokoloff, ''Assessing student learning of Newton's laws: The Force and Motion Conceptual Evaluation and the evaluation of active learning laboratory and lecture curricula,'' *ibid.* **66**, 338–352 (1998); F. Reif and L. A. Scott, Ref. 10; K. Cummings, J. Marx, R. Thornton, and D. Kuhl, ''Evaluating innovation in studio physics,'' Am. J. Phys. **67**, S38–S44 (1999); R. N. Steinberg, ''Computers in teaching science: To simulate or not to simulate?,'' *ibid.* **68**, S37–S41 (2000); Z. Zacharia and O. R. Anderson, ''The effects of an interactive computer-based simulation prior to performing a laboratory inquiry-based experiment on students' conceptual understanding of physics,'' *ibid.* **71**, 618–629 (2003); S. Yeo, R. Loss, M. Zadnik, A. Harrison, and D. Treagust, ''What do students really learn from interactive multimedia? A physics case study,'' *ibid.* **72**, 1351–1358 (2004).

[13]E. F. Redish, J. M. Saul, and R. N. Steinberg, ''Student expectations in introductory physics,'' Am. J. Phys. **66**, 212–224 (1998); D. Hammer, ''Student resources for learning introductory physics,'' *ibid.* **68**, S52–S59 (2000); D. B. May and E. Etkina, ''College physics students' epistemological self-reflection and its relationship to conceptual learning,'' *ibid.* **70**, 1249–1258 (2002).

[14]A. Elby, ''Another reason that physics students learn by rote,'' Am. J. Phys. **67**, S52–S57 (1999); ''Helping physics students learn how to learn,'' *ibid.* **69**, S54–S64 (2001).

[15]F. Reif, ''Millikan Lecture 1994: Understanding and teaching important scientific thought processes,'' Am. J. Phys. **63**, 17–32 (1995).

[16]L. Bao and E. F. Redish, ''Concentration analysis: A quantitative assessment of student states,'' Am. J. Phys. **69**, S45–S53 (2001); L. Bao, K. Hogg, and D. Zollman, ''Model analysis of fine structures of student models: An example with Newton's third law,'' *ibid.* **70**, 766–778 (2002).

[17]E. Bagno and B.-S. Eylon, ''From problem solving to a knowledge structure: An example from the domain of electromagnetism,'' Am. J. Phys. **65**, 726–736 (1997); N. S. Rebello and D. A. Zollman, ''The effect of distracters on student performance on the force concept inventory,'' *ibid.* **72**, 116–125 (2004).

[18]R. K. Thornton, ''Uncommon knowledge: Student behavior correlated to conceptual learning,'' in *Research on Physics Education: Proceedings of the International School of Physics ''Enrico Fermi'' Course CLVI*, edited by E. F. Redish and M. Vicentini (IOS, Amsterdam, 2004), pp. 591–601.

[19]P. R. L. Heron, ''Empirical investigations of learning and teaching, Part I: Examining and interpreting student thinking,'' in Redish and Vicentini, Ref. 18, pp. 341–350; ''Part II: Developing research-based instructional materials,'' *ibid.* pp. 351–365; D. E. Meltzer, ''The questions we ask and why: methodological orientation in physics education research,'' in *2003 Physics Education Research Conference (Madison, Wisconsin, 6-7 August 2003)*, edited by J. Marx, S. Franklin, and K. Cummings [AIP Conf. Proc. **720**, 11–14 (2004)]; P. R. L. Heron, ''Empirical investigations of student understanding,'' *ibid.* pp. 15–18.

[20]D. Hestenes, ''Toward a modeling theory of physics instruction,'' Am. J. Phys. **55**, 440–454 (1987); E. F. Redish, ''Millikan lecture 1998: Building a science of teaching physics,'' *ibid.* **67**, 562–573 (1999).

[21]E. F. Redish, ''Implications of cognitive studies for teaching physics,'' Am. J. Phys. **62**, 796–803 (1994); E. F. Redish, Ref. 20; E. F. Redish, ''A theoretical framework for physics education research: Modeling student thinking,'' in Redish and Vicentini, Ref. 18, pp. 1–63.

[22]L. C. McDermott, ''A view from physics,'' in *Toward a Scientific Practice of Science Education*, edited by M. Gardner, J. G. Greeno, F. Reif, A. H. Schoenfeld, A. diSessa, and E. Stage (Lawrence Erlbaum, Hillsdale, New Jersey, 1990), pp. 3–30.

[23]H. Burkhardt and A. H. Schoenfeld, ''Improving educational research: toward a more useful, more influential, and better-funded enterprise,'' Educational Researcher **32**, 3–14 (2003).

[24]C. Henderson and M. Dancy, ''Teaching, learning, and PER: Views from mainstream faculty,'' Poster CP-IP08, Physics Education Research Conference 2004, Sacramento, California, 4–5 August, 2004.

[25]http://www.aps.org/statements/99_2.cfm.

Paula R. L. Heron
Department of Physics, University of Washington, Seattle, Washington 98195-1560

David E. Meltzer
Department of Physics and Astronomy, Iowa State University, Ames, Iowa 50011-3160

MAXWELL'S GENIUS

In 1861, James Clerk Maxwell had a scientific idea that was as profound as any work of philosophy, as beautiful as any painting, and more powerful than any act of politics of war. Nothing would be the same again.

In the middle of the nineteenth century the world's best physicists had been searching for a key to the great mystery of electricity and magnetism. The two phenomena seemed to be inextricably linked but the ultimate nature of the linkage was subtle and obscure, defying all attempts to winkle it out. Then Maxwell found the answer with as pure a shaft of genius as has ever been seen.

Basil Mahon, *The Man Who Changed Everything: The Life of James Clerk Maxwell* (Wiley, 2003), p. 1.