A Brief History of Physics Education Research Among University Students

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Probably, one of the most significant truths learned through our recent [physics] testing programs, is the failure of students to accomplish any large fraction of the supposed requirements of courses pursued. In other words, what the teacher thinks he is teaching is usually many times what he actually teaches.

[A. W. Hurd, “Achievements of students in physics,” Science Education **14**, 437 (1930)]

Outline

- My focus is research on the learning and teaching of physics at the university level, excluding pre- and post-university students
- I will focus on empirical studies (not theoretical analyses) of students enrolled in physics classes, aimed at improving the effectiveness of instruction
- I will emphasize developments in the United States (1880-1990), with brief discussion of examples of work done in other countries

➢ To provide perspective, I begin with a brief history of the U.S. educational system

Development of the U.S. Educational System

- Public secondary “high school” education (age 14+) began to develop in the U.S. during the 1800s
- Science—including physics—gained an increasing role in the high school curriculum after 1865
- Laboratory-based high school physics instruction spread rapidly during 1880-1900
- High school physics came to be taught in the U.S. as a single, *one-year* course
- From 1880 to 1940, proportion of U.S. population attending high school exploded from <5% to >65%
- Initially, most U.S. high schools were very small (≈50 students) with 2−4 teachers

Therefore…

Development of the U.S. Educational System

- Very few professional physics teachers during most of U.S. education history
- U.S. high school physics is taught primarily at a low introductory level (by international standards)
- Most U.S. university students have had only 0-1 years of previous study of physics
- ***U.S. research on in-depth student understanding of physics has occurred primarily at the university level***

U.S. Physics Education Research (PER) Has Always Been Linked to Physics Instruction …

- Research in physics education has been motivated by efforts to improve instruction
- The history of PER is closely linked to developments in physics pedagogy

So, to understand the history of PER, we must review developments in physics instruction…

Physics Pedagogy Overview: 1860-1960

- Early science educators advocated instruction based on hands-on investigation and discovery, however…
- In the 1890s, school physics instruction emphasized rote problem solving and execution of prescribed labs
- In the 1920s, instructional emphasis shifted to superficial descriptions of technological devices
- In the 1960s, university scientists attempted to transform school and university physics back towards its original instructional goals, emphasizing deep conceptual understanding

Physics Pedagogy Overview: 1970-2000

- In the 1970s, university-based physicists initiated systematic research to support instructional reforms at the college level, building on pedagogical reforms of 1950s and 1960s
- In the 1980s, this movement expanded rapidly and led to many new, research-based instructional approaches.
- After 1990, there was rapid growth in the development of research-based instructional materials in physics

Physics Teaching in U.S. Schools

Nationwide surveys of high-school and college physics teachers in 1880* and 1884** revealed:

- Rapid expansion in use of laboratory instruction
- Strong support of “inductive method” of instruction in which experiment precedes explicit statement of principles and laws

*F.W. Clarke, *A Report on the Teaching of Chemistry and Physics in the United States*, Circulars of Information No. 6, Bureau of Education (1880)

**C.K. Wead, *Aims and Methods of the Teaching of Physics*, Circulars of Information No. 7, Bureau of Education (1884).

First U.S. "Active-Learning" Physics Textbook:

Alfred P. Gage, *A Textbook of the Elements of Physics for High Schools and Academies* (Ginn, Boston, 1882).

"The book which is the most conspicuous example now in the market of this inductive method is Gage's. Here, although the principles and laws are stated, the experiments have preceded them;

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Aims and Methods of the Teaching of Physics (1884), p. 120.

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A TEXT-BOOK

OF THE

ELEMENTS OF PHYSICS

FOR

HIGH SCHOOLS AND ACADEMIES.

BY

ALFRED P. GAGE, A.M.,

INSTRUCTOR IN PHYSICS IN THE ENGLISH HIGH SCHOOL, BOSTON, MASS.

BOSTON:

PUBLISHED BY GINN, HEATH, & CO.

1882.

Early Precursors of Modern Physics Pedagogy

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

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."

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

Teaching Physics by the "Problem Method": The Views of Robert Millikan

"...the material with which [physics] deals is almost wholly available to the student *at first hand,* so that in it he can be taught to observe, and to begin to interpret *for himself* the world in which he lives, instead of merely memorizing text-book facts, and someone else's formulations of so-called laws…the main object of the course in physics is to teach the student to *begin to think for himself*...*"*

[R. A. Millikan, Sch. Sci. and Math. **9**, 162-167 (1909)]

The “New Movement” for Physics Education Reform; ~ 1905-1915

- Reaction against overemphasis on formulaic approach, quantitative measurement, and overly complex apparatus in laboratory-based high-school physics instruction
- Strong emphasis on qualitative understanding of “processes and principles underlying natural phenomena”

Early Assessment of Students’ Thinking

“I have generally found very simple questioning to be sufficient to show the exceedingly vague ideas of the meaning of the results, both mathematical and experimental, of a large part of what is presented in the texts and laboratory manuals now in use.”

H.L. Terry, 1909
Wisconsin State Inspector of High Schools

The Teaching of Physics for Purposes of General Education, C. Riborg Mann (Macmillan, New York, 1912).

- Physics professor at University of Chicago
- Leader of the New Movement
- Stressed that students' laboratory investigations should be aimed at solving problems that are both practical and interesting: called the "Problem" method, or the "Project" method

  "…the questions and problems at the ends of the chapters are not mathematical puzzles. They are all real physical problems, and their solution depends on the use of physical concepts and principles, rather than on mere mechanical substitution in a formula."

  C. R. Mann and G. R. Twiss, *Physics* (1910), p. ix

Instructional Developments 1920-1950

- *At university level:* evolution of “traditional” system of lecture + “verification” labs
- *At high-school level:* Evolution of textbooks with superficial coverage of many topics, terse and formulaic; heavy emphasis on devices used in “everyday life”

Instructional Developments in the 1950s

Revival of the "Inductive" Method

- *At university level:* development and wide dissemination of inservice programs for high-school teachers; Arnold Arons begins development of inquiry-based introductory college course (~1955)

- *At high-school level:* Physical Science Study Committee (1956): massive, well-funded collaboration of leading physicists to develop and test new curricular materials; emphasis on deep conceptual understanding of broad principles using challenging lab investigations

- *At elementary level [around 1962]:* Proliferation of active-learning curricula; Intense involvement by some leading physicists

Physical Science Study Committee (1956)

- Textbook that strongly emphasized conceptual understanding, with detailed and lengthy exposition
  - Rejected superficial coverage of a large number of topics and memorization of terse formulations
- Incorporated laboratory investigations that were lightly guided through questions, suggestions, and hints.
  - Rejected use of “cookbook”-style instructional laboratories designed to verify known principles.

➢ *Became one of the models for future research-based instruction*

“The Physical Science Study Committee,” G. C. Finlay, Sch. Rev. **70**(1), 63–81 (Spring 1962).

Emphasizes that students should be active participants using inquiry, including laboratory investigations:

“In this course, experiments…are not used simply to confirm an earlier assertion.”

Arnold Arons, Amherst College, 1950s: Independently developed new, active-learning approach to calculus-based physics

"Structure, methods, and objectives of the required freshman calculus-physics course at Amherst College,"
A. B. Arons, Am. J. Phys. **27**, 658–666 (1959).

Arons characterized the nature of this course's laboratory work as follows: "Your instructions will be very few and very general; so general that you will *first be faced with the necessity of deciding what the problem is*. You will have to formulate these problems in your own words and then proceed to investigate them." [Emphasis in original.]

“Definition of intellectual objectives in a physical science course for preservice elementary teachers,” A. Arons and J. Smith, Sci. Educ. **58**, 391–400 (1974).

- Instructional staff for the course were explicitly trained and encouraged to conduct “Socratic dialogues” with students.

- Utilized teaching strategies directed at improving students’ reasoning skills.

The Various Language: An Inquiry Approach to the Physical Sciences, A. Arons (Oxford University Press, New York, 1977).

A hybrid text and activity guide for a college-level course; provides extensive questions, hints, and prompts. The original model for *Physics by Inquiry*.

Active-Learning Elementary Science

- More than a dozen new, NSF-funded curricula were developed in the 1960s
- Well-known physicists played a key role in several of the leading programs
- The curricula emphasized inquiry and investigation, and introduced the “Learning Cycle”
- The curricula embodied a revival and transformation of the “Inductive Method” of the 1880s

➢ *These curricula became another model for future research-based instruction*

Timeline: Research on Student Learning

- **Science Education**
  - Educators in the 1880s and 1890s probed children's ideas about the physical world to inform instruction

[1891]

THE CONTENTS OF CHILDREN'S MINDS ON ENTERING SCHOOL.

By G. Stanley Hall.

In Oct. 1869 the Berlin Pedagogical *Verein* issued a circular inviting teachers to investigate the individuality of children on entering the city schools so far as it was represented by ideas of their environment. Individuality in children it was said differed in Berlin not only from that of children in smaller cities or in the country, but surroundings caused marked differences in culture-capacity in different wards. Although concepts from the environment were only one important cause of diversity of individuality, this cause once determined, inferences could be drawn to other causes. It was expected that although city children would have an experience of moving things much larger than country children, they would have noticed very little of

Timeline: Research on Student Learning

- **Science Education**
  - Educators in the 1880s and 1890s probed children's ideas about the physical world to inform instruction
  - In the 1920s, Piaget introduced extended, in-depth one-on-one interviews to carry out more effective probes of children's thinking about nature

The Child's Conception of Physical Causality

Jean Piaget

With a new introduction by Jaan Valsiner

[1930]

Transaction Publishers

Timeline: Research on Student Learning

- **Physics Education**
  - 1880-1920: ferment in U.S. physics education community regarding instructional methods, but little pedagogical research
  - 1920s-1930s: some statistical studies of “reformed” high school physics curricula, and probes of high school students’ reasoning
  - 1920-1960: very little research on physics learning at the university level
  - 1960s: some physicists led systematic studies of students’ formal reasoning abilities (both K-12 and college-level)
  - 1970s: (1) science educators worldwide expanded investigations of school students’ thinking; (2) university-based physicists began systematic investigations of physics learning at university level

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 high school instructional methods; a few investigations of high school students' ideas in physics (e.g., Black [1931], Kilgore [1941])
- *Early 1960s:* "Rediscovery" of value of inquiry-based science teaching [e.g., Arons (1959); Bruner (1960); Schwab (1960, 1962)] motivated renewed research

Early Research on University Physics Students

- ***A. W. Hurd (1927, 1929…1933, 1934):*** Prolific researcher in high school and college physics education, author of >25 papers; examined issues such as:
  - the effects of taking high school physics on performance in college physics
  - whether taking lab or changing class size might affect performance in college physics courses
- ***J. Rudy (1941):*** Found that university students who had taken high school physics received higher grades than those who had not taken high school physics (but that the difference was smaller for second-semester students)

Early Research on University Physics Students

- ***Haym Kruglak (1950, 1952…1969, 1970):*** Researcher in university physics education, author of ~20 papers; published findings such as:
  - no difference in performance on a theory test between students who had lab, and those who did not
  - paper-and-pencil lab tests are poor substitute for lab performance tests

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

- ***School Science:*** R. Driver (1973) and Driver and Easley (1978) reviewed the literature and began to systemize work on K-12 students' ideas in science ["miscon-ceptions," "alternative frameworks," etc]; loosely tied to development of curriculum and instruction
- ***University Physics:*** In the early 1970s, L. McDermott (U. Washington) and F. Reif (U. California) initiated detailed investigations of U.S. physics students' reasoning at the university level; similar work was begun around the same time by L. Viennot (U. Paris VII) and her collaborators in France.

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
- ***R. 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.

Workshop on Physics Teaching and the Development of Reasoning, F. P. Collea, R. G. Fuller, R. Karplus, L. G. Paldy, and J. W. Renner (AAPT, Stony Brook, NY, 1975).

“Can physics develop reasoning?” R. G. Fuller, R. Karplus, and A. E. Lawson, Phys. Today **30**(2), 23–28 (1977).

Description of pedagogical principles of the workshop.

College Teaching and the Development of Reasoning, edited by R. G. Fuller, T. C. Campbell, D. I. Dykstra, Jr., and S. M. Stevens (Information Age Publishing, Charlotte, NC, 2009).

Includes reprints of most of the workshop materials.

Frederick Reif, 1970s:

Research on Learning of University Physics Students

"Teaching general learning and problem-solving skills,"
F. Reif, J. H. Larkin, and G. C. Brackett, Am. J. Phys.
44, 212 (1976).

Students' reasoning in physics investigated through:

- observations of student groups engaged in problem-solving tasks
- "think-aloud" problem-solving interviews with individual students
- analysis of written responses.

This paper foreshadowed much future work on improving problem-solving ability through explicitly structured practice, carried out subsequently by other researchers.

Laurence Viennot, 1970s:
Research on Learning of University Physics Students

"Spontaneous reasoning in elementary dynamics,"
L. Viennot, Eur. J. Sci. Educ. **1**, 205-221 (1979).

Detailed, systematic investigation of students' reasoning in dynamics, primarily through analysis of responses on paper-and-pencil tests.

This paper culminated a series of papers that began in 1974, originally published in French, some with collaborators Malgrange, Saltiel, and Maury; they formed the basis for a extensive research and curriculum development program that is still ongoing.

Lillian McDermott, 1970s:
Development of Research-Based Curricula

"Investigation of student understanding of the concept of velocity in one dimension," D. E. Trowbridge and L. C. McDermott, Am. J. Phys. **48**, 1020–1028 (1980).

•Primary data sources were "individual demonstration interviews" in which students were confronted with a simple physical situation and asked to respond to a specified sequence of questions.

•Curricular materials were designed to address specific difficulties identified in the research; students were guided to confront directly and then to resolve confusion related to the physics concepts.

This paper provided a model and set the standard for an ongoing program of research-based curriculum development unmatched in scope and productivity: The UW Physics Education Group has published over 50 research papers in peer-reviewed journals.

David Hestenes and Ibrahim Halloun, 1980s:
Systematic Investigation of Students' Ideas about Forces

"The initial knowledge state of college physics students," I. A. Halloun and D. Hestenes, Am. J. Phys. **53**, 1043–1055 (1985).

Development and administration of a research-based test of student understanding revealed the ineffectiveness of traditional instruction in altering college physics students' mistaken ideas about Newtonian mechanics.

"Common sense concepts about motion," I. A. Halloun and D. Hestenes, Am. J. Phys. **53**, 1056–1065 (1985).

Comprehensive and systematic inventory of students' ideas regarding motion.

Alan Van Heuvelen, 1991:

Use of Multiple Representations in Structured Problem Solving

“Learning to think like a physicist: A review of research-based instructional strategies,” A. Van Heuvelen, Am. J. Phys. **59**, 891–897 (1991).

Development of active-learning instruction in physics with a particular emphasis on the need for qualitative analysis and hierarchical organization of knowledge. Explicitly builds on earlier work.

“Overview, Case Study Physics,” A. Van Heuvelen, Am. J. Phys. **59**, 898–907 (1991).

Influential paper that discussed methods for making systematic use in active-learning physics instruction of multiple representations such as graphs, diagrams, and verbal and mathematical descriptions.

Ronald Thornton, David Sokoloff, and Priscilla Laws:
Adoption of Technological Tools for Active-Learning Instruction

“Tools for scientific thinking—Microcomputer-based laboratories for physics teaching,” R. K. Thornton, Phys. Educ. **22**, 230–238 (1987).

“Learning motion concepts using real-time microcomputer-based laboratory tools,” R. K. Thornton and D. R. Sokoloff, Am. J. Phys. **58**, 858–867 (1990).

Discusses potential for improving students’ understanding of physics concepts and graphical representations using microcomputer-based instructional curricula. [This work later expanded to include collaboration with E. Sassi (Italy), e.g., in *Proceedings of TIE* (1992).]

“Calculus-based physics without lectures,” P. W. Laws, Phys. Today **44**(12), 24–31 (1991).

Describes the principles and origins of the Workshop Physics Project at Dickinson College, begun in collaboration with Thornton and Sokoloff in 1986.

Other Early Research on University Physics Students

- ***Warren [UK] (1971; 1972):*** Student difficulties with dynamics and thermodynamics identified by analyzing responses to single-item free-response questions
- ***Preece [UK] (1976):*** Using word association, probed "conceptual structure" regarding electromagnetism of university physics graduates
- ***Helm [South Africa] (1978):*** University physics majors beginning their studies harbored "misconceptions" on a variety of topics, according to assessment with a multiple-choice test
- ***Fredette and Lochhead [USA] (1980):*** Used both clinical interviews and a written quiz to probe ideas about electric circuits held by engineering majors, most of whom were enrolled in an introductory physics course

Other Early Research on University Physics Students

- ***Champagne, Klopfer, and Anderson [USA] (1980):*** Probed introductory physics students' ideas about mechanics by having them observe, describe, and explain the motion of objects
- ***Clement [USA] (1982):*** describes evidence from written tests and problem-solving interviews, and argues that preconceptions may be treated as "zeroth-order models" that can be modified to achieve greater precision and generality.
- ***Posner, Strike, Hewson, and Gertzog [USA] (1982):*** Enunciated model for "conceptual change"; probed introductory college physics students' thinking regarding special relativity using interviews; students solved problems while "thinking aloud"

Differences Among Research Methodologies

- Earlier studies (1920s-1950s) employed broad-based, multi-topic measures of student learning; emphasized *organizational* aspects of teaching (e.g., class size, use of laboratory, effect of high school preparation)

Differences Among Research Methodologies

- Later studies (1970s-1980s) focused on investigations of students' thinking
  - Limited studies (e.g., Warren, Helm, Champagne et al.) employed broad, multi-topic surveys or 1-2 diagnostic items to gain insight into some aspects of student thinking
  - In-depth studies (e.g., McDermott, Reif, Viennot) were extended, systematic investigations, often employed interviews and multiple, focused written instruments to probe student ideas in depth, and ***to create a basis for curriculum development***

Summary and Transition…

- This carries the story to around 1990; most developments since then can be traced in one form or another to these streams of thought…
- One can also describe developments in physics education research from:
  - a topical perspective; for example:
    - Student reasoning
    - Problem-solving ability
    - Learning trajectories
  - a research-based instructional perspective; for example:
    - instruction in lecture courses
    - Instruction in laboratory courses
    - Instruction in upper-level courses

- **Reference:** David E. Meltzer and Ronald K. Thornton, "Resource Letter ALIP-1: Active-Learning Instruction in Physics," Am. J. Phys. **80**(6), 479-496 (2012).