An Introduction to Physics Education Research

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Abstract:

This article aims to introduce the reader to the field of Physics Education Research (PER). Topics include the difference between Physics Education Research and Physics Education/curriculum development, a brief history of PER in the US, and some of the research traditions within PER (current types of PER, types of questions asked, research methods used, etc.). By necessity, many important aspects of the field have been omitted in an effort to produce a short, readable overview.

"**Teaching, I say, is an art, and not a science."** Floyd K. Richtmyer's statement, appearing in the very first article in the premier issue of the *American Journal of Physics*, accurately represented the prevailing mindset in 1933, as well as a common belief today. Richtmyer further states, "Probably everyone would agree with this statement and perhaps it is therefore unnecessary to make it, except as a starting point for the discussion."[1]

Part of what Richtmyer said is absolutely correct…the statement *is* an excellent starting point for a discussion! In all fairness, when he wrote his article there was not a large research base dealing with the teaching and learning of physics. The collection in which this article appears, and indeed decades of education research literature, attests to the fact that a different situation exists today.

Of course, people have long been concerned about education. In 1893 J. M. Rice reported[2] on a children's lesson in geometric shapes where student after student stood and recited the name of a shape and its characteristics. He noted, "In no single exercise is a child permitted to think. He is told just what to say, and he is drilled not only in what to say, but also in the manner in which he must say it" (pg. 38). This is reminiscent of Richard Feynman's visit to a Brazilian school, where he describes[3] a strikingly similar situation. Numerous reports like *A Nation at Risk*[4] or the more recent *Rising Above the Gathering Storm*[5] attest that we are a long way from providing the best possible education to our nation's citizens. Nonetheless, we are making progress toward approaching education in a scholarly manner. Len Jossem, who has supported PER for decades, notes that "…Research in Physics Education did not spring, like Athena, the goddess of wisdom, full grown from the head of Zeus. Its successes grew out of the work of previous generations, the development of instructional media including video and computer related applications and materials, the recognition of the importance to physics education research, as to physics itself, of a balance between theory and experiment, and, in my view, the very important development of effective *quantitative measurement instruments*. [italics in original]"[6]

Major strides are being made. Instructional reforms are being instituted that attest to the fact that scientific tools and methods can and should be used to improve teaching and learning. Implementation of research-based reforms has resulted in significant learning gains, plummeting failure rates, and more success in later courses. (For just one example—that

happens to be very familiar to me—review the outcomes of the SCALE-UP project.[7] Further findings will be discussed throughout this collection.) Since Richtmyer's time, the Physics Education Research (PER) community has flourished, attesting to a very different situation today: while some may yet agree with Richtmyer, the tide is indeed turning.

1. Who are Physics Education Researchers?

Physics Education Research has become recognized as a legitimate research subfield of physics only recently. Not too long ago, one could easily pick out physics faculty who did not conduct research. You would just open Barron's or Peterson's phonebook-like guide to graduate programs, turn to your favorite department's page, and see who was listed as "Physics Education." Those would be the faculty who focused exclusively on teaching. Today it is more difficult to make this distinction. Many departments have faculty who are conducting rigorous research on how students learn our subject. They are physicists who treat education as a topic worthy of scientific study.

Nonetheless, there is still confusion about this subfield of physics. Perhaps we should adapt the graduate program guide approach and explain what PER is not. Physics education research is not just curriculum development or instructional design. It is not merely a service enterprise for teachers, although its findings can certainly be put to good use by them. Instead, PER is focused inquiry into what happens as students struggle to grasp and use the concepts of physics. Obviously there are limitations to discerning a person's thoughts, but repeated patterns of responses (either in a single student or across many students at different times and places) can lead us to generate theories that explain other situations and, in some cases, have predictive power. This would be considered "basic" PER, in the sense that it is fundamental or foundational research. There is also "applied" PER where the researcher uses results from basic PER to modify instruction, examine the educational efficacy of the new approach, and use these results to iteratively improve instruction with more follow-up assessment. There is a small but growing number of PER researchers whose work is harder to classify. Even though they remain focused on what is going on while students learn physics, they examine socio-cultural issues like learning in collaborative groups, discourse models, etc. PER explores a rich array of cognitive and social phenomena.

One may well wonder, "Does PER belong in physics departments or a

school of education?" Actually, it can be appropriate in either location, depending on the type of investigation. Studies involving college students are most often done from university physics departments. There are several reasons for this. First of all, physicists are familiar with the complex and often subtle aspects of physics as covered in college-level coursework and they appreciate the peculiar culture of physics. Also, it can be argued that the researchers studying learning by college students should actually teach those classes. Researchers looking at learning by pre-college students are usually, but not exclusively, found in education departments. An unfortunate truth is that some physics faculty will only listen to other physicists, and not regard the work of science education researchers as valid. This is regrettable because science education researchers have usually had training in the complicated methodologies needed to carry out this type of work. Not surprisingly, both PER workers and science education researchers can benefit from each other's knowledge and background.

PER specialists are most often found in physics departments. But what should be their role? It would be unreasonable to expect a theoretical condensed matter physicist to manage the computer systems for an entire department simply because they are experienced with high-end workstations. Similarly, it should not automatically be assumed that a PER faculty member's job is to "set up the labs" or "manage the introductory courses." While someone trained in PER might be especially well-prepared to do this sort of work and could even volunteer for the duty, you might just as easily find someone from the rest of the department's faculty or hire a specialist. I often tell the story of my job interview at NC State. I asked the question, "Are you looking for someone to get a good research group going, or do you want a person to fix your intro courses?" The answer I received, while blunt, was exactly what I wanted to hear: "If you don't get a good research group going, you won't be here long enough to do anything in the introductory courses!" This was good news because it meant I would be treated just like any other faculty member at a research intensive university—publish or perish—and I was willing and able to play that game. A PER faculty member can make an excellent departmental colleague because they can conduct research, give talks, publish articles, get funding, and recruit graduate students. And hopefully s/he will be a pretty good teacher!

Thus, physics education researchers are colleagues of science educators, cognitive scientists, psychologists, and even instructional designers. But

primarily they are physicists who are studying the teaching and learning of their subject. (This is discussed in more depth in Heron and Meltzer's opinion piece[8] on the future of PER.) PER specialists appreciate the diverse nature of students as well as the deep and meaningful structure of physics. Additionally, they are part of a cause that is both very old and very new: understanding learning and improving physics instruction for generations of students.

2. A Brief History of PER in the US

In many ways, Lillian McDermott is the "founder" of college-level PER in the United States. At the pre-college level, Bob Karplus laid the foundations for work carried on by many others in both physics departments and schools of education. Michael Wittmann has produced a sort of "family tree" of who influenced whom. It is available online[9] and is quite instructive. The community is very tightly knit and most members freely admit sharing and learning amongst each other.

The Physics Education Group at the University of Washington essentially started the PER field when McDermott, initially hired by Arnold Arons as an instructor in courses for teacher education, branched out into studies of student difficulties with many of the central concepts in physics. The Washington team has grown and is certainly one of the most widely recognized and probably one of the largest groups in the world. Other pioneering groups include those started by Dean Zollman at Kansas State, Bob Fuller at Nebraska and David Hestenes at Arizona State. Fred Reif, first at UC-Berkeley and later at Carnegie Mellon, continues to influence many others. Seymour Papert's work[10] also had a substantial impact, especially on the use of technology as a tool to be used by children as they learn. Some of the larger current US groups include those at North Carolina State University, University of Maryland, University of Colorado, University of Maine, and The Ohio State University. There is a sizable number of international groups that are having an increasing influence on the PER field in the US.[11] These and other groups—along with many individuals—are exploring a wide range of subjects, but all PER specialists are basically continuing the legacy started by McDermott.

There has been a series of meetings that focused on physics education research. One of the first of these was held at North Carolina State University in the fall of 1994. Discussion topics ranged from the types of studies carried out by physics education researchers to the curriculum that

PER graduate students needed to see. An outcome of the meeting was a 1995 white paper[12] submitted to NSF by a prominent group of physics education researchers which may have had some influence on NSF's generally positive view of PER. Joe Redish believes the white paper contributed to him securing funding for the International Conference on Physics Education (ICPE), which was held at Maryland just before the American Association of Physics Teachers (AAPT) summer meeting in 1996. Between the ICUPE and AAPT meetings there was an "Interval Day" meeting where approximately 75 people discussed what was needed to advance the PER field. It was decided that Redish would pursue additional publication space and Dean Zollmann would attempt to create a piggy-back conference for the next AAPT summer meeting.[13] Since 1997 there has been such a conference (called PERC) held every summer. A biennial conference series, Foundations and Frontiers in PER, has been organized through the University of Maine since 2005. There have also been international conferences at LaLonde, Bremen, Varenna, along with numerous meetings sponsored by the International Commission on Physics Education. During recent years the proportion of conference talks given at AAPT meetings on the findings and applications of PER has increased dramatically. There are also regular PER sessions at meetings of the APS, sponsored by the Forum on Education.

A pivotal event in the rise of physics education research was the 1992 publication[14] of the Force Concept Inventory (FCI), by Hestenes, Swackhammer, and Wells. This test, based on the dissertation research of Ibrahim Halloun,[15] covers basic Newtonian mechanics and is deceptively easy in appearance. In fact, it can be difficult to convince faculty to give this test because they fear insulting their students' intelligence. However, if they do offer the test, they are usually shocked at the resulting low scores. This has been the start of many adoptions of PER-based instructional materials. The most well-known example of this is described in Eric Mazur's book, *Peer Instruction*.[16] Mazur relates his own experience where students were able to successfully complete difficult quantitative problems on his exams and yet missed what appeared (to him) to be easy conceptual questions on the test. This led Mazur and his colleagues to develop and then evaluate[17] the instructional technique described in his book.

In 1998 Richard Hake published an article[18] where he examined FCI data for more than 6000 students. He was able to show that students taking interactive classes performed significantly better on the test than did

students in traditional lecture-style courses. Although there has been some re-examination of the Force Concept Inventory and critiques of how it is used, it is generally recognized as having played a significant part in the advancement of the field of physics education research. Hake's article had an important role in promoting pre-post testing using validated assessment instruments, a mainstay of PER methods.

At its spring meeting in 1999, the APS Council adopted[19] a "Statement on Research in Physics Education" that recognized the growing interest in the field and supported the acceptance of PER in physics departments. In it, the APS noted the usefulness and, in fact, the validity of having physics education researchers located in physics departments. They stated that not only does the field itself benefit greatly from a physics presence, but the department also profits by having another rigorous research effort that, as a side effect, can improve its instructional program. Because of this statement and ongoing efforts of the PER community, many departments are now including physics education research amongst their research programs. The departments are hiring, as attested to by David Meltzer's list of approximately 60 tenure-track PER faculty who had been hired within a decade.[20]

Connections between PER and other fields have been in place since the 1980's, beginning with Trowbridge and McDermott's Piaget-based papers[21,22] on velocity and acceleration, which are recognized as the first "modern" PER papers. As the field has matured, more and more links have been formed to other areas including science education, educational psychology, linguistics, cognitive science, computer science and even anthropology. Early studies tended to focus on what students did not know (cf. Duit's bibliography[23] of "Previous Ideas" or the proceedings[24] of several seminars from Cornell). More recent work is looking at how students use what they do know. For example, several studies have examined how students apply cognitive resources[25] and employ "epistemic games"[26] to learn new material. Analysis of multiple choice assessment tests has become more sophisticated[27] and even qualitative research is benefiting from statistical analyses.[28]

As the acceptance of physics education research grew, a stubborn stumbling block was the difficulty of publishing research results. This was seen as a formidable problem by new faculty in the field as they tried to establish a strong case for their tenure committees. Fortunately, multiple avenues of publication are now available. In the United States, the first

large-scale publication of PER work was done in the *American Journal of Physics*. In fact, a key resource for learning about PER comes from that journal in the form of the 1999 resource letter[29] by McDermott and Redish. Besides regular theme issues which often include PER-related articles, there was also a supplement that appeared for several years that was the outcome of Redish's efforts after the 1996 "Interval Day" meeting described earlier. These separately-bound supplements demonstrated that there were solid PER articles to be published and that readers wanted to see them. The AAPT's *The Physics Teacher* also produced some rather important PER articles, including the original publication of the Force Concept Inventory. In 2005, the American Physical Society, in cooperation with the AAPT, began publishing[30] *Physical Review Special Topics—Physics Education Research*. This online journal is part of the APS's world-renowned *Physical Review* series. Tenure and promotion committees, which might not know how to evaluate the quality of physics education research, nonetheless recognize that the *Physical Review* masthead implies rigorously reviewed publications. Occasionally physics education research articles will appear in other journals, including *Cognition and Instruction, Learning and Instruction, Journal of the Learning Sciences,* and the *Journal of Research in Science Teaching*. There are also some non-US journals, most notably the *International Journal of Science Education*, which publish articles relevant to the physics education research community.

As has been true in all areas of physics, finding PER funding has often been quite a struggle. Early researchers would often embed their studies within a very rigorous evaluation component in an instructional materials development project. Today, the National Science Foundation and the Department of Education are open to pure research on the teaching and learning of science, math, and engineering. There are multiple programs in these agencies that are appropriate and accept proposals from physics education researchers.

The job market for graduate students earning a degree in physics education research is quite strong. Because of the interests, training, and flexibility of these new physics PhDs, they are able to secure positions at a wide variety of academic institutions. Because of the growth of PER groups in research-intensive institutions, graduate students interested in a career of rigorous research can find positions. On the other hand, graduating PER students who are more interested in teaching can find ready employment at smaller colleges where instruction is the main focus,

as well as medium-size institutions, where some limited amount of research is encouraged. Because of low startup costs and the availability of students, physics education research can be conducted at schools of any size. It is interesting to note that Principal Investigators report difficulties in finding post-docs to work on PER grants because of the open job market. Most PER graduates take a faculty position immediately upon graduation, reducing the pool of post-doctoral candidates.

The new faculty workshops[31] that are co-sponsored by the AAPT, APS, and the American Astronomical Society have done an excellent job of familiarizing new faculty with the findings of physics education research. This project, initiated by Ken Krane, reaches 20 to 25% of all new hires in physics and astronomy. Workshop attendees hear from leaders in physics education research and have an opportunity to ask questions and experience some examples of PER-based instructional materials.

There have been several efforts over the years to consider and/or create an organizing body for physics education researchers (cf. "The Perfect Parent Organization for PER").[32] For US researchers, there are strong ties to both the American Association of Physics Teachers and the American Physical Society. Recently the PER Leadership Organizing Council has been formed as part of the PER Topical Group within AAPT. The APS Forum on Education has been in existence for many years. Quite a few PER specialists are members of both groups. Most members of the European Physics Education Network and the International Commission on Physics Education are from outside the US. Certainly everyone could benefit from sharing information across national boundaries. (Many US PER specialists are embarrassingly illiterate when it comes to knowing of relevant studies conducted in other countries.) The Physics Education Research Community Enhancing Network for Research and Learning, known as PER-CENTRAL, is a website[33] that tries to be a sort of "home base" for the world-wide PER community.

For those most interested in applying the results of PER in the classroom, I have several suggestions. Arnold Aron's book[34] has a table of contents that reads like a physics textbook, but its pages deal with teaching and student understanding. It combines some of what has been learned from PER with Aron's own decades of experience as a physics teacher. For those interested in applying what we know about learning to real physics classrooms, it is a very good place to start. Joe Redish's *Teaching Physics With the Physics Suite*[35] and Randy Knight's *Five Easy Lessons*[36] are more

thoroughly steeped in the lessons learned from PER and also provide solid, practical guidance to teachers looking to improve their instruction.

3. Methods: The Plural Of Anecdote Is Not Anecdata

There are two main types of research methodologies in physics education research. Each has different strengths and each answers different questions. The key, as the reader will see in other articles of this collection, is that research methods should match research questions. In any case, it is important to realize the level of sophistication of physics education research. Simply tabulating final exam scores is not the same as systematically developing, validating, and ascertaining the reliability of an assessment instrument—a process that can take several years. Similarly, recalling something a student said is just not the same as a rigorous, iterative analysis of an interview transcript. As noted in the section heading, the plural of anecdote is not anecdata. Although accumulating a set of anecdotes may help make findings concrete and memorable, this does not replace the careful gathering and analysis of data from representative samples of student populations.

When working with individuals or small groups of students, investigators can employ what is called qualitative research. In these studies, students are often interviewed or they relate their thinking while they are doing some specific task. Whether done as a "think aloud" protocol[37] (where students are only interrupted to remind them to keep talking) or students are asked probing questions that depend on previous answers, this type of study allows considerable insight into how students think. Both the main strength and the primary difficulty with this type of research is the extremely rich and excessively large data set it generates.[38] It can be a daunting task to transcribe and analyze hours of interview data. Because the work can be so difficult and tedious, it is generally done with small numbers of students. Thus, it is difficult to generalize findings to an entire population of physics students. In the late 1990s, analysis of video interview data came to the attention of the PER community thorough the work of Fred Goldberg from San Diego State, Valerie Otero,[39] now at Colorado, and Ron Thornton of Tufts. David Hammer brought the methodology, widespread in education schools at the time, to the University of Maryland's PER group in 1998. A recent article[40] describes what is involved in setting up a video recording facility for research purposes.

Quantitative research does allow generalization from very large samples of students to most (or at least many) physics students. In these studies, researchers often create a pencil-and-paper test, usually in multiple-choice format, that can be given and scored on a large scale. The Force Concept Inventory mentioned earlier is the most well-known example of this type of instrument. There is now a large assortment[41] of validated and reliable tests that cover many physics concepts. These tests offer complementary insights compared to qualitative research. Because they can be given to large numbers of students, they have substantial statistical power and the results can be generalized. However, the resolution is generally poor, and it can be difficult to gain much understanding of what is happening within an individual student's mind as they consider some physical situation or solve a problem.

A very powerful type of research employs mixed methods. That is, there are both qualitative and quantitative aspects to the research. Assessment instruments are often developed from results of earlier interviews or open-ended written questions. This often provides otherwise unexpected choices for multiple-choice questions. For example, in developing the FCI, it was discovered that students often commented that a ball resting on a table did not fall simply because the table "got in the way," without referring to any forces applied to the ball. This replicated an observation first reported by Minstrell[42] in 1982. When creating the Test of Understanding Graphs in Kinematics,[43] I found that nearly three-quarters of the approximately 1000 students taking the test could correctly find distance traveled by looking at a graph of 1-D velocity vs. time. However, when presented with five graphs sporting identical (but unnumbered) velocity-time axes, only 10% could pick the graph indicating greatest change in position. Interviews of students displaying this pattern found that most needed to multiply velocity by time by reading the values directly from the axes in order to "cancel out units" or "use v = dt." None mentioned area under the curve as being relevant.

Later articles in this collection discuss a variety of research methodologies and should be consulted for further insight.

4. Research Trends in PER

Many different areas have come under the scrutiny of physics education researchers. Most of the major research trends are briefly described below.

For a more extensive overview, see McDermott and Redish's PER Resource Letter,[22] Thacker's review article,[44] and Knight's *Five Easy Lessons*.[7] Additional information is available on the web at PER-CENTRAL.[30]

4.1 Conceptual Understanding

Most of the work in physics education research has been looking at what students know and how they learn. Early work searched for "misconceptions." This term, over time, has been modified to "student difficulties," "naïve conceptions," or "intuitive understanding" in an attempt (which was not entirely successful) to minimize the negative connotations of the original name. Regardless of title, this work formed the basis of most early physics education research as content was systematically scanned topic by topic and student difficulties were uncovered and analyzed. The University of Washington group has specialized in this type of study and has published extensively.[21,45] They are experts at developing very clever questions and tasks for students that elicit difficulties in specific areas.

As mentioned earlier, assessment instruments were often developed based on student difficulties that were known at the time. The FCI and the Force and Motion Conceptual Evaluation[46] were two early tests, along with the Test of Understanding Graphs in Kinematics[43] (TUG-K). The TUG-K article not only described the results of surveying graph interpretation ability, but also outlined the steps necessary to develop a valid and reliable assessment instrument.

Although conceptual tests are useful in their own right, follow-up articles often extend their analysis. For example, there have been several additional evaluations of the FCI, including the Hake paper[5] noted earlier, a factor analysis[47] seeking to find meaningful patterns in student answers, and Bao's quantum-mechanical-like approach[9] to modeling cognition by looking at wrong answers.

While many instruments have been designed to measure students' concepts, some researchers have re-cast cognition in terms of pieces smaller than "concepts." In the early 1980's diSessa introduced[48] the notion of phenomenological primitives (p-prims). P-prims are fundamental ideas held by students that need no further explanation (like "force as a mover," "closer is more") that appear in what students say and are often

misdiagnosed as larger-scale "misconceptions." This work has been very influential in the development of contemporary cognitive models in PER.

Some researchers have focused on how students' ideas are modified as they learn. The area of physics conceptual development and change has been spearheaded by Brown,[49] Dykstra,[50] Clement,[51] and Posner.[52] This type of research could also be classified under the next heading.

4.2 Epistemology

The University of Maryland is perhaps the most well-known group working on theories of the cognition involved in learning physics. Redish, Hammer, Elby and others[53] have looked at what tools and ideas students bring to the task of learning physics and how concepts change as students learn. They make the point that without a theoretical basis, PER is not much more than a series of trial-and-error attempts to improve learning. diSessa's knowledge in pieces approach[54] provides a major component of the theoretical base for their work.

Chi's 1993 paper[55] on fragmented and coherent misconceptions is a good example of how scholarship outside traditional PER areas can be quite useful in extending our understanding. Johnson-Laird is a leading contributor to cognitive science and his book, *How We Reason*,[56] can readily be applied to learning physics. Dedre Gentner described how students form coherent mental models of the world around them. (See the book *Mental Models*[57] for many examples from physics.)

4.3 Problem Solving

Because physicists are considered problem solvers, the underlying mental processes relevant to attacking problems have been of great interest to researchers. David Maloney's article[58] in the *Handbook of Research on Science Teaching* is a good resource for information on problem solving. A newer review[59] appeared the *American Journal of Physics*. A great deal of this research has focused on the differences between novices and experts as they solve problems, most notably the work by Chi.[60] She found novices tend to focus on surface features as they categorized problems. For example, they might see two problems involving inclined planes as very similar, even though an expert would note that one solution requires Newton's Laws while the other involves energy. The University of Minnesota has been studying[61] student solutions to context-rich problems,

which they distinguish from the more traditional exercises found at the end of most textbook chapters. Recent work[62] is trying to evaluate the cognitive processes underlying the solving of difficult problems.

4.4 Attitudes

There have been multiple studies of the attitudes and expectations of students about physics. The most recent instrument is the CLASS,[63] developed at the University of Colorado. Additional surveys include the VASS[64] from Arizona and the popular MPEX[65] or Maryland Physics Expectations Survey. Earlier work can be found in the 1994 work[66] of David Hammer. The bad news is that most students' attitudes toward physics tend to decline after traditional instruction. The good news is that we have instruments to detect this problem so perhaps we can find ways to deal with it. (In fact, very recent work[67] by Redish and Hammer indicates that good progress is being made.)

4.5 Social Aspects

In all areas of education, not just physics, gender and race issues have been a concern for quite some time. (For insight into how easily student performance can be influenced by these "non-academic" considerations, see Steele's seminal research[68] on stereotype threat.) In PER, a variety of studies[69] have explored the ramifications of membership in an underrepresented group. A few researchers have examined[70] the inertia slowing the adoption of educational innovations. Others are looking at the effect of learning environments, collaboration and other student interactions, and even the gestures[71] that students make while talking about physics. Studies of studio classrooms, where learning is fundamentally a social enterprise, have been carried out by Cummings[72] at Rensselaer, Dori and Belcher at MIT,[73] and Beichner[7] at NC State. Much of the work on collaboration is based on decades of effort[74] by David and Roger Johnson of the University of Minnesota, with theoretical underpinnings provided by Vygotsky's ideas of social constructivism.[75]

4.6 Technology

One might argue that early work on microcomputer-based labs (MBLs) led to the more in-depth studies that characterize today's physics education research and even contributed to the lead PER has compared to education research in other disciplines. Ronald Thornton and Priscilla Laws first

proposed a "unified platform" for data collection (eventually called the ULI—Universal Lab Interface) and a "shoebox full of probes" at a meeting at Dickinson College in 1987.[11] Thornton, Robert Tinker, and David Sokoloff[76] developed the earliest position sensors based on ultrasonic sound detection. Modern probes can measure everything from air pressure to oxygen concentration. Video-based labs (VBL) were developed by Beichner[77] in the mid-1980's and also provide students with a connection between the real world and abstract representations of that reality. Complex three-dimensional simulations can be generated[78] with very little effort from the teacher or students. Student response systems, or "clickers," have proven[79] to be effective in the traditional lecture setting and are becoming popular as a "low-cost, low-effort" means of implementing PER. Additional work on simulations, like that of Steinberg,[80] Dancy,[81] and the Colorado group,[82] as well as studies of web-based assessment systems like that of Bonham,[83] shows that instructional technology is still a fruitful area of investigation. The NC State PER group is well-known for the development and evaluation of various kinds of instructional technology, perhaps because their definition of the term is more inclusive than most. WebAssign,[84] VBL, VPython,[85] and the round tables of SCALE-UP are all technologies that sprang from the group's efforts. It is interesting to note that Law's Workshop Physics[86] inspired Jack Wilson's Studio Physics[87] at Rensselaer (based on the CUPLE project[88] at Maryland), which in turn was a forerunner of SCALE-UP, which influenced MIT's TEAL rooms.[68] Technological innovation, most of it PER-based, has directly resulted in many changes in physics instruction.

4.7 Evaluation of Specific Instructional Interventions

Numerous studies have reported the educational impact of different pedagogies. Thousands of students (including preservice teachers) have learned though the use of the University of Washington's *Tutorials in Introductory Physics*.[89] Jeff Saul[90] made a comparison of some modern research-based curricular approaches including Dickinson College's *Workshop Physics*.[91] Previously noted research has examined studio settings. Interactive lecture demonstrations have been evaluated by Sokoloff and Thornton.[92] As noted earlier, cooperative group problem solving was studied[61] at the University of Minnesota. Research on student response systems, i.e. clickers, has also been mentioned previously. Just-in-time teaching, a pedagogy that has students report their difficulties before class, was developed and evaluated[93] by Novak and Patterson.

Hestenes and others at Arizona State University have examined[94] their modeling approach to instruction and have disseminated it state-wide and at workshops across the US.

4.8 Instructional Materials

As happens in other research areas, successful PER has resulted in commercial ventures. Publishers now emphasize a PER basis for their physics textbooks as a major selling point. Occasionally this underpinning actually exists. *Physics by Inquiry*[95] led the way in this area, and *Tutorials in Introductory Physics*[96] has provided the standard for how to provide feedback between research and curriculum development. One of the earliest, if not the first, comprehensive physics textbooks to incorporate PER findings was written by Serway and Beichner.[97] Knight's text[98] is probably the most widely adopted PER-based textbook. *Real-Time Physics*[99] works to incorporate physics education research into a more traditional setting in the lab. *The Physics Suite*[100] has taken one of the most popular textbooks[101] (Halliday, Resnick and Walker), and updated it with the latest applications of physics education research. These last two products have been combined with *Workshop Physics* materials and Washington's *Physics by Inquiry* and *Tutorials* into the *Activity Based Physics* project.[102] Along with *Physics by Inquiry*, P*hysics and Everyday Thinking*,[103] and *Powerful Ideas in Physical Science*[104] are widely used curricula aimed at non-majors. As you might surmise from the name, the TIPERs (Tasks Inspired by Physics Education Research) project[105] has produced an assortment of activities proven to be effective in the classroom. WebAssign,[106] the largest web-delivered homework system in the world, grew out of the dissertation research of Aaron Titus,[107] who was trying to discern the type of physics problems that could best be understood via video-based lab techniques. The actual content of textbooks has also been changing, most notably in the *Matter and Interactions* curriculum[108] by Chabay and Sherwood and Moore's *Six Ideas that Changed Physics*.[109] Work continues, with the developers of the Rutger's ISLE materials,[110] as well as Eric Mazur, working on new textbooks. The developers of many of these innovative instructional materials offer regular workshops at AAPT meetings.

5. PER: A Scientific Approach to Instructional Innovation

Physics Education Research is a vital, fast-growing field. Over the years

we have made impressive gains in our understanding of how students learn physics. Both experimental methods and theoretical models are improving. PER graduates find jobs, faculty find funding, and applications of PER work are widespread and have proven to be effective. More and more physics departments are finding PER specialists to be good colleagues and academic citizens. PER is an exciting area and should continue to be for a long time.

This article started out with a quote illustrating old ideas about teaching and learning. It ends with another quote, this time by Nobel Laureate Carl Wieman, that appeared recently in the APS News. In it he comments on the non-intuitive nature of student thinking:

> "The clever physics community has already found an approach for how to make progress in areas where one's initial intuition is obviously flawed, e.g. figuring out the structure of atoms. That approach is to rely on careful objective experimental measurements and to use that data to develop new improved understanding and intuition. For teaching physics, this means looking at data on how people learn and how students do and don't learn the various topics in physics."[111]

So, returning to Richtmyer's discussion statement, is teaching an art or a science? Clearly there are performance-related skills to be mastered. But as physicists, we have begun to treat teaching (or more precisely, learning) as a science—because that's the one thing we know how to handle!

6. Acknowledgements

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