Surveying the Conceptual and Temporal Landscape of Physics Education Research

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Supported in part by U.S. National Science Foundation

Grant Nos. DUE 9981140, PHY 0108787, PHY 0406724, PHY 0604703, and DUE 0817282

Areas of Interest in PER

- ***Macro (program level)***
  - Historical evolution: what is taught, why it is taught;
  - *Learning goals:* concepts, scientific reasoning, problem-solving skills, experimentation skills, lab skills, “transfer,” etc.
- ***Meso (classroom level)***
  - Instructional methods
  - Logistical factors K-20 (group size and composition; class-size scaling, etc.)
  - Teacher preparation and assessment
- ***Micro (student level)***
  - Student ideas and knowledge structures; Learning behaviors
  - Assessment; Learning trajectories; Individual differences

Spectral Parameters

- ***Basic vs. Applied Research:*** Degree of proximity to classroom implementation
- ***Theoretical vs. Empirical:*** Degree of proximity to observational data

➢ [My emphasis will be empirical]

Some historical perspective

- The question of what subjects should be taught in schools and colleges, and how they should be taught, has occupied educators for centuries
- So, let's dial back around one century…

Why Teach Science?

“Science …consists of the special …methods which the race has slowly worked out in order to conduct reflection under conditions whereby its procedures and results are tested. It is artificial (an acquired art), not spontaneous; learned, not native. To this fact is due the unique, the invaluable place of science in education, and also the dangers which threaten its right use.

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"Without initiation into the scientific spirit one …fails to understand the full meaning of knowledge. … On the other hand, …its results, taken by themselves, [are] remote from ordinary experience…abstract. When this isolation appears in instruction, scientific information is even more exposed to the dangers attendant upon presenting ready-made subject matter than are other forms of information…" [J. Dewey, *Democracy and Education*, 1916; Chap. 14, Sec. 3]

How Teach Science?

"…observation is an *active* process… [it] is exploration, inquiry for the sake of discovering something previously hidden and unknown…Pupils learn to observe for the sake…of …inferring hypothetical explanations for the puzzling features that observation reveals; and…of testing the ideas thus suggested.

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“In short, observation becomes scientific in nature…For teacher or book to cram pupils with facts which, with little more trouble, they could discover by direct inquiry is to violate their intellectual integrity by cultivating mental servility.” [J. Dewey, *How We Think*, 1910; pp. 193-198]

How Teach Science?

“…[In] the…method which begins with the experience of the learner and develops from that the proper modes of scientific treatment …The apparent loss of time involved is more than made up for by the superior understanding and vital interest secured. What the pupil learns he at least understands.

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"…Students will not go so far, perhaps, in the 'ground covered,' but they will be sure and intelligent as far as they do go. And it is safe to say that the few who go on to be scientific experts will have a better preparation than if they had been swamped with a large mass of purely technical and symbolically stated information." [J. Dewey, *Democracy and Education*, 1916; Chap. 17, Sec. 1]

Earlier Precursors

- What happened when scientists first took on a prominent role in designing modern-day science education?

A Chemist and a Physicist Examine Science Education

- In 1886, at the request of Harvard President Charles Eliot, physics professor Edwin Hall developed physics admissions requirements and created the "Harvard Descriptive List of Experiments."
- In 1902, Hall teamed up with chemistry professor Alexander Smith (University of Chicago) to lay a foundation for rigorous science education. Together they published a 400-page book:

  "The Teaching of Chemistry and Physics in the Secondary School" (A. Smith and E. H. Hall, 1902)

Teaching Physics by Guided Inquiry: The Views of Edwin Hall

"…It is hard to imagine any disposition of mind less scientific than that of one who undertakes an experiment knowing the result to be expected from it and prepared to work so long, and only so long, as may be necessary to attain this result…

Teaching Physics by Guided Inquiry: The Views of Edwin Hall

"…It is hard to imagine any disposition of mind less scientific than that of one who undertakes an experiment knowing the result to be expected from it and prepared to work so long, and only so long, as may be necessary to attain this result….I would keep the pupil just enough in the dark as to the probable outcome of his experiment, just enough in the attitude of discovery, to leave him unprejudiced in his observations, and then I would insist that his inferences…must agree with the record…of these observations…the experimenter should hold himself in the attitude of genuine inquiry." [Smith and Hall, pp. 277-278]

Teaching Physics by Guided Inquiry:
The Views of Edwin Hall

*But why teach **physics**, in particular?*

Teaching Physics by Guided Inquiry: The Views of Edwin Hall

"…physics is peculiar among the natural sciences in presenting in its quantitative aspect a large number of perfectly definite, comparatively simple, problems, not beyond the understanding or physical capacity of young pupils. With such problems the method of discovery can be followed sincerely and profitably."

[E.H. Hall, 1902]

[from Smith and Hall, p. 278]

Instructional Developments 1900-1950

- *At university level:* evolution of “traditional” system of lecture + “verification” labs
- *At high-school level:* Departure of [most] physicists from involvement with K-12 instruction; Evolution of textbooks with superficial coverage of large number of topics, terse and formulaic; heavy emphasis on detailed workings of machinery and technological devices used in “everyday life”
- *At K-8 level:* limited use of activities, few true investigations, *“teachers rarely ask a question because they are really curious to know what the pupils think or believe or have observed”* [Karplus, 1965]

Research on Physics Learning

- *Earliest days:* In the 1920s, Piaget began a fifty-year-long investigation of children's ideas about the physical world; development of the "clinical interview"
- *1930s-1960s:* Most research occurred in U.S. and focused on analysis of K-12 instructional methods; scattered reports of investigations of K-12 students' ideas in physics (e.g., Oakes, *Children's Explanations of Natural Phenomena*, 1947)
- *Early 1960s:* "Rediscovery" of value of inquiry-based science teaching: Arons (1959); Bruner (1960); Schwab (1960, 1962)

Instructional Developments in the 1950s

- *At university level:* development and wide dissemination of inservice programs for high-school teachers; Arnold Arons begins development of inquiry-based introductory college course (1959)
- *At high-school level:* Physical Science Study Committee (1956): massive, well-funded collaboration of leading physicists (Zacharias, Rabi, Bethe, Purcell, et al.) to develop and test new curricular materials; emphasis on deep conceptual understanding of broad principles; challenging lab investigations with very limited guidance; textbook, films, supplements, etc.
- *At K-8 level [around 1962]:* Proliferation of active-learning curricula (SCIS, ESS, etc.); Intense involvement by some leading physicists (e.g., Karplus, Morrison); *"Scientific information is obtained by the children through their own observations…the children are not told precisely what they are going to learn from their observations."* [Karplus, 1965].

Research on Students' Reasoning

- Karplus et al., 1960s-1970s: Carried out an extensive, painstaking investigation of K-12 students' abilities in proportional reasoning, control of variables, and other "formal reasoning" skills;
  - demonstrated age-related progressions;
  - revealed that large proportions of students lacked expected skills (See Fuller, ed. *A Love of Discovery*)
- Analogous investigations reported for college students (McKinnon and Renner, 1971; Renner and Lawson, 1973; Fuller et al., 1977)

Beginning of Systematic Research on Students' Ideas in Physical Science: 1970s

- *K-12 Science:* Driver (1973) and Driver and Easley (1978) reviewed the literature and began to systemize work on K-12 students' ideas in science ["misconceptions," "alternative frameworks," etc]; only loosely tied to development of curriculum and instruction
- *University Physics:* In 1973, McDermott initiated detailed investigations of U.S. physics students' reasoning at the university level, incorporating and adapting the clinical-interview method; similar work was begun around the same time by Viennot and her collaborators in France (Viennot, 1976-1979; Trowbridge [thesis], 1979; Trowbridge and McDermott, 1980)

Initial Development of Research-based Curricula

- University of Washington, 1970s: initial development of *Physics by Inquiry* for use in college classrooms, inspired in part by Arons' *The Various Language* (1977)*:* emphasis on development of physics concepts; "elicit, confront, and resolve" strategy
- Karplus and collaborators, 1975: development of modules for *Workshop on Physics Teaching and the Development of Reasoning*, directed at both high-school and college teachers: emphasis on development of ["Piagetian"] scientific reasoning skills and the "learning cycle" of guided inquiry.

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Effect of Physics Instruction on Development of Science Reasoning Skills

- Improvement of students' science-reasoning skills is a broad consensus goal of physics instructors everywhere
- Little (or no) published evidence to show improvements in reasoning due to physics instruction, traditional or "reformed"
- Bao et al. (2009) showed that good performance on FCI and BEMA not necessarily associated with improved performance on Lawson Test of Scientific Reasoning
- Various claims in science education literature regarding improvements in reasoning skills of K-12 students from inquiry-based instruction (e.g., Adey and Shayer [1990-1993], Gerber et al. [2001] are not specifically in a physics context and have simultaneous variation of multiple variables

Physics Problem-Solving Ability

- *The challenge:* Improve general problem-solving ability, and assess by disentangling it from conceptual understanding and mathematical skill
  - Develop general problem-solving strategies (Reif et al., 1982,1995; Van Heuvelen, 1991; Heller et al., 1992)
  - Expert-novice studies: Larkin (1981)
  - Review papers: Maloney (1993); Hsu et al. (2004)

➢ Improvement in physics problem-solving skills has been demonstrated, but disentanglement is still largely an unsolved problem. (How much of improvement is due to better conceptual understanding, etc.?)

Physics Process Skills

- *The challenge:* Assessing complex behaviors in a broad range of contexts, in a consistent and reliable manner
  - design, execution, and analysis of controlled experiments; development and testing of hypotheses, etc.
  - Assessment using qualitative rubrics; examination of trajectories and context dependence (Etkina et al., 2006-2008)

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Research and Practice

- All research results in education have explicit or implicit bearing on activities in actual classrooms
- However broad the research result may be, its classroom implementation is accompanied by a myriad of population and context variables
- Simultaneous quest for:
  - broadly generalizeable results that may be applied anywhere at any time
  - narrowly engineered implementations to optimize a particular instructional environment

From Research to Practice, and Back

- Detailed “Instructor’s Guides” (perhaps enhanced with multimedia) are appropriate mechanisms for documenting implementation of specific curricula and activities
- Broader, “generalizable lessons” may be extracted and documented through process of developing Instructor’s Guides, and should be disseminated beyond immediate users of curriculum

Issues with Research-Based Instruction

- Instruction informed and guided by research on students' thinking
  - *Still many topics yet to be investigated*
- Known student difficulties are addressed
  - *Need to know specific reasoning patterns, and extent of difficulties in diverse populations*
- Use of problem-solving, guided inquiry activities
  - *Strategies must be formulated, and effectiveness assessed with specific populations*

Issues with Research-Based Instruction

- Students encouraged to express their reasoning, with rapid feedback
  - *Cost-benefit analysis to address logistical challenges*
- Emphasis on qualitative reasoning
  - *Balance with possible trade-offs in quantitative reasoning*
- Use of diverse contexts and representations, physical objects
  - *Assess effectiveness with different populations*

Retention of Learning Gains

- *The challenge:* carry out longitudinal studies to document students' knowledge long after (~ years) instruction is completed
  - Above-average FCI scores retained 1-3 yrs after UW tutorial instruction (Francis et al., 1998)
  - Above-average gains from *Physics by Inquiry* curriculum retained one year after course (McDermott et al., 2000)
  - Improved scores on BEMA *after* junior-level E&M for students whose freshman course used UW tutorials (Pollock, 2009)
  - Higher absolute scores (although same loss rate) 0.5-2 yrs after instruction with *Matter and Interactions* curriculum (Kohlmeyer et al., 2009)

Assessment of Physics Teaching Skills

- *The challenge:* “Direct” measures (learning gains of teacher’s students) difficult to acquire; “indirect” measures (e.g., teachers’ concept knowledge, and “pedagogical content knowledge” [PCK]) difficult to assess, and have undetermined relationship to actual teaching effectiveness
  - Studies of high-school students’ FCI scores (ASU and FIU modeling groups)
  - Instruments for assessing physics PCK (U. Maine, U. Colorado, SPU)
  - Observational protocols (e.g. RTOP [MacIsaac and Falconer, 2002])

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Descriptions of Students' Ideas

- Focus on specific difficulties, including links between conceptual and reasoning difficulties
  - (McDermott, 1991; 2001)
- Focus on diverse knowledge elements
  - "facets": Minstrell, 1989, 1992
  - "phenomenological primitives": diSessa, 1993
  - "resources": Hammer, 2000

Assessing and Strengthening Students' Knowledge Structures

- *The challenge:* students' patterns of association among diverse ideas in varied contexts are often unstable and unexpected, and far from those of experts; how can they be revealed, probed, and prodded in desired directions?
  - Emphasize development of hierarchical knowledge structures (Reif, 1995)
  - Stress problem-solving *strategies* to improve access to conceptual knowledge (Leonard et al.,1996)
  - Analyze shifts in students' knowledge structures (Bao et al., 2001; 2002; 2006; Savinainen and Viiri, 2008; Malone, 2008)

Behaviors (and Attitudes) with Respect to Physics

- The challenge: Assess complex behaviors, and potentially *more* complex relationships between those behaviors and learning of physics concepts and process skills
  - Behaviors (e.g., questioning and explanation patterns) linked to learning gains (Thornton, 2004)
  - Beliefs link to learning gains (May and Etkina, 2002)
  - Evolution of attitudes (VASS (Halloun and Hestenes, 1998); MPEX [Redish et al., 1998], EBAPS [Elby, 2001], CLASS [Adams et al., 2006], etc.)

Learning Trajectories:
Kinematics and Dynamics of Students' Thinking

- *The challenge:* How can we characterize the evolution of students' thinking, K-20? This includes:
  - sequence of knowledge elements and interconnections
  - sequence of difficulties, study methods, and attitudes
- Probes of student thinking must be repeated at many time points, and the effect of the probe itself taken into account
- Can provide measured and sequenced hints and answers, to assess students' ability to respond to instructional cues
  - "Learning Experiments" and "Dynamic Assessment": methods for probing Vygotsky's Zone of Proximal Development

Issues with Learning Trajectories

- Are there common patterns of variation in learning trajectories? If so, do they correlate with individual student characteristics?
- To what extent does the student's present set of ideas and difficulties determine the pattern of his or her thinking in the future?
  - Are there *well-defined* "transitional mental states" that characterize learning progress?
- To what extent can the observed sequences and patterns be altered as a result of actions by students and instructors?

Learning Trajectories: Microscopic Analysis

- *The challenge:* Probe evolution of student thinking on short time scales (~ days-weeks) to examine relationship of reasoning patterns to instruction and other influences
  - Identification of possible "transition states" in learning trajectories (Thornton, 1997; Dykstra, 2002)
  - Revelation of micro-temporal dynamics, persistence/evanescence of specific ideas, triggers, possible interference patterns, etc. (Sayre and Heckler, 2009)

Learning Trajectory: Early (K-12)

- Vast diversity of grade levels and ages is a huge challenge
- Much previous work, but very little by physicists testing out possible modifications of college-level curricula
  – Dykstra and Sweet (2009)

Learning Trajectory: Late (upper-level and graduate courses)

- The challenge: small samples, frequently diverse populations, significant course-to-course variations
  - Undergraduate: Ambrose (2003); Singh et al. (2005-2009)
  - Graduate: Patton (1996)

Learning Difficulties with Learning

- What specific difficulties *with the learning process* itself are encountered when learning physics through guided inquiry?
  - e.g., difficulties in exercising suspension of judgment, seeking of coherence, tolerance of frustration
- May be reflected in:
  - Professed beliefs about learning
  - Actual learning behaviors

Assessments

- The challenge: Develop valid and reliable probes of students' knowledge, along with appropriate metrics, that may be administered and evaluated efficiently on large scales
  - FCI (Halloun and Hestenes, 1985; Hestenes et al., 1992);
  - FMCE (Thornton and Sokoloff, 1998)
  - CSEM (Maloney et al., 2001)
  - Many others: see www.ncsu.edu/PER/TestInfo.html
  - Normalized Gain metric: Hake, 1998
- Much work remains to be done…

Summary

- Behold the expanding balloon effect: the more that is known, the greater is the extent of the frontier
- PER has (potentially) the capabilities and the resources to improve effectiveness of physics learning at all levels, K-20 and beyond
- Practical, classroom implementation of research findings with diverse populations has been a hallmark of PER from the beginning; it is a critical, and never-ending challenge