TRENDS IN PHYSICS EDUCATION RESEARCH

A personal perspective by

N. Sanjay Rebello & Dean A. Zollman
Department of Physics, Kansas State University, Manhattan, KS 66506-2601

Contemporary discipline-based physics education research can trace its roots to the post-Sputnik era beginning in the late 1950s. The task of mapping out the history of a recent and growing field spanned by diverse agendae will undoubtedly be colored by one's own experiences and interests. Therefore, our description of the foundations and frontiers of the field presented in this paper is a personal perspective that may not be shared by all other researchers in the field. However, we have attempted to present a balanced view in this document.

In this document we first present a summary of the current status of the field. We then describe our vision of where we believe the field is headed in the future and highlight the major issues facing physics education research. The appendices offer a historical account of the field and list the research groups and individual faculty contributing to physics education research.

HOW FAR HAVE WE COME?

The climate for physics education research is far different today than it was when the field began 50 years ago. Physics departments appear to be much more supportive of the field today than before. With greater awareness of the effectiveness of research-based instructional methods, a growing number of physics departments both at primarily undergraduate institutions as well as research universities are hiring faculty members who have Ph.D.s in physics with a specialization in physics education research. Human capacity development in the field is increasing with over a dozen physics departments granting physics Ph.D.s with a specialization in physics education research. (http://web.phys.ksu.edu/PERgroups.htm)

Each year, the physics education research community converges at the Physics Education Research Conference (PERC) (http://web.phys.ksu.edu/perc2004/) that is organized directly following the American Association of Physics Teachers (AAPT) (http://www.aapt.org) summer meeting. The field also has a section of *Physical Review*, the premier physics research journal published by the American Physical Society (APS). Thus, physics education research has been accorded the same status as other sub-disciplines within physics. This recognition in the U.S. is supported by similar international endeavors. In the summer of 2003 the prestigious Enrico Fermi International School of Physics devoted its first conference to physics education research. (Redish & Vincentini, 2004)

In the appendices we present a historical account of the field. Each appendix describes what we believe are the paradigms or trends of thought in the field. Most of these appendices titled with starting dates and no ending dates to reflect our belief that the each of these paradigms of physics education research and curriculum development are relevant and active today. In a sense, the term 'paradigm' may in fact be a misnomer, as there is significant overlap between them. Together these varied perspectives complement each other and furnish the field with a diverse set of research agendas.

In spite of the coexistence of various research agendae, we believe that over the past five to 10 years there appears to be a greater interest in learning about students' sense-making processes rather than the scientific correctness of their knowledge. Table 1 below contrasts this emerging view with current and prior views prevalent in the field.

Table 1: Trends in Physics Education Research & Curriculum Development

	Current View	**Emerging View**
Research Questions	What are student misconceptions and difficulties? How can we help students overcome these barriers?	What knowledge structures do students use? How do students construct these knowledge structures?
Typical Expectations	Few students acquire scientific conceptions through traditional instruction.	Most students' conceptions change in some way through instructional and other experiences.
Assessment	Focus on whether students' conceptions match those of scientists.	Focus on whether students can engage in the process of model building based on evidence.
Researcher's Role	The researcher pre-defines the target conceptions that students should have after instruction.	The researcher investigates the process of model construction rather than solely its end product.
Dynamism	Gains in students' conceptual understanding often are measured pre vs. post instruction.	The dynamics of students' process of model construction is deemed worthy of investigation.
Domain	Attention paid mostly to the cognitive aspect of learning and conceptual understanding.	Attention *also* paid to student epistemology, beliefs and expectations.
Curriculum	Instructional materials developed to address specific misconceptions.	Instructional materials developed to *also* address students' epistemological stance.

WHERE DO WE GO FROM HERE?

Melba Phillips, one of leaders in physics education in the last century and president of the AAPT in the 1960s is reported (Redish, 1999) to have once remarked

"The trouble with problems in physics education is they don't stay solved."

That comment rings true today. With the advent of technology, the students of tomorrow will live in a world exposed to a set of experiences quite different from those today. They will have many more tools that mediate their learning both in and out of the classroom. Therefore, physics education researchers, like others, need to continuously reinvent themselves to better prepare the rising generation to meet their challenges and capitalize on their opportunities. The diverse agendae in the field make predictions of future directions difficult. We firmly believe, however, that to adequately meet the needs of the students of tomorrow, physics education research must reach beyond its own boundaries.

Several issues faced by physics education researchers are not unique to the teaching and learning of physics. Therefore, as we build on our strengths and expertise, we must also collaborate with researchers outside of our field. These interactions will enhance our understanding of how students think and learn and help us design effective strategies to reach our students. This multidisciplinary approach alone will enable us to grow to meet the needs of the rising generation effectively and efficiently. Below we briefly describe some of the emerging areas of multidisciplinary collaboration that will enhance the potential of our field in the coming years.

Cognitive Psychology and Neuroscience

While physics education researchers follow diverse agendae, we expect that the trends summarized in Table 1 will continue. Along these lines we expect that the field will become more connected with ongoing research in cognitive psychology and neuroscience. The extent of that connection is not clear, however. It is likely that some of the modern techniques such as functional MRI (f-MRI), MEG or EEG might be used by physics education researchers in the future to examine how students think. Such techniques are already being used by cognitive neuroscientist to gain insights about students' thinking in mathematics and physics domains (e.g. Dehaene, Spelke, Pinel, Stanescu & Tsivkin, 1999; Fulbright *et al*., 2000; Kim & Spelke, 1999) and also interpersonal interactions. (King-Casas *et al*., 2005) However, it remains to be seen whether these techniques could be used to gain insights into students' sense-making processes in the physics domain. Regardless of the outcome, we believe this direction is an important one for the field to pursue.

Information Technologies

Information technology is clearly becoming ubiquitous in our everyday lives. It is inevitable that these technologies will mediate the experiences of the students and teachers of tomorrow and will consequently affect the ways in which these students learn. The use of the technologies is not unique to the teaching and learning of physics, therefore to teach the students of tomorrow, physics education researchers must work with information technologists and other researchers who may already use it to investigate how these technologies can both harness and investigate new modes of student learning. One area where these developments are already being experienced is the use of hand-held technologies and mobile computing in physics education research. (Rebello & Zollman, 2004b) Another area that has also been previously explored is the use of digital video analysis (Zollman, 1993) and other real-world data collection systems that can help bring the real-world data into the classroom. We expect that the use of these technologies will continue to grow and that physics education researchers must keep themselves abreast of the latest developments in the area and explore ways in which these technologies can be harnessed both as teaching tools as well as tools to conduct physics education research.

Knowledge and Understanding in Emerging Areas

Another aspect of the field that necessitates multidisciplinary collaborations pertains to the scientific knowledge, understanding and skills that students need to acquire to be competitive in this technological age. At this point, student understanding of virtually every topic covered in introductory physics courses has been thoroughly researched. This focus was partly because introductory classes, with their large enrollments provide for a larger cross-section of impact for any new instructional methods. It was also reasonable to address the needs of introductory students before moving on to upper-division students. However, we now find ourselves at the dawn of a new era. With the advent of new developments such as nanoscience and nanotechnology it is important that our citizens of tomorrow be informed and educated so that they can participate in the debates and discussions regarding the nature and use of these technologies. We believe that these changes will impact physics education research in at least two ways.

First, they will necessitate a change in content of the upper division as well as the introductory physics courses. With new content comes a new set of student ideas, misconceptions and mental models. To help these students learn and succeed it would be important to conduct research on their understanding of physical phenomena, particularly at a microscopic level. Research (Rebello *et al*., 2005) has shown that most students do not have well developed models in these microscopic physical phenomena and therefore, our common investigative tools such as clinical interviews or surveys may be inadequate to understand student reasoning. Early research indicates that a new research tool – the teaching interview (Engelhardt, Corpuz, Ozimek & Rebello, 2003) may prove to be particularly useful in exploring the dynamics of students' in vivo knowledge construction. The teaching interview is an adaptation of the teaching experiment that is often used in mathematics education research, (Steffe, 1983; Steffe & Thompson, 2000) which again underscores the need for our field to collaborate with other STEM education researchers.

Second, emerging areas such as nanotechnology are essentially interdisciplinary in nature. Therefore, to adequately prepare students to learn about these areas, learning would need to be a multidisciplinary experience that transcends the typical notions of courses restricted to the departmental boundaries. New team-taught courses in nanoscience and technology (e.g. NBTC, 2005) are already becoming commonplace. Therefore, physics education researchers should seek to collaborate with other discipline-based STEM education researchers and hone their expertise to work toward interdisciplinary educational goals.

Science & Mathematics Education Research Methodologies

Physics education research often lacks a robust methodological framework that integrates a philosophical standpoint and set of research instruments. Although several physics education researchers adopt research methodologies similar to those used by science and mathematics education researchers based in Colleges of Education, many others do not.

In general, we believe that the methodologies used in science and mathematics education research will provide a useful set of strategies that can be adapted to the contexts of physics education research. For instance, the multi-tiered teaching experiment methodology by Lesh and Kelly (2000) that has been successfully used to integrate the efforts of researchers, teachers and students at the secondary level could be adapted to provide a framework to integrate physics education research with teaching at the undergraduate level as well as the professional development of graduate teaching assistants.

Overall, we believe that efforts to collaborate with researchers outside our community will enhance the credibility of the research emerging from our field and help us better prepare our students for the future that they will inherit.

APPENDIX A: Foundations of Physics Education Research (1950-1970)

The sense of awareness of the state of science, mathematics and technology education in the U.S. spawned by Sputnik led to a curriculum development movement in the sciences, particularly in physics. Several K-12 curriculum projects focused on active involvement of the students in the learning process. Two major high school physics curricula, Physical Science Study Committee (PSSC, 1960) and Project Physics (Holton, 1967) had long lasting effects on the teaching of physics at both high school and college levels. At least equally important were the efforts in elementary school science. Of particular importance to the physics community was the Science Curriculum Improvement Study (SCIS) led by Robert Karplus beginning in 1962. Karplus, who was an accomplished research physicist, had become interested in the teaching and learning of physics. (Karplus & Their, 1969; Karplus & Their, 1967) His SCIS curriculum (Karplus & Their, 1971) applied the intellectual development model that Jean Piaget developed to the learning of elementary science. An important underlying theoretical framework, called constructivism, proposed that knowledge is constructed in the mind of the learners based on their experiences and that the role of instruction was to create experiences that facilitated active student learning, rather than passively transferring from the teacher to the student. All of these curriculum development efforts, at least to some extent, were based on the notion of active student learning. Although they were not necessarily based on rigorous research on learning of a particular physics topic, they were nevertheless based on general principles derived from science education or cognitive research.

About a decade later, McKinnon and Renner (McKinnon & Renner, 1971) published a seminal paper “Are colleges concerned about in intellectual development?” This paper, along with a workshop led by Karplus (Karplus, 1974) introduced the physics teaching community to the value of looking beyond its own discipline for models of learning and instruction such as the Learning Cycle. (Karplus & Karplus, 1970) From these efforts we learned that the knowledge which students bring to the physics class is an important part of their learning. We must understand what that knowledge is and address it directly. However, telling the student to change is not sufficient. We must help the students confront and address their own ideas and incorporate scientifically accepted concepts into their thinking.

APPENDIX B: Addressing Students’ Misconceptions & Difficulties (1970 –)

Starting in the early 1970s a paradigm shift occurred among some sectors of the emerging physics education research community. While general principles were useful guidelines that laid out the overarching characteristics of the curricular materials such as active engagement or experiences to create cognitive dissonance, they provided few insights into the specific difficulties and conceptions that students brought with them to the physics classroom. To gain these insights, an extensive research program to investigate students’ difficulties and conceptual understanding was begun. The pioneering effort for this research was led by Lillian McDermott at the University of Washington. (Arons, 1976; McDermott, 1984) Not only did the Washington group conduct research on student conceptual understanding, they then used those research results to create new instructional materials. Thus, they developed the idea of research-based instructional materials.

Similar research programs and efforts to develop curricular materials and models instruction for introductory physics courses were spawned throughout the 1980s and 1990s across the U.S. A large fraction of these efforts were federally supported, primarily by the NSF with some funding by the Department of Education. While some curricula such as *Physics by Inquiry* (L.C. McDermott, 1996) or *Tutorials in Physics* (McDermott & Shaffer, 1998) were based on research of student learning of specific topics, others were guided by general principles on student learning applied to physics. These efforts included changes in the format and layout of the physics classroom as well as taking advantage of modern technology such as video, computers and computer-based sensors. Some of these efforts are Concepts of Physics, (Zollman, 1990) Workshop Physics, (Laws, 1991) Studio Physics, (Wilson, 1994) Socratic Dialog Laboratories, (Hake, 1992) Interactive Lecture Demonstrations (Sokoloff & Thornton, 1997) and Modeling Physics. (Wells, Hestenes & Swackhamer, 1995) Several, though not all, of these research and curriculum development efforts have been cataloged in a review by McDermott and Redish. (McDermott & Redish, 1999) Several books outlining these approaches were also written starting in the early 1990s. (Arons, 1990; Knight, 2002; Redish, 2003a; Swartz & Miner, 1997)

In spite of all of this research and curricular development efforts, teaching by a vast majority of physics faculty was not immediately affected because the changes required substantial commitments of funds and human resources. Moreover, most physics faculty felt that they were already doing a 'good' job teaching and that their students were learning well based on performance on tests and exams, which mainly assessed end-of-chapter problem solving. Early in 1990, Hestenes and coworkers designed a set of conceptual questions, the Mechanics Baseline Test. (Hestenes & Wells, 1992) A short time later the same group created the more popular Force Concept Inventory targeted at high school students. (Hestenes, Wells, & Swackhammer, 1992) The Force Concept Inventory (FCI) provided a much-needed benchmark to assess student conceptual understanding in physics, and continues to be widely used by college and university faculty. Most physics faculty, when they first learned about the FCI, considered it to be very simple and were surprised to learn that their students were unable to correctly answer seemingly simple conceptual questions. (Mazur, 1997) This realization made several physics faculty and departments amenable to change. Data emerging from universities that had adopted research-based, interactive engagement methods showed that students performed significantly better on the FCI than students who had traditional instruction. A landmark paper published by Hake (Hake, 1998) presented conclusive evidence from over 6000 students across a broad spectrum of schools and colleges that supported the superiority of interactive engagement methods in fostering student learning as measured by the FCI.

In addition to the aforementioned curricular reform efforts, the FCI also spawned efforts by physics education researchers to develop conceptual inventories in other topical areas of physics that were typically covered in an introductory physics course. Development of these inventories was guided by careful research methodology often used to create assessment instruments by science education researchers. These methodologies often included conducting careful interviews to validate the interview questions. Some of the more popular conceptual assessments are shown in Table 2 below. While none of these instruments have achieved the popularity of the FCI, they are often used as benchmarks of learning in each of their topical areas and as assessments of the impact of curricular reform efforts. The focus on conceptual understanding as measured by instruments has been a major force in both the physics teaching and physics education research for over twenty years.

Table 2: Commonly used Conceptual Evaluations in Physics*

Conceptual Evaluation	**Reference**
Force & Motion Conceptual Evaluation (FMCE)	(Thornton & Sokoloff, 1998)
Test of Understanding Graphs - Kinematics (TUG-K)	(Beichner, 1994)
Electric Circuits Conceptual Evaluation (ECCE)	(D. Sokoloff, 1993)
Light & Optics Conceptual Evaluation (LOCE)	(D. Sokoloff, 1997)
Electric & Magnetic Conceptual Evaluation (EMCE)	(Maloney, O'Kuma, Heiggelke & Van Heuvelen, 2001)
Diagnosing and Interpreting Resistor Circuits (DIRECT)	(Engelhardt & Beichner, 2004)
Energy and Momentum Conceptual Evaluation (EMCE)	(Singh & Rosengrant, 2003)
Quantum Mechanical Visualization Inventory (QMVI)	(Cataloglu & Robinett, 2002)

* This list is not exhaustive.

Another development that promoted the implementation of physics education research in physics departments was the advent of classroom response systems, which was a cost-effective way to introduce research-based strategies into an otherwise traditional lecture format. Since the mid 1990s, ever since Mazur (1997) had been surprised by his Harvard students' poor performance on Hestenes' FCI, he had begun to think about ways in which his large lecture classes could become more interactive and devised a "Peer Instruction" method to engage his students. Before Mazur, Thornton and Sokoloff had developed Interactive Lecture Demonstrations (Sokoloff & Thornton, 1997) to help increase student engagement in a large lecture, which is still the predominant mode of instruction in most university physics classes and will most likely remain so for a long time in the future. While inexpensive, flash-card based classroom response systems had been popularized previously, (Meltzer & Manivannan, 1996) the advent of the wired ClassTalk™ system, (Abrahamson, 1998, 1999) and more recently several wireless systems such as PRS™ (Personal Response System) helped promote the use of these interactive methods in large classes. These systems also provided useful real-time feedback to the instructor, who could then use it to respond to students' difficulties. We anticipate that in the future, mobile technologies such as Pocket PCs will further enhance the capabilities and use of classroom response systems. (Rebello & Zollman, 2004b)

One of the previously mentioned barriers to the curricular reform movement was the lack of resources and interest among faculty to adopt reformed curricula. However, another barrier came from the students. Most students who had become accustomed to traditional pedagogical approaches such as the lecture were not necessarily favorably disposed toward new approaches. Similar issues had been researched quite extensively in the science education research community and some physics education researchers e.g. Halloun (1997) and Redish (Redish, Saul, & Steinberg, 1998) built on this research to develop instruments that measure students' views and expectations about physics. However, in spite of the existence of these instruments, the physics education research community as a whole did not pay much attention to these issues pertaining to student learning. For instance, there are few, if any widely known studies that examine correlations between students' performance on conceptual assessments and their scores on attitudinal assessments.

APPENDIX C: Understanding Students' Models (1995 –)

Until the late 1990s and early 2000s, most physics education research focused on investigating whether students had understood a particular concept by asking them to apply it in a variety of contexts. If students were unsuccessful at applying the concept correctly researchers concluded that the students lacked conceptual understanding. Some diagnostic instruments, such as the FCI attempted to go a step further to identify the students' misconceptions by using carefully selected distracters based on prior research on students' misconceptions. However, researchers (Bao, 1999; Bao, Zollman, Hogg, & Redish, 2002) soon realized that students' misconceptions were often manifestations of a flawed deeper understanding of how the world worked. In a sense, the misconception was analogous to the symptom, while the more deeply flawed world-view was analogous to the disease. It was the latter that needed to be identified and treated.

This notion of a world view or mental model has been studied extensively by cognitive psychologists. No consensus exists, even among cognitive psychologists about the exact definition a mental model. However, Redish (1994) and others in the physics education research community adopted the term in a functional sense to describe the underlying understanding students might have about a particular phenomenon. When asked a question about a particular aspect of the phenomenon, a student's flawed mental model expresses itself in form of a misconception. Staring in the late 1990s Bao and Redish (Bao, 1999; Bao & Redish, 1999) began investigating ways in which data from the FCI could be analyzed to extract information about students' mental models. They developed a new mathematical formalism called model analysis which was based on a probabilistic view of student thinking – analogous to the probabilistic descriptions of quantum mechanical systems such as electrons. By combining a single student's response to different questions that researchers believed addressed a particular mental model, it was possible to find out the probability that students used that mental model.

One of the factors that may have limited the widespread use of model analysis is the fact that it involves complex mathematical processes that may be difficult to understand and therefore made the analysis process less transparent. More importantly, many of the questions on the FCI and other inventories were not conducive for model analysis because there was no one-to-one relationship between answer choices on each question and the various mental models that a student could have. Another barrier to use widespread use of model analysis was the nature of concept inventories themselves. Even before the development of model analysis, the FCI, which is often used to understand students' mental models, has been subjected to significant scrutiny. For example Huffman and Heller (Huffman & Heller, 1995) analyzed FCI data using factor analysis. They found that the factors obtained by this statistical tool did not match those which were used to construct the instrument. One possible conclusion from this analysis is that student knowledge was much more fragmented than could be captured by neatly described choices on a multiple-choice question. Other researchers found that the multiple-choice nature of the exam (Rebello & Zollman, 2004a) or the order in which questions were asked (Gray & Rebello, 2002) could alter students' responses to the FCI. All of these research results appeared to indicate that the FCI, though most widely used and quite effective in discerning students' conceptual understanding of basic mechanics, may not be appropriate for gleaning students' mental models. One likely reason is that the models themselves appeared to be fragmented and unstable.

APPENDIX D: Modeling Student Understanding (2000 –)

The recognition that student knowledge is fragmented is not new. diSessa, (1998) Hammer, (1996, 2000) Minstrell (1992) and Redish (1994, 1999) have all alluded to the notion that students do not have well developed or coherent mental models that they use, but rather activate pieces of knowledge. In turn the activation of these pieces depends upon the problem context. diSessa (1998) points out these pieces themselves may not be correct or incorrect, but rather they may be correctly or incorrectly activated in a particular context.

Also in relation to the knowledge-in-pieces view proposed by several researchers, recent findings by Hrepic (Hrepic, Rebello & Zollman, 2002; Hrepic, Zollman & Rebello, 2005) demonstrate that students often make up answers on the spot. Often students combine ideas and dynamically choose, apply and reject ideas as they think through the answer to a question – for example, during a clinical interview. Often they combine seemingly disparate ideas to form a hybrid mental model (Hrepic *et al*., 2002) that "works" in a given set of contexts.

Based on these findings, several researchers have begun to focus on the process by which students construct these models, regardless of whether these models are scientifically accepted or not. The focus then is on the dynamics of the knowledge construction process by the students rather than on the scientific correctness of the end product. This perspective is a more student-centered approach to thinking about students' mental models than previous perspectives.

The value of attending to the pieces of knowledge that are activated by students when they are asked a question is a useful perspective to adopt because it allows us to develop instructional strategies that help students activate and build on the productive nuggets of knowledge that they already possess while inhibiting the activation of unproductive pieces of knowledge. Evidence exists that some students who are successful in their classes may be doing that already. These students often obtain a 'good' grade in their course based on 'traditional' assessments such as class examinations. Also, many of these students go on to take more advanced classes in physics or engineering and have successful professional careers in these fields. Again, these students clearly do learn something even though it may not be evident from their performance on the conceptual assessments. This dichotomy between poor performance on conceptual assessments and relatively successful performance on other measures is indicative of the fact that we need to do more to understand how students think and under what conditions they activate their productive pieces of knowledge. (Rebello *et al*., 2005)

Thus, over the last few years some physics education researchers have begun to focus more on the process by which students dynamically construct their knowledge rather than on the scientific correctness of the end product.

Another aspect of the paradigm shift is manifested in the attention that is paid not merely to the development of students' cognitive abilities in physics, but also in their expectations of a physics course and epistemological beliefs about what constitutes learning science in general or physics in particular. This work builds on the previous attitudinal assessment developed by Halloun (Halloun, 1997) to assess students' views about science and Redish (Redish *et al*., 1998) to measure students' expectations in a physics class. Hammer and Elby (Hammer, 1995; Hammer & Elby, 2001) have pointed out that student beliefs and epistemologies are worthy of attention because they influence how students may respond to new instructional strategies. In his recent paper (Redish, 2003b) has proposed an overarching theoretical framework to model student thinking. The framework draws from a knowledge base that encompasses research in cognitive psychology, neuroscience and socio-linguistics. The framework aims to synthesize knowledge from these different fields and reflect on how this knowledge informs our understanding about student learning in physics. The framework models a learner in terms of a "two level system." The lower level includes associative relationships between cognitive entities and the higher level includes student epistemologies and expectations that control the associations in the lower level.

Based on the aforementioned evidence it appears that a paradigm shift seems to be occurring in physics education research. There appears to be a greater appreciation for learning about how students make sense of things and modeling their sense-making processes. This view contrasts an earlier stance which focused solely on the scientific correctness of student knowledge. We believe that this emerging view (see Table 1) promises to yield productive avenues of investigation in the future.

REFERENCES

Abrahamson, A. L. (1998). *An overview of teaching and learning research with classroom communication systems.* Paper presented at the International Conference on the Teaching of Mathematics, Village of Pythogarean, Greece.

Abrahamson, A. L. (1999). *Teaching with a classroom communication system: What it involves and why it works.* Paper presented at the International Workshop: New Trends in Physics Teaching, Puebla, Mexico.

Arons, A. B. (1976). Cultivating the capacity for formal reasoning. *American Journal of Physics, 44*, 834.

Arons, A. B. (1990). *A Guide to Introductory Physics Teaching*: John Wiley & Sons.

Bao, L. (1999). *Dynamics of Student Modeling: A Theory, Algorithms, and Application to Quantum Mechanics.* Unpublished Ph.D., University of Maryland, College Park, MD.

Bao, L., & Redish, E. F. (1999). Model Analysis: A Quantitative Approach to Study Student Understanding of Physics. *AAPT Announcer, 29*(2), 95.

Bao, L., Zollman, D., Hogg, K., & Redish, E. F. (2002). Model Analysis of Fine Structures of Student Models: An Example with Newton's Third Law. *Physics Education Research: A Supplement to the American Journal of Physics, 70*(7).

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

Cataloglu, E., & 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*(3), 238-251.

Dehaene, S., Spelke, E., Pinel, P., Stanescu, R., & Tsivkin, S. (1999). Sources of Mathematical Thinking: Behavioral and Brain Imaging Evidence. *Science, 284,* 970-974.

diSessa, A. A. (1988). Knowledge in pieces. In G. Forman & P. B. Pufall (Eds.), *Constructivism in the computer age* (pp. 49-70). Hillsdale, NJ: Lawrence Erlbaum Associates.

diSessa, A. A. (1998). What changes in conceptual change? *International Journal of Science Education, 20*(10), 1155-1191.

Engelhardt, P. V., & Beichner, R. J. (2004). Students’ understanding of direct current resistive electrical circuits. *American Journal of Physics, 72*(1), 98-115.

Engelhardt, P. V., Corpuz, E. G., Ozimek, D. J., & Rebello, N. S. (2003). *The Teaching Experiment - What it is and what it isn't.* Paper presented at the Physics Education Research Conference, 2003, Madison, WI.

Fulbright, R. K., Molfese, D. L., Stevens, A. A., Skudlarski, P., Lacadie, C. M., & Gore, J. C. (2000). Cerebral Activation during Multiplication: A Functional

MR Imaging Study of Number Processing. *American Journal of Neuroradiology, 21*, 1048–1054.

Gray, K. E., & Rebello, N. S. (2002). *Effect of question order on student responses to multiple choice questions.* Paper presented at the Physics Education Research Conference, 2002, Boise, ID.

Hake, R. R. (1992). Socratic pedagogy in the introductory physics lab. *The Physics Teacher, 30*, 546-552.

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*(1), 64-74.

Halloun, I. (1997). *Views about science and physics achievement: The VASS story*. Paper presented at the The Changing Role of Physics Departments in Modern Universities: Proceedings of the International Conference on Undergraduate Physics Education (ICUPE), College Park, MD.

Hammer, D. (1995). Epistemological considerations in teaching introductory physics. *Science Education*, *79*(4), 393-413.

Hammer, D. (1996). More than misconceptions: Multiple perspectives on student knowledge and reasoning, and an appropriate role for education research. *American Journal of Physics, 64*(10), 1316-1325.

Hammer, D. (2000). Student Resources for Learning Introductory Physics. *American Journal of Physics - Physics Education Research Supplement, 68*(7), S52-S59.

Hammer, D., & Elby, A. (2001). In B. K. Hofer & P. R. Pintrich (Eds.), *Personal Epistemology: The Psychology of Beliefs about Knowledge and Knowing*: Lawrence Erlbaum.

Hestenes, D., & Wells, M. (1992). Mechanics Baseline Test. *The Physics Teacher, 30*, 159-169.

Hestenes, D., Wells, M., & Swackhammer, G. (1992). Force Concept Inventory. *The Physics Teacher, 30*, 141-151.

Holton, G. (1967). Project Physics. *The Physics Teacher, 5*, 198-211.

Hrepic, Z., Rebello, N. S., & Zollman, D. A. (2002). *Identifying student models of sound propagation.* Paper presented at the 2002 Physics Education Research Conference, Boise, ID.

Hrepic, Z., Zollman, D. A., & Rebello, N. S. (2005). *Eliciting and Representing Hybrid Mental Models.* Paper presented at the Annual Meeting of the National Association for Research in Science Teaching, Dallas, TX.

Huffman, D., & Heller, P. (1995). What does the Force Concept Inventory Really Measure? *The Physics Teacher*, *33*, 138-143.

Karplus, E., Karplus, R. (1970). Intellectual development beyond elementary school. *School Science and Mathematics, 70*, 398-406.

Karplus, R., & Their, H. D. (1969). *A new look at elementary school science*. Chicago, IL: Rand McNally.

Karplus, R., & Their, H. D. (1971). *SCIS: The Science Curriculum Improvement Study*. New York, NY: Macmillan.

Karplus, R. J. (1974). Science teaching and development of reasoning. *Journal for Research in Science Teaching, 12*, 213-218.

Karplus, R. J., & Their, H.D. (1967). *A new look at elementary school science*. Chicago: Rand McNally.

Kim, I.-K., & Spelke, E. (1999). Perception and understanding of effects of gravity and inertia on object motion. *Developmental Science*, *2*(3), 339-362.

King-Casas, B., Tomlin, D., Anen, C., Camerer, C. F., Quartz, S. R., & Montague, P. R. (2005). Getting to Know You: Reputation and Trust in a Two-Person Economic Exchange. *Science*, *308*, 78-83.

Knight, R. (2002). *Five Easy Lessons: Strategies for Successful Physics Teaching*.

Laws, P. (1991). Workshop Physics: Learning introductory physics by doing it. *Change Magazine*, 20-27.

Lesh, R., & Kelly, A. E. (2000). Multitiered Teaching Experiments. In R. Lesh & A. E. Kelly (Eds.), *Handbook of Research Design in Mathematics and Science Education*. Mahwah, NJ: Lawrence Erlbaum Associates.

Maloney, D. P., O'Kuma, T. L., Heiggelke, C. J., & Van Heuvelen, A. (2001). Surveying students' conceptual knowledge of electricity and magnetism. *American Journal of Physics*, *69*(7), S12-S23.

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

McDermott, L. C. (1984). Research on Conceptual Understanding in Mechanics. *Physics Today*, *37*(7), 24-32.

McDermott, L. C. (1996). *Physics by Inquiry* (Vols. I & II). New York: Wiley.

McDermott, L. C., & Redish, E. F. (1999). Resource Letter: PER-1: Physics Education Research. *American Journal of Physics, 67*(9), 755-767.

McDermott, L. C., & Shaffer, P. (1998). *Tutorials in Introductory Physics*. Upper Saddle River, NJ: Prentice Hall,.

McKinnon, J. W., & Renner, J. W. (1971). Are Colleges Interested in Intellectual Development? *American Journal of Physics, Vol. 39*, 1047.

Meltzer, D. E., & Manivannan, K. (1996). Promoting Interactivity in Physics Lecture Classes. *The Physics Teacher, 34*(2), 72-73.

Minstrell, J. (1992). Facets of students' knowledge and relevant instruction. In R. Duit, F. Goldberg & H. Niedderer (Eds.), *Research in Physics Learning: Theoretical Issues and Empirical Studies* (pp. 110-128). Kiel, Germany: Institut für Pädagogik der Naturwissenschaften.

NBTC. (2005). *Nanobiotechnology Course, Spring 2005*, from www.nbtc.cornell.edu/edu_course.htm

PSSC. (1960). *Physics*. Boston, MA: Raytheon Education Co.

Rebello, N. S., & Zollman, D. A. (2004a). The Effect of Distracters on Student Performance on the Force Concept Inventory. *American Journal of Physics, 72*(1), 116-125.

Rebello, N. S., & Zollman, D. A. (2004b). *Using Hand-Held Computers in Our Classrooms*, from http://web.phys.ksu.edu/HP_project/

Rebello, N. S., Zollman, D. A., Allbaugh, A. R., Engelhardt, P. V., Gray, K. E., Hrepic, Z., *et al*. (2005). Dynamic Transfer: A Perspective from Physics Education Research. In J. P. Mestre (Ed.), *Transfer of Learning from a Modern Multidisciplinary Perspective*. Greenwich, CT: Information Age Publishing Inc.

Redish, E. F. (1994). The Implications of Cognitive Studies for Teaching Physics. *American Journal of Physics, 62*(6), 796-803.

Redish, E. F. (1999). Millikan Award Lecture (1998): Building a Science of Teaching Physics. *The American Journal of Physics, 67*(7), 562-573.

Redish, E. F. (2003a). *Teaching Physics with the Physics Suite*: John Wiley & Sons.

Redish, E. F. (2003b, July 15-25, 2003). *A Theoretical Framework for Physics Education Research: Modeling Student Thinking.* Paper presented at the International School of Physics, "Enrico Fermi", Course CLVI, Varenna, Italy.

Redish, E. F., Saul, J. M., & Steinberg, R. N. (1998). Students' expectations in introductory physics. *American Journal of Physics, 66*(212-224).

Redish, E. F., & Vincentini, M. (2004). *Research on Physics Education* (Vol. 156). Amsterdam, Netherlands: IOS Press.

Singh, C., & Rosengrant, D. (2003). Multiple-choice test of energy and momentum concepts. *American Journal of Physics, 71*(6), 607-617.

Sokoloff, D. (1993). Electric Circuit Concept Test.

Sokoloff, D. (1997). Light and Optics Conceptual Evaluation.

Sokoloff, D. R., & Thornton, R. K. (1997). Using Interactive Lecture Demonstrations to Create an Active Learning Environment. *The Physics Teacher, 35*(9), 340-347.

Steffe, L. P. (1983). *The Teaching Experiment Methodology in a Constructivist Research Program.* Paper presented at the Fourth International Congress on Mathematical Education., Boston, MA.

Steffe, L. P., & Thompson, P. W. (2000). Teaching experiment methodology: Underlying principles and essential elements. In R. K. Lesh, A. E. (Ed.), *Research design in mathematics and science education.* (pp. 267-307). Hillsdale, NJ: Erlbaum.

Swartz, C. E., & Miner, T. (1997). *Teaching Introductory Physics: A Resource Book*. Woodbury, NY: AIP Press.

Thornton, R. K., & Sokoloff, D. R. (1998). Assessing student learning of Newton's laws: The Force and Motion Conceptual Evaluation and the Evaluation of Active Learning Laboratory and Lecture Curricula. *American Journal of Physics, 66*(4), 338-352.

Wells, M., Hestenes, D., & Swackhamer, G. (1995). A Modeling Method for High School Physics Instruction. *American Journal of Physics, 63*, 606-619.

Wilson, J. M. (1994). The CUPLE Physics Studio. *The Physics Teacher, 32*, 518-523.

Zollman, D. A. (1990). Learning cycles for a large-enrollment class. *The Physics Teacher, 28*(1), 20-25.

Zollman, D. A. (1993). Interactive video activities for elementary education students. In J. V. Boettcher (Ed.), *101 Success Stories of Information Technology in Higher Education*. New York, NY: McGraw Hill.