The Development of Research-Based Physics Instruction in the United States

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Outline: Phase I

- Early advocates of school science instruction envisioned students actively engaged in investigation and discovery, leading to deep conceptual understanding.
- As availability of science instruction exploded in the 1890s, school physics instruction came to emphasize rote problem solving and execution of prescribed laboratory procedures; strenuous efforts to counter this trend were unsuccessful.
- Later, instructional emphasis shifted to descriptions of technological devices accompanied by superficial summaries of related physical principles.

Outline: Phase II

- In the 1960s, powerful movements led by university scientists attempted to transform school science back towards its original instructional goals. Parallel efforts focused on related transformations in college physics.
- In the 1970s, university-based physicists initiated systematic research to support instructional reforms at the college level. In the 1980s, this movement expanded rapidly and led to many new, research-based instructional approaches.
- Although a vast array of research-based instructional materials in physics are now available, wide dissemination and application of these materials are constrained by social and cultural forces identical to those that derailed analogous efforts over one hundred years ago.

Prelude: Scientists' Critique of Textbook-Centered Science Teaching in the Public Schools

[From report by AAAS Committee on Science Teaching in the Public Schools]

"Through books and teachers the pupil is filled up with information in regard to science. Its facts and principles are explained as far as possible, and then left in his memory with his other school acquisitions…Only in a few exceptional schools is he put to any direct mental work upon the subject matter of science, or taught to think for himself…

"As thus treated the sciences have but little value in education.…They are not made the means of cultivating the observing powers, stimulating inquiry, exercising the judgment in weighing evidence, nor of forming original and independent habits of thought. The pupil…becomes a mere passive accumulator of second-hand statements.

“But it is the first requirement of the scientific method, alike in education and in research, that the mind shall exercise its activity directly upon the subject-matter of study. Otherwise scientific knowledge is an illusion and a cheat…This mode of teaching science…has been condemned in the most unsparing manner by all eminent scientific men as a ‘deception,’ a ‘fraud,’ an ‘outrage upon the minds of the young,’ and ‘an imposture in education…’

“The mind cannot be trained in such circumstances to originate its own judgments. The exercise of original mental power or independent inquiry is the very essence of the scientific method and with this the practice of the public schools is at war.”

AAAS Committee on Science Teaching in the Public Schools (1881)

Cultural Context, 1880-1940: Explosive Increase in High School Enrollment

- Around 1880, 1 in 30 attended high school and only a fraction of the 1 attended college
- By 1940, 2 in 3 attended high school
- High school attendance increased by a factor of 60
- Number of high schools increased by more than an order of magnitude; initially, the overwhelming majority were small (≈ 50 students) with 2−4 teachers

How Did Science Teaching Get Started?

- Traditionally, college curricula had focused on ancient languages and literature—the "classics"
- Initially, the small (though growing) high school movement focused on preparing students for a classical college education
- During the 1800s, post-secondary scientific and technological education advanced but was slow to gain acceptance and respect

Initial Context: mid-1800s

- During the 1800s, science fought a long, slow battle for inclusion in the curriculum offerings of both colleges and high schools
- Teaching of science spread widely after the Civil War
- Initially, physics was primarily taught through a “lecture/recitation” method emphasizing repetition of memorized passages, along with occasional lecture demonstrations

Early Advocates for Science Education

- The question of what subjects should be taught in schools and colleges, and how they should be taught, had occupied educators for centuries (and still does)
- The rise and evolution of science education in the U.S. formed the basis for modern research in physics education
- So, what was the original motivation for introducing science into the school curriculum…?

Why Teach Science? [I]

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[Herbert Spencer, *Education: Intellectual, Moral, and Physical*, 1860; pp. 78-79.]

Why Teach Science? [II]

“If the great benefits of scientific training are sought, it is essential that such training should be real: that is to say, that the mind of the scholar should be brought into direct relation with fact, that he should not merely be told a thing, but made to see by the use of his own intellect and ability that the thing is so and no otherwise.

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[Thomas Huxley, *Science and Education*, 1893; pp. 125-126.]

How Teach Science? [I]

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"…Children should be led to make their own investigations, and to draw their own inferences. They should be *told* as little as possible, and induced to *discover* as much as possible"

[Herbert Spencer, *Education: Intellectual, Moral, and Physical*, 1860; pp. 119-120.]

How Teach Science? [II]

“…in teaching [a child] physics and chemistry, you must not be solicitous to fill him with information, but you must be careful that what he learns he knows of his own knowledge. Don’t be satisfied with telling him that a magnet attracts iron. Let him see that it does; let him feel the pull of the one upon the other for himself.

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[Thomas Huxley, *Science and Education*, 1893; p. 127.]

How Teach Science? [III]

“…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]

What about the practical issues?

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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]

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).

1880-1900: Rise of Laboratory Instruction

- Before 1880, only a handful of schools engaged students in hands-on laboratory instruction
- Between 1880 and 1900, laboratory instruction in physics became the norm at hundreds of high schools and colleges
- Laboratory instruction increasingly became a requirement for college admission after 1890

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).

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A TEXT-BOOK

ON 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 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." [from 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]

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*…

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[R.A. Millikan, 1909]

*[Sch. Sci. Math. **9**, 162-167]*

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

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

Early Assessment of Students' Thinking

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"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. Anxiety to secure the accurate results demanded in experimentation leads to the use of such complicated and delicate apparatus that the underlying principle is utterly lost sight of in the confusion resulting from the manipulation of the instrument."

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:* 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]

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].

Physical Science Study Committee (1956)

- Textbook that strongly emphasized conceptual understanding, with detailed and lengthy exposition and state-of-the-art photographs
- Incorporated laboratory investigations that were only lightly guided through questions, suggestions, and hints.
- Rejected traditional efforts that had relied heavily on superficial coverage of a large number of topics and memorization of terse formulations
- Rejected use of “cookbook”-style instructional laboratories with highly prescriptive lists of steps and procedures designed to verify known principles.

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

Emphasizes that students are expected to be active participants by wrestling with lines of inquiry, including laboratory investigations, that lead to basic ideas of physics:

“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 Science in K-8

- More than a dozen new, NSF-funded curricula were developed in the 1960s
- Well-known physicists played a key role in SCIS (Science Curriculum Improvement Study) and ESS (Elementary Science Study), among others.

“Reflections on a decade of grade-school science,” J. Griffith and P. Morrison, Phys. Today **25**(6), 29–34 (1972).

In the context of the “Elementary Science Study” curriculum, emphasizes the importance of students engaging in “the process of inquiry and investigation” to build understanding of scientific concepts.

“The Science Curriculum Improvement Study,” R. Karplus, J. Res. Sci. Teach. **2**, 293–303 (1964).

“Science teaching and the development of reasoning,” R. Karplus, J. Res. Sci. Teach. **14**, 169–175 (1977).

Describes the early implementation, and psychological and pedagogical principles underlying Karplus’s three-phase “learning cycle”: students’ initial exploration activities led them (with instructor guidance) to grasp generalized principles (concepts) and then to apply these concepts in varied contexts.

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)

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 the early 1970s, McDermott and Reif initiated detailed investigations of U.S. physics students' reasoning at the university level; similar work was begun around the same time by Viennot 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
- 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.

Lillian McDermott, 1970s:
Development of Research-Based University 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 a still-ongoing program of research-based curriculum development that has been unmatched in scope and productivity.

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 the potential for improving university students’ understanding of physics concepts and graphical representations using microcomputer-based instructional curricula.

“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.

Summary

- Most developments since 1990 can be traced in some form to one or more of the strands discussed here.
- Despite unprecedented levels of development and dissemination of research-based, active-learning curricula in both K-12 and colleges, most U.S. science education resembles “traditional” models.
- Logistical and cultural resistance to full-fledged implementation of research-based models remains a primary impediment.