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

David E. Meltzer

Arizona State University

Supported in part by U.S. National Science Foundation
Grant Nos. DUE 9981140, PHY 0108787, PHY 0406724, PHY 0604703, DUE 0817282 and DUE 1256333

In collaboration with Valerie Otero, and based in part on:

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

PER developed in the U.S. as a means for improving physics instruction…

- The development of research in physics education has been continuously linked to efforts to improve physics instruction
- Therefore, a full history of physics education research needs to be set in the context of developments in the theory and practice of physics pedagogy

So first, for perspective, an overview of both research and 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
  - In the 1920s, Piaget introduced extended, in-depth one-on-one interviews to carry out more effective probes of children's thinking about nature

[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 pouring down water; thunder as barrels, boards falling, or cannon; heaven as a well-appointed nursery, etc. They bring more or less developed apperceiving organs with them into school, each older and more familiar concept gaining more apperceptive power over the newer concepts and percepts by use. The older impressions are on the lurch, as it were, for the new ones, and mental freedom and all-sidedness depend on the number and strength of these appropriating concepts. If there are very few, as with children, teaching is like pouring water from a big tub into a small narrow-necked bottle. A teacher who acts upon the now everywhere-admitted fallacy that knowledge of the subject is all that is needed in teaching children pours at random onto more than into the children, talking to rather than with them, and gauging what he gives rather than what they receive. All now agree that the mind can learn only what is related to other things learned before, and that we must start from the knowledge that the children really have and develop this as germs, otherwise we are showing objects that require close scrutiny only to indirect vision, or talking to the blind about color. Alas for the teacher who does not learn more from his children than he can ever hope to teach them! Just in proportion as teachers do this do they cease to be merely mechanical, and acquire interest, perhaps enthusiasm, and surely an all-compensating sense of growth, in their work and life.

From the above tables it seems not too much also to infer —I. That there is next to nothing of pedagogic value the

The Child's Conception of Physical Causality

Jean Piaget

With a new introduction by Jaan Valsiner

[1930]

Transaction Publishers

the hands simply collect and then send out again the air that surrounds them.

Here are some examples from the first stage, which is very interesting from the point of view of the child's conception of physical causality: the air from outside comes in obedience, as it were, to a call, and comes through the closed window.

BAT (4) tells us that the sound he hears is due to the air: "Where does it come from? . . ."[1] "Where does the air come from?—*Through the window.*—Is it open?—*No, shut.*—And yet the air could get through?—*Yes.*—Where?— . . . Look at my hands [they are open before him]. Is there any air in them?—*No.*—And now [pressing them one against the other]?—*Yes.*—Where does it come from?—*From the window.*—Is there any in the room?—*No.*"

Timeline: Research on Student Learning

- **Physics Education**
  - From 1880-1920, great ferment in physics education community, but very little pedagogical research
  - In the 1920s and 1930s, some high school physics educators carried out careful statistical studies of “reformed” high school physics curricula, and probed high school students’ reasoning
  - 1940-1960: little research, but dissatisfaction with outcomes
  - In the 1960s some physicists led systematic studies of students’ formal reasoning abilities (both K-12 and college-level)
  - In parallel (but independent) developments in the 1970s, science educators began investigations of K-12 students’ thinking, while a few university-based physicists launched systematic investigations of physics learning at the university level

Physics Pedagogy Overview: 1860-1960

- 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.

Physics Pedagogy Overview: 1960-2000

- 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]

“The constant habit of drawing conclusions from data, and then of verifying those conclusions by observation and experiment, can alone give the power of judging correctly. And that it necessitates this habit is one of the immense advantages of science…

Why Teach Science? [I]

"The constant habit of drawing conclusions from data, and then of verifying those conclusions by observation and experiment, can alone give the power of judging correctly. And that it necessitates this habit is one of the immense advantages of science…Its truths are not accepted upon authority alone; but all are at liberty to test them−−nay, in many cases, the pupil is required to think out his own conclusions…And the trust in his own powers thus produced, is further increased by the constancy with which Nature justifies his conclusions when they are correctly drawn.."

[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.

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. The great peculiarity of scientific training, that in which it cannot be replaced by any other discipline whatsoever, is this bringing of the mind directly into contact with fact, and practising the intellect in the completest form of induction; that is to say, in drawing conclusions from particular facts made known by immediate observation of nature."

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

How Teach Science? [I]

“Science is organized knowledge; and before knowledge can be organized, some of it must first be possessed. Every study, therefore, should have a purely experimental introduction; and only after an ample fund of observations has been accumulated, should reasoning begin.

How Teach Science? [I]

"Science is organized knowledge; and before knowledge can be organized, some of it must first be possessed. Every study, therefore, should have a purely experimental introduction; and only after an ample fund of observations has been accumulated, should reasoning begin.

"…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.

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. And, especially, tell him that it is his duty to doubt until he is compelled, by the absolute authority of Nature, to believe that which is written in books."

[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.

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.

"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?

“…[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.

What about the practical issues?

"…[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.

"…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).

“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;

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; many questions are asked in connection with the experiments that tend to make the student active, not passive, and allow him to think for himself before the answer is given, if it is given at all."

C.K. Wead,

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

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; many questions are asked in connection with the experiments that tend to make the student active, not passive, and allow him to think for himself before the answer is given, if it is given at all."

C.K. Wead,

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

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. 277]

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*…

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…* the greatest need…is the kind of teaching which actually starts the pupil in the habit of independent thinking—which actually gets him to attempting to *relate;* that is, to *explain* phenomena in the light of the fundamental hypotheses and theories of physics."

[R.A. Millikan, 1909]

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

4. **Electricity, Sound, and Light.**—A general college course in Electricity, Sound, and Light, presented mainly from the experimental point of view, and involving the performance of eighteen laboratory exercises in electricity, four in sound, and six in light. Prerequisite: Physics 3. Mj. Summer Quarter, 3 sections, ASSOCIATE PROFESSORS MILLIKAN AND MR. HAM; Winter Quarter, 2 sections, ASSOCIATE PROFESSORS MANN AND MILLIKAN; Spring Quarter, ASSOCIATE PROFESSOR KINSLEY.

5. **Lecture Demonstration Course.**—A course of lectures, demonstrations, and recitations supplementing courses 3 and 4 and completing a year's work in college Physics. Recent discoveries and developments in Physics are given especial attention. 5 hours a week. Prerequisite: Physics 4. Mj. Summer Quarter, ASSISTANT PROFESSOR GALE; Spring Quarter, ASSOCIATE PROFESSOR MANN.

6. **General Survey of Physical Science.**—A lecture demonstration course in which familiar physical phenomena are presented and discussed with reference both to their scientific interpretation and to their relations to modern life. Primarily for Arts students. Not accepted in satisfaction of specific requirements in Physics. ASSOCIATE PROFESSOR MANN. [Not given in 1909–10.]

SENIOR COLLEGE COURSES

11. **Heat and Molecular Physics.**—A lecture course for advanced and graduate students, covering the Kinetic Theory, Capillarity, Elementary Thermodynamics, Solution, and Electrolysis. Prerequisite: Physics 4 and Calculus. Mj. Winter Quarter, ASSOCIATE PROFESSOR MILLIKAN.

12. **Light.**—A lecture course for advanced students covering the more important sections of geometrical and physical optics. [Not given in 1909–10.]

13. **Electricity and Magnetism.**—A course of advanced work in theoretical Electricity and Magnetism, intended to supplement the work in General Physics or to prepare for graduate work. Prerequisite: Physics 4 and Calculus. ASSOCIATE PROFESSOR KINSLEY. [Not given in 1909–10.]

14. **The Pedagogy of Physics.**—A course designed for teachers of Physics in high schools, consisting of lectures and discussions upon choice of subject-matter and methods of presentation best suited to elementary courses in Physics. Prerequisite: courses 3, 4, and 5, or equivalents. M. First Term, Summer Quarter, ASSOCIATE PROFESSOR MILLIKAN.

15. **Mechanics and Wave Motion.**—A lecture course on the physical meaning and the mathematical derivation of the fundamental equations of Mechanics and Wave Motion. Prerequisite: Physics 4 and Calculus. Mj. Autumn Quarter, 2:00, ASSISTANT PROFESSOR GALE.

16. **Experimental Physics (Advanced): Molecular Physics and Heat.**—A course of advanced laboratory work involving the determination of vapor pressures and densities, coefficients of friction of gases and liquids, molecular electrical conductivities, freezing- and boiling-points, latent and specific heats, high and low temperatures, radio-active constants, etc. Prerequisite: course 4. Mj. Spring Quarter, ASSOCIATE PROFESSOR MILLIKAN.

17. **Experimental Physics (Advanced): Light.**—A course of advanced laboratory work in Light, consisting of accurate measurements in diffraction, dispersion, interference, and polarization. Prerequisite: course 4. Mj. Autumn Quarter, ASSOCIATE PROFESSOR MANN.

18. **Experimental Physics (Advanced): Electricity and Magnetism.**—Laboratory work of the same grade as courses 16 and 17, but consisting of measurements in Electricity and Magnetism. Prerequisite: Mathematics 27 and Physics 4. Mj. Summer Quarter. Mj. Winter Quarter, ASSOCIATE PROFESSOR KINSLEY.

20. **Physical Manipulation.**—A series of exercises not provided in the regular courses of Experimental Physics, but important to the teacher or advanced student. It consists of the following groups:

Calculus. Mj. Winter Quarter, Associate Professor Millikan.

12. **Light.**—A lecture course for advanced students covering the more important sections of geometrical and physical optics. [Not given in 1909–10.]

13. **Electricity and Magnetism.**—A course of advanced work in theoretical Electricity and Magnetism intended to supplement the work in General Physics or to prepare for graduate work. Prerequisite: Physics 4 and Calculus. Associate Professor Kinsley. [Not given in 1909–10.]

14. **The Pedagogy of Physics.**—A course designed for teachers of Physics in high schools, consisting of lectures and discussions upon choice of subject-matter and methods of presentation best suited to elementary courses in Physics. Prerequisite: courses 3, 4, and 5, or equivalents. M. First Term, Summer Quarter, Associate Professor Millikan.

15. **Mechanics and Wave Motion.**—A lecture course on the physical meaning and the mathematical derivation of the fundamental equations of Mechanics and Wave Motion. Prerequisite: Physics 4 and Calculus. Mj. Autumn Quarter, 2:00, Assistant Professor Gale.

16. **Experimental Physics (Advanced): Molecular Physics and Heat.**—A course of advanced laboratory work involving the determination of vapor

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

"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.

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. 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
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 (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
- Rejected traditional efforts that had relied heavily on superficial coverage of a large number of topics and memorization of terse formulations
- Incorporated laboratory investigations that were only lightly guided through questions, suggestions, and hints.
- 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 [e.g., Arons (1959); Bruner (1960); Schwab (1960, 1962)] motivated renewed research

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.

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…*
- *Now, a re-examination of developments in physics education research from a topical perspective…*
- *Note: This will be an overview, not encyclopedic coverage (I won't mention everybody's work!)*

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, etc.
- ***Meso (classroom level)***
  - Instructional methods
  - Logistical factors (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

Areas of Interest in PER

- ***Macro (program level)***
  - Historical evolution: what is taught, why it is taught; [DONE]
  - *Learning goals:* concepts, scientific reasoning, problem-solving skills, experimentation skills, lab skills, 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, student difficulties; Learning behaviors
  - Assessment; Learning trajectories; Individual differences

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, 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, student difficulties; Learning behaviors
  - Assessment; Learning trajectories; Individual differences

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 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; studies have potentially confounding factors

*However, Kozhevnikov and Thornton (2006) suggest improvements in spatial visualization ability

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)

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, 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

Research and Practice

- Classroom implementation of education research results 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

Issues with Research-Based Instruction

- Instruction informed and guided by research on students' thinking
  - *Need to know students' specific reasoning patterns, and extent of difficulties in diverse populations*
  - *Specific strategies must be formulated, and effectiveness assessed with specific populations*
- 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 ability*

Common Characteristics of Research-Based Active-Learning Physics Instruction:*

*See, Meltzer and Thornton, “Resource Letter ALIP-1,” AJP (2012)

A. Instruction is informed and explicitly guided by research regarding students' pre-instruction knowledge state and learning trajectory, including:

- *Specific learning difficulties related to particular physics concepts*
- *Specific ideas and knowledge elements that are potentially productive and useful*
- *Students' beliefs about what they need to do in order to learn*
- *Specific learning behaviors*
- *General reasoning processes*

A vast area of research with much context- and topic-specificity

B. Specific student ideas are elicited and addressed.

- What are effective ways of doing this?

C. Students are encouraged to "figure things out for themselves."

- Trade-off between time-efficiency and effectiveness?

D. Students engage in a variety of problem-solving activities during class time.

- Broad array of possibilities from which to choose

E. Students express their reasoning explicitly.

- How will this be assessed and graded?

F. Students often work together in small groups.

- Is there an optimum group size and/or structure?

G. Students receive rapid feedback in the course of their investigative or problem-solving activity.

   - How and by whom will feedback be provided?

H. Qualitative reasoning and conceptual thinking are emphasized.

   - Is quantitative problem-solving skill at risk?

I. Problems are posed in a wide variety of contexts and representations.

   - But students have *technical* difficulties with representations

J. Instruction frequently incorporates use of actual physical systems in problem solving.

   - Often an extreme logistical challenge

K. Instruction recognizes the need to reflect on one's own problem-solving practice.

- Time-consuming, particularly if assessed and graded

L. Instruction emphasizes linking of concepts into well-organized hierarchical structures.

- Among the most challenging (yet important) objectives

M. Instruction integrates both appropriate content (based on knowledge of students' thinking) and appropriate behaviors (requiring active student engagement).

- Maximum effectiveness requires *both*

Crucial Caveat

- There exists no clear quantitative measure of how, and in what proportion, the various characteristics of effective instruction need be present in order to make instruction actually effective.
  - Does or does not a score of "4 out of 4" on characteristics *E*, *F*, *G*, and *H* on the above list outweigh a score of (e.g.) "3 out of 4" on characteristics *A*, *B*, *C*, and *D?*

“Teaching” and Curriculum are Linked

- Instructional developers gather and analyze evidence on *specific instructional implementations of specific curricula*

- Evidence of effective instructional practice always occurs in the context of a large set of tightly interlinked characteristics, each characteristic (apparently) closely dependent on the others for overall instructional success.

- Evaluation or assessment of particular “physics teaching methods” as isolated from or independent of *specific curricula linked to specific combinations of instructional methods* is not supported by current research.

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)

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, 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

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 and Physics Learning

- 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 in Physics: Kinematics and Dynamics of Students' Thinking

- *The challenge:* How can we characterize the evolution of students' thinking? 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

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; Heckler and Sayre, 2010)

Learning Trajectory: 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); Pollock (2009); Masters and Grove (2010)
  - Graduate: Patton (1996); Carr and McKagan (2009)

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

- We are faced with 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…

…However…

- 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.