Research-based active learning in Physics: Principles, methods, and materials

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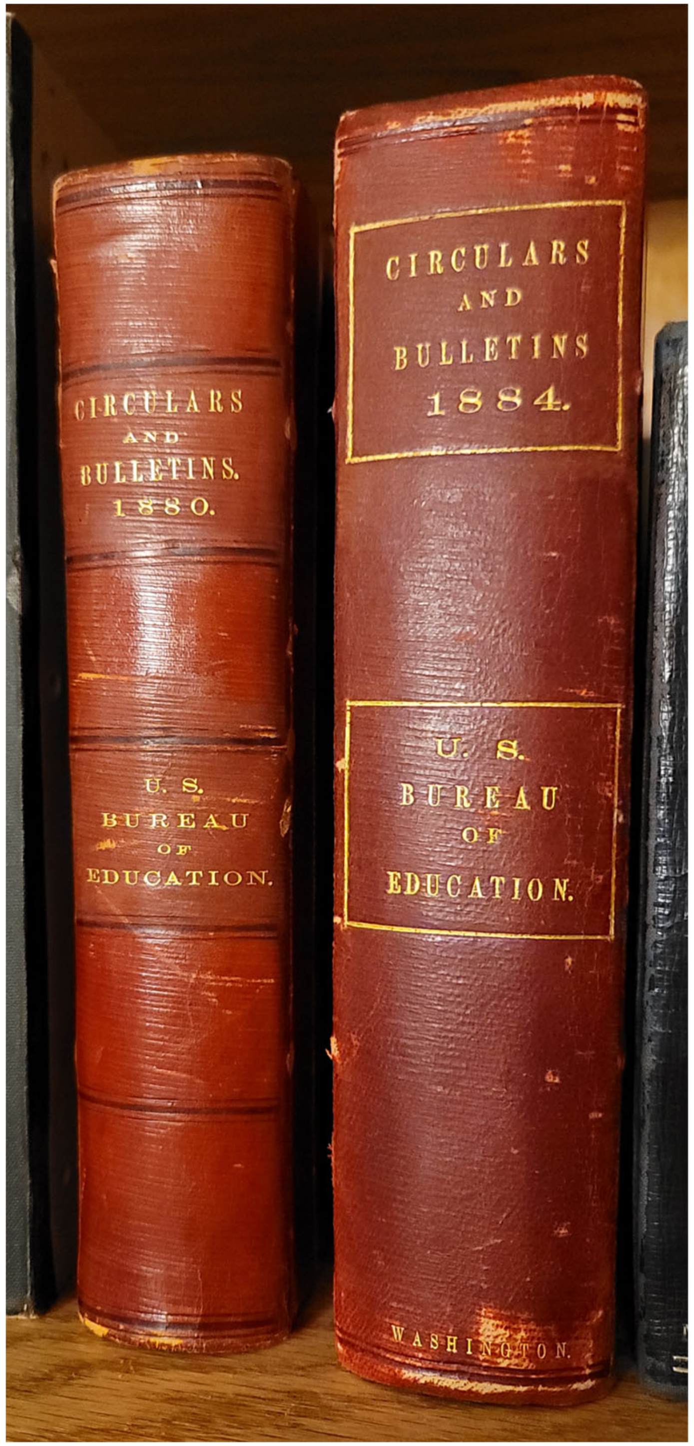
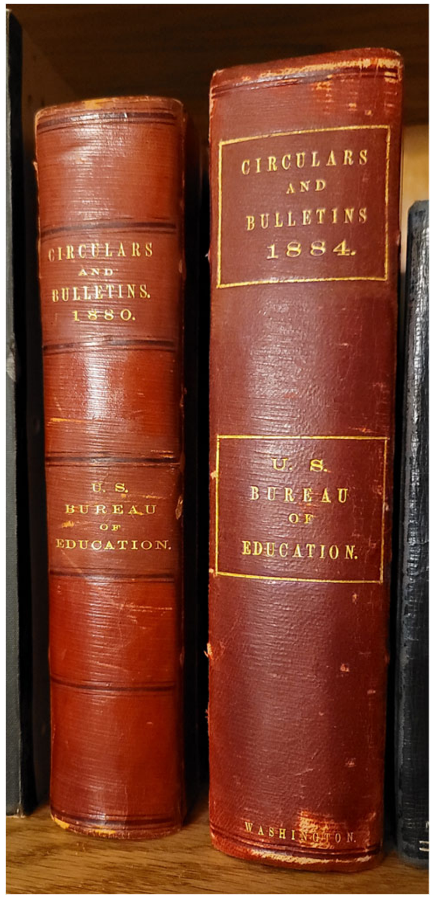
Outline

- Origins of active-learning instruction in physics in the USA
- Evolution of research on student learning in physics
- Development of research-based active-learning instruction in physics

In 1880 and 1884, two major reports were published by the U.S. Bureau of Education regarding the teaching of physics and chemistry throughout the United States. Thousands of schools were surveyed, and hundreds of instructors were asked to submit comments.



Nationwide surveys of science teaching in U.S. schools



*F.W. Clarke, *A Report on the Teaching of Chemistry and Physics in the United States* (1880)

**C.K. Wead, Aims and Methods of the Teaching of Physics (1884)

Nationwide surveys of science teaching in U.S. schools

- Surveys of secondary-school and university teachers of chemistry and physics in 1880 and 1884 revealed:
  - Rapid expansion in use of laboratory instruction
  - Strong support of “inductive method” of instruction for secondary school in which experiment precedes explicit statement of principles and laws

The "Inductive Method"

Students were guided to deduce general concepts and principles through analysis of their own experiments and observations.

In the United States in the present day, this general method has come to be called "inquiry-based active learning."

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.

1882: First U.S. secondary-school physics textbook to employ the “inductive method”

First U.S. “Active-Learning” Physics Textbook (1882):

A. P. Gage, *A Textbook of the Elements of Physics for High Schools and Academies*

> *“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;*

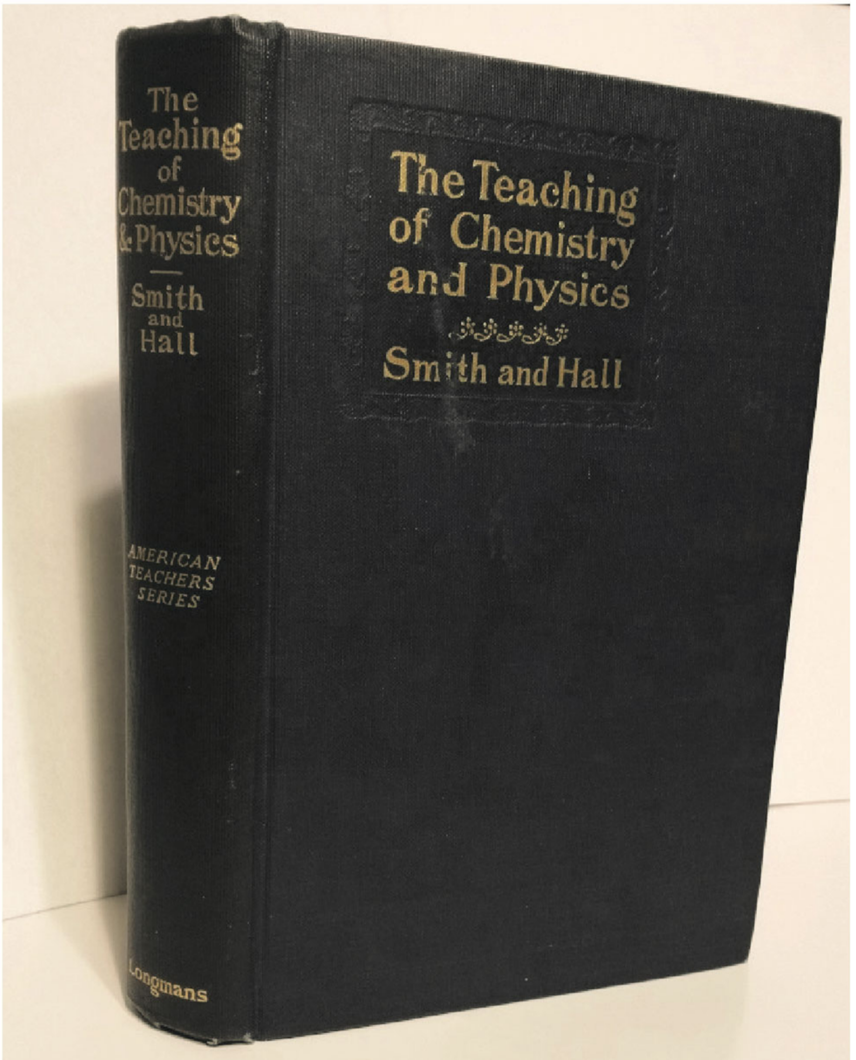
First U.S. “Active-Learning” Physics Textbook (1882):

A. P. Gage, *A Textbook of the Elements of Physics for High Schools and Academies*

“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.



E.H. Hall:

“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…the experimenter should hold himself in the attitude of genuine inquiry.”

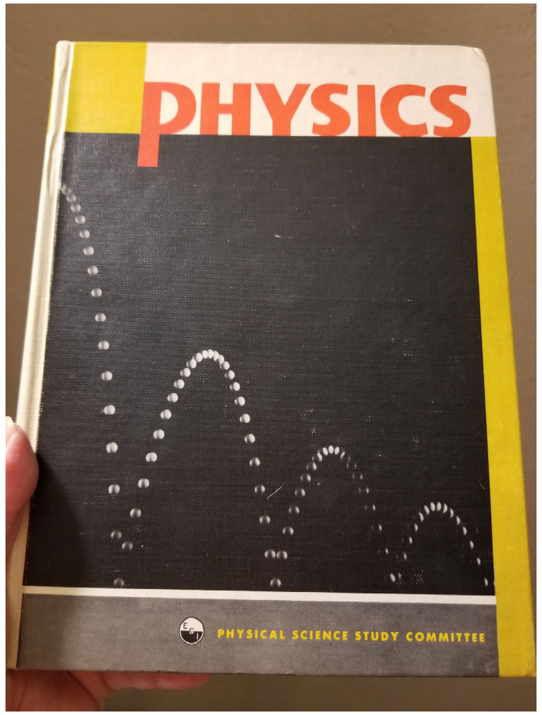
[The Teaching of Chemistry and Physics in the Secondary School (A. Smith and E. H. Hall, 1902)]

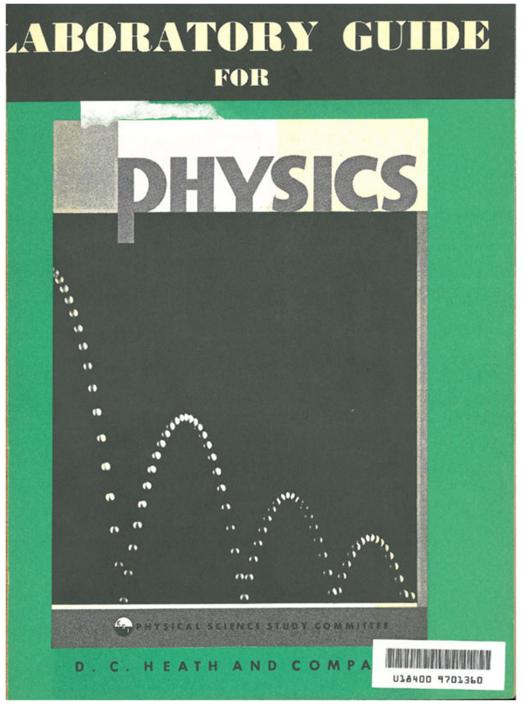
1950s: A New Beginning

In the 1950s and 1960s, university physicists attempted to transform physics instruction in secondary schools

1960: Physical Science Study Committee (PSSC)

- University physicists designed a new secondary school physics course
- The textbook strongly emphasized conceptual understanding
- Laboratory exercises were lightly guided, leaving much up to the student
- PSSC became one of the models for future research-based instruction





Outcome of the 1950s reforms

- The new physics curricula of the 1950s and 1960s had an enormous influence on future curriculum development efforts; however…
- …they had only limited effectiveness in improving student learning
- …they were limited to secondary schools, not used in universities
- …they employed active-learning instructional methods, but *they lacked support from research* targeted at students' thinking in physics.

1950s-1960s: Arnold Arons

During the 1950s, Arnold Arons developed a highly innovative physics course at Amherst College, requiring *post-secondary* students to explain their reasoning in great detail.

Structure, Methods, and Objectives of the Required Freshman Calculus-Physics Course at Amherst College

A. B. Arons
Amherst College, Amherst, Massachusetts

(Received, February 24, 1959)

A description is given of the Amherst freshman calculus-physics course with specific examples of test questions, term paper assignments, and laboratory instructions. A few quotations are given from student papers, and fairly detailed syllabi of the mathematics and physics work are included.

I. INTRODUCTION

A FRESHMAN calculus-physics course, required of all students, was instituted at Amherst College in 1947 as part of a major postwar curriculum revision.[1]

The objective was a course which would deal with the main stream of physical concepts, laws, and ideas; would examine these matters in some depth, with sophistication and with adequate mathematical tools; would consider logical, epistemological, philosophical, and historical aspects; and would be of such nature in subject matter and content as to be simultaneously a proper introductory course for science majors, a terminal course in physical science for nonscience majors, and a "general education" course for both groups.

In the first few years of operation, the "common experience" aspects were compromised to some extent, and the freshman class was divided into two halves of higher and lower aptitude as indicated by various C.E.E.B. test scores. The lower aptitude group proceeded at a somewhat slower pace in mathematics and received a more descriptive development in physics than did the higher aptitude group. As the experiment progressed and more confidence developed, the separation was eliminated, and for the past few years the entire class has been treated as a single unit, all students taking the same program in calculus and physics.

A description of the course in its present state

[1] G. Kennedy, *Education at Amherst* (Harper and Brothers, New York, 1955).

Am. J. Phys. 27, 658-666 (1959)

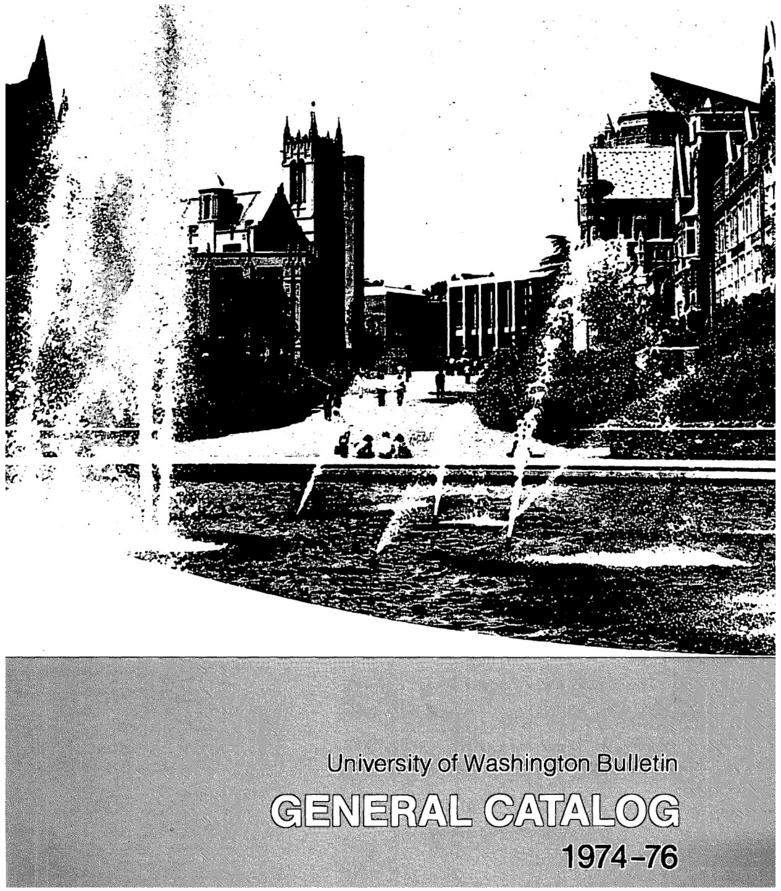
Arons to U. Washington; McDermott joins him

- 1968: Arons joined the faculty at the University of Washington to develop an inquiry-based physics course for elementary school teachers in training.

- 1969: After obtaining her Ph.D. in nuclear physics and beginning to teach, Lillian McDermott joined Arons at the University of Washington. Together, they created courses and curricular materials that used Socratic questioning to build students' conceptual understanding and reasoning skill.

Beginning of Physics Education Research in USA

1973: Lillian McDermott hired as Assistant Professor at UW; begins to guide Ph.D. students in systematic research on the teaching and learning of physics at the *university* level, breaking away from secondary-school constraints.



PHYSICS
215 Physics

Physics is the study of the fundamental structure of matter and the interactions of its constituents, as well as the basic natural laws governing the behavior of matter.

Faculty

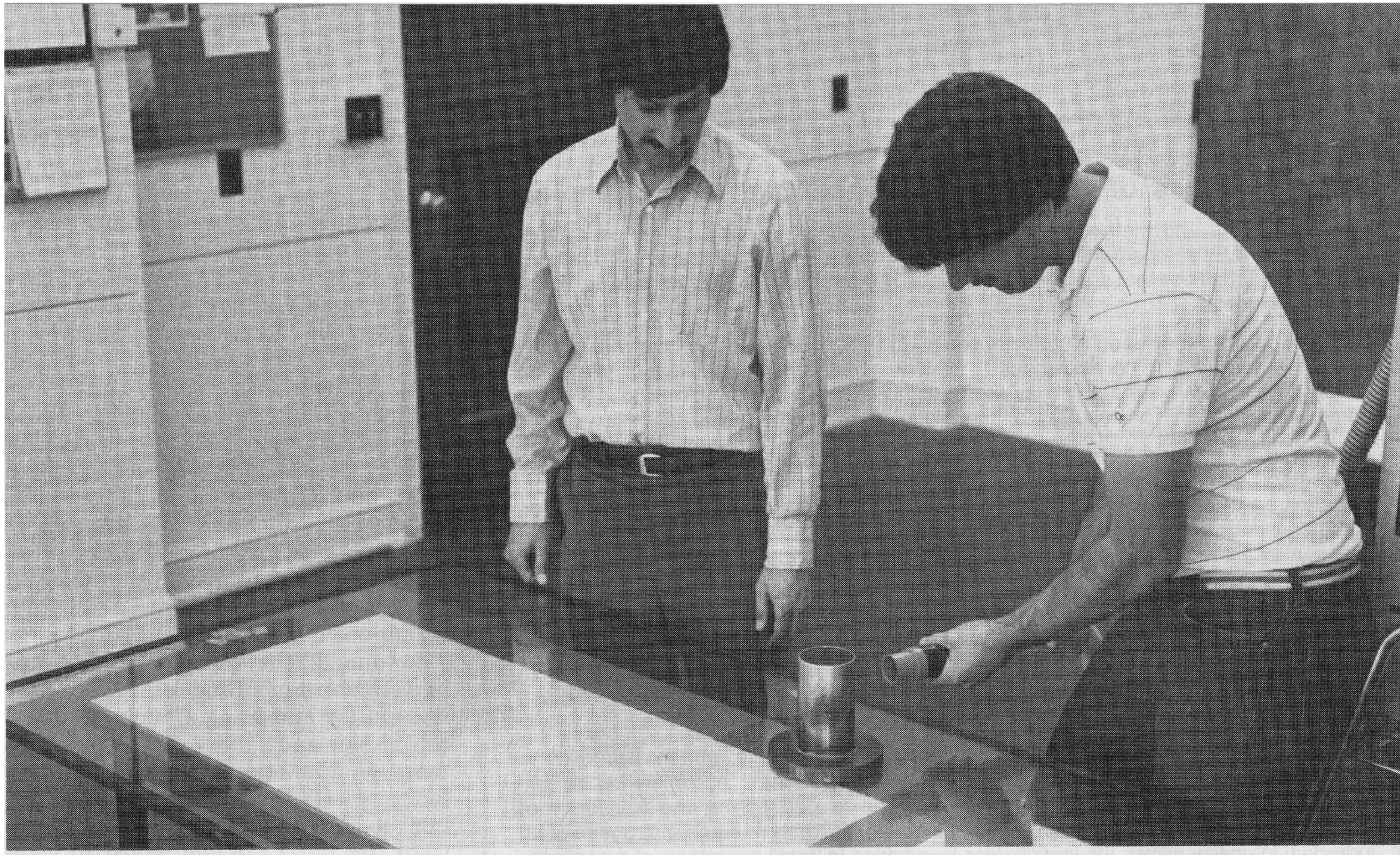
Ernest M. Henley, Chairman; Adelberger, Arons, Baker, Bali, Blair, Bodansky, Boulware, Brakel (emeritus), Brown, Cahn, Clark, Cook, Cramer, Dash, Davisson, Dehmelt, Fain, Farwell, Fortson, Geballe, Gerhart, Halpern, Henderson (emeritus), Henley, Higgs (emeritus), Ingalls, Kenworthy (emeritus), Kirkpatrick, Lee, Lord, Lubatti, L. McDermott, M. McDermott, Moriyasu, Neddermeyer (emeritus), Peters, Puff, Rothberg, Sabo, Sanderman (emeritus), Schick, Schmidt, Stern, Streib, Uehling (emeritus), Vilches, Weis, Weitkamp, Wilets, Williams, Young. D. Boulware, graduate program adviser.

Other early research on physics learning

- Laurence Viennot (1974-79): Research on French university physics students
- Robert Karplus (1975): Research to improve physics students' reasoning
- Frederick Reif (1976): Research on physics students' reasoning patterns in order to develop instructional methods for improving problem-solving skill

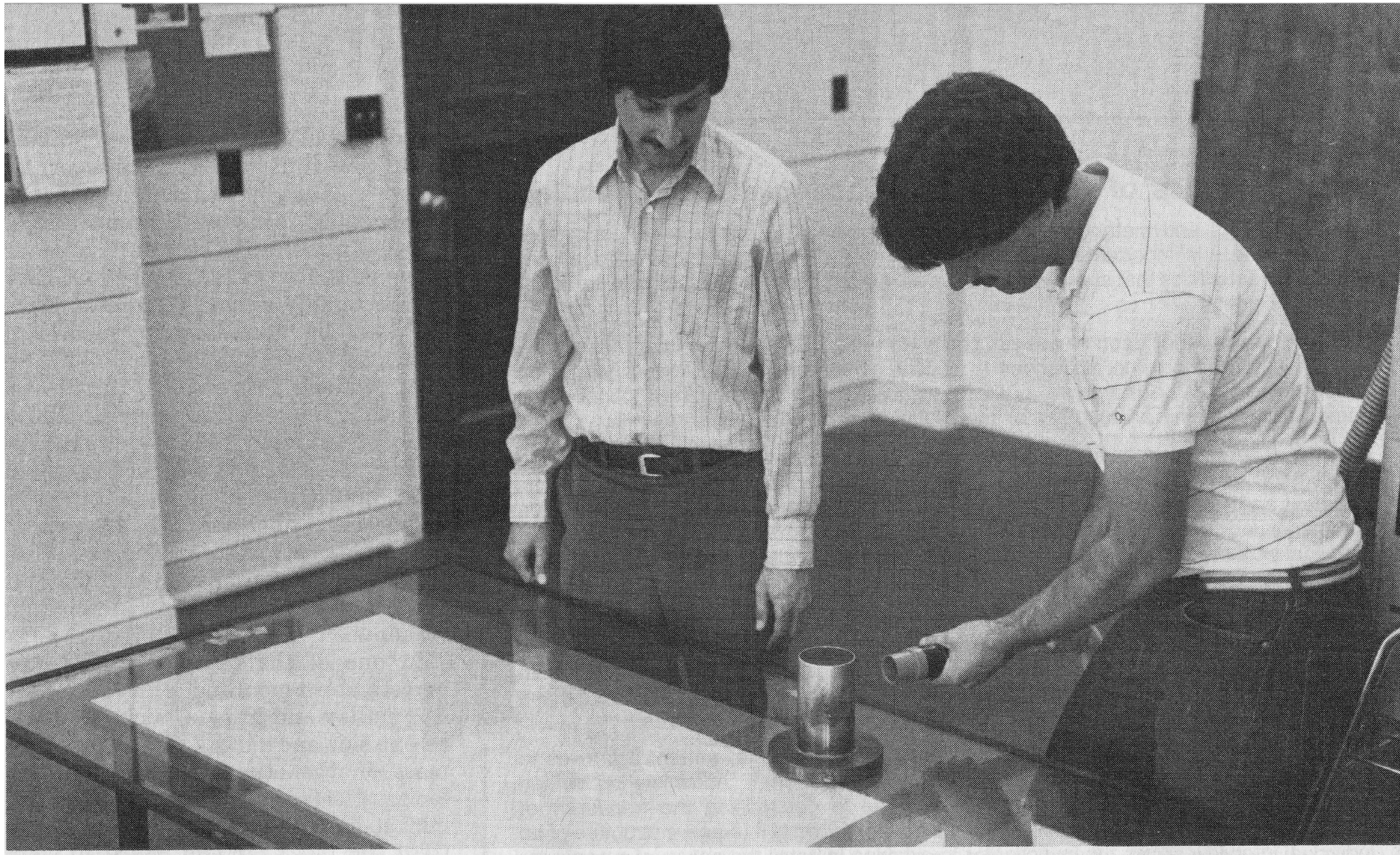
McDermott's research program

- Recognize that *research is required* to best decide "the right questions to ask" during active-learning instruction.
- Recognize that students' difficulties often originate from weak conceptual understanding *and* underdeveloped reasoning skills; researchers must investigate both simultaneously.
- To investigate students' thinking in depth, ask them to explain their reasoning while engaged in interpreting physics experiments: "Individual Demonstration Interview."
- Develop instructional materials that are *rigorously and repeatedly tested*, to ensure they actually help students learn.



Investigating student understanding of force. Ronald Lawson (left) is asking a student to deflect a moving dry-ice puck at a 45° angle to its direction of motion using a blast of air from the hose; the student's reactions and comments will be recorded. In this research project, conducted by the Physics Education Group at the University of Washington, students were asked to perform this and similar tasks in individual demonstration interviews. As in other research conducted by the group, the major criterion used to assess conceptual understanding was the ability to apply concepts learned in class to actual physical systems.

"Individual Demonstration Interview": Investigator and student "one-on-one"



Investigating student understanding of force. Ronald Lawson (left) is asking a student to deflect a moving dry-ice puck at a 45° angle to its direction of motion using a blast of air from the hose; the student's reactions and comments will be recorded. In this research project, conducted by the Physics Education Group at the University of Washington, students were asked to perform this and similar tasks in individual demonstration interviews. As in other research conducted by the group, the major criterion used to assess conceptual understanding was the ability to apply concepts learned in class to actual physical systems.

Student explains his thinking while carrying out experiment (~1980)

These were among the very first articles to report detailed research on the learning of physics by university students

Investigation of student understanding of the concept of velocity in one dimension

David E. Trowbridge[a] and Lillian C. McDermott
Department of Physics, University of Washington, Seattle, Washington 98195
(Received 25 February 1980; accepted 20 May 1980)

This paper describes a systematic investigation of the understanding of the concept of velocity among students enrolled in a wide variety of introductory physics courses at the University of Washington. The criterion selected for assessing understanding of a kinematical concept is the ability to apply it successfully in interpreting simple motions of real objects. The primary data source has been the individual demonstration interview in which students are asked specific questions about simple motions they observe. Results are reported for the success of different student populations in comparing velocities for two simultaneous motions. It appears that virtually every failure to make a proper comparison can be attributed to use of a position criterion to determine relative velocity. Some implications for instruction are briefly discussed.

I. INTRODUCTION

The Physics Education Group at the University of Washington has been engaged for several years in a systematic study of the ways in which students in introductory college physics courses think about motion. The degree of difficulty of the courses ranges from compensatory (for academically disadvantaged students) to calculus based (for physics, engineering, and mathematics majors). This article is the first of two devoted to the kinematical concepts. The present paper reports on the ability of students to apply the concept of velocity in interpreting simple motions of real objects. A subsequent article will discuss student under-

critical to the study of almost all of p
has been research by other investiga
of conceptual understanding of dynar
studies on kinematics have appeare
beginning our investigation with the
we hoped not only to identify speci
have with kinematics but also to g
possible kinematical origins of
namics.

B. Criterion for understanding

An important distinction must

1980

1981

Investigation of student understanding of the concept of acceleration in one dimension

David E. Trowbridge[a] and Lillian C. McDermott
Department of Physics, University of Washington, Seattle, Washington 98195
(Received 15 April 1980; accepted 23 July 1980)

This paper describes a systematic investigation of the understanding of the concept of acceleration among students enrolled in a variety of introductory physics courses at the University of Washington. The criterion for assessing understanding of a kinematical concept is the ability to apply it successfully in interpreting simple motions of real objects. The main thrust of this study has been the qualitative understanding of acceleration as the ratio $\Delta v / \Delta t$. The primary data source has been the individual demonstration interview in which students are asked specific questions about simple motions they observe. Results are reported for the success of different student populations in comparing accelerations for two simultaneous motions. Failure to make a proper comparison was due to various conceptual difficulties which are identified and described. Some implications for instruction are briefly discussed.

I. INTRODUCTION

The Physics Education Group at the University of Washington has been engaged for several years in a systematic study of the ways in which students in introductory college physics courses think about motion. The degree of difficulty of the courses ranges from compensatory (for academically disadvantaged students) to calculus based (for

angle to the horizontal. The accelerations of the balls can be varied by using channels of different widths as shown in Fig. 1. Thus prior knowledge about the dependence of acceleration on slope yields no clues for making correct comparisons. A mechanism for releasing the balls automatically insures that the motions are reproducible.

The interviews are conducted according to a standard questioning format but at any point the interviewer may

Examples of research-based curriculum development:

1. Thermodynamics
2. Buoyancy

Examples of research-based curriculum development:

1. Thermodynamics

Student ideas regarding entropy and the second law of thermodynamics in an introductory physics course

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(Received 15 March 2008; accepted 10 June 2009)

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Students enrolled in introductory physics courses are asked to respond to several questions related to entropy and the second law of thermodynamics. Based on an analysis of students' responses, new instructional materials are developed.

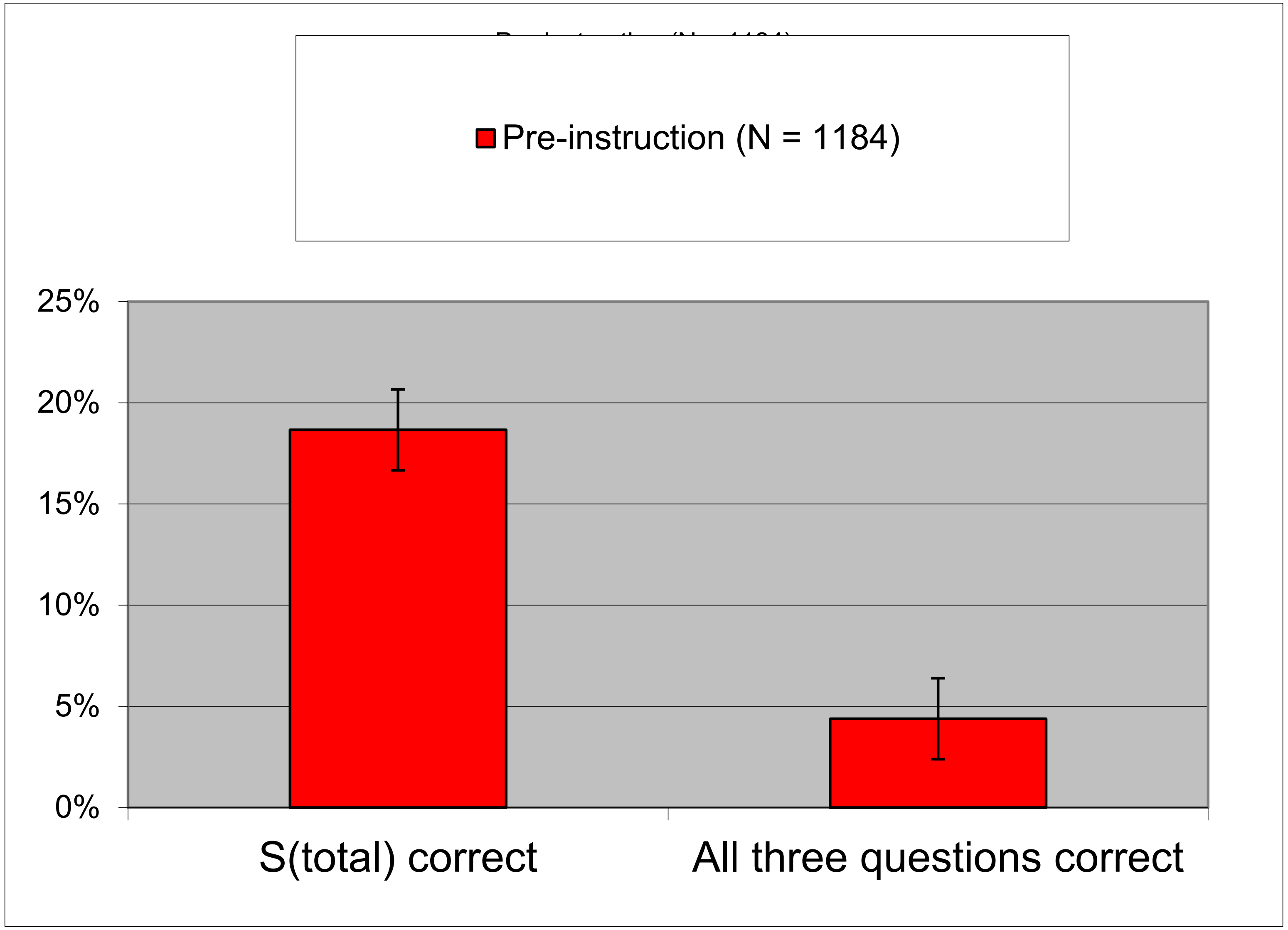
Question #1 of 3 questions:

An object is placed in a thermally insulated room that contains air. The object and the air in the room are initially at different temperatures.

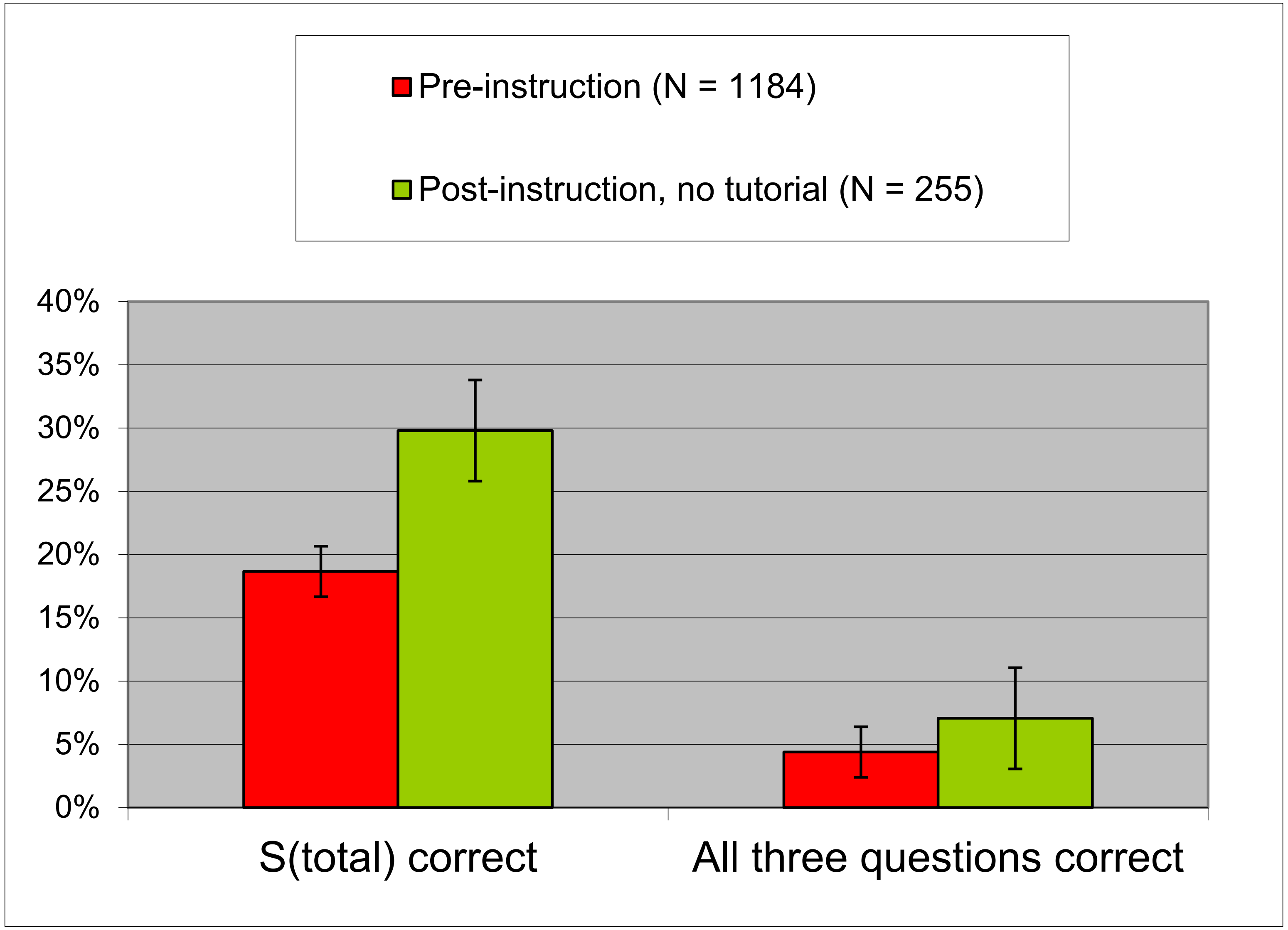
Will the total entropy (object + air) *increase*, *decrease*, or *remain the same*?

- *Correct answer:* The total entropy will increase, as it does in any heat-flow process
- Common incorrect response: Most students (71%) think that the entropy will remain unchanged.

Correct responses, pre- and post-instruction



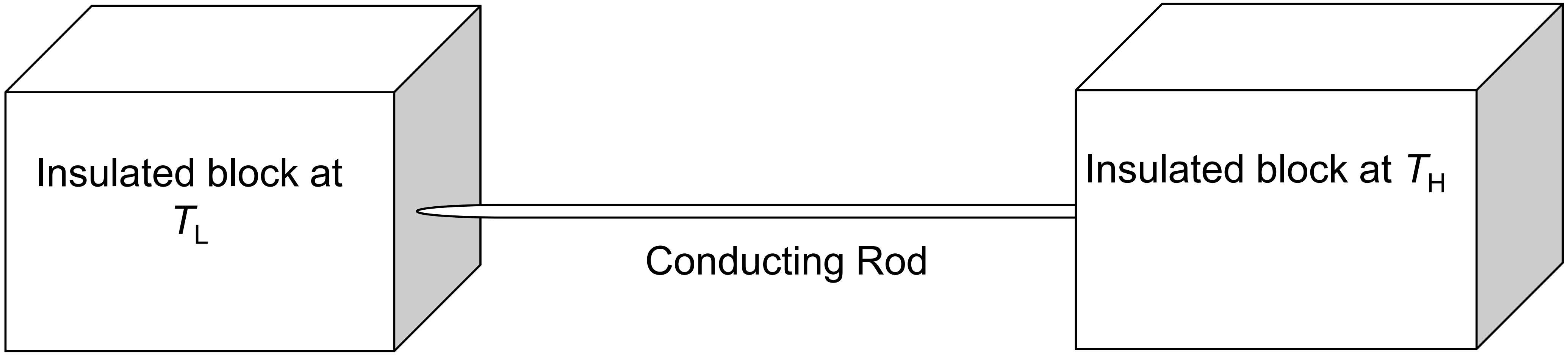
Correct responses, pre- and post-instruction



Analysis of Students' Reponses

- We found that most introductory students think that the total entropy will not change —that the entropy will be "conserved"
- We had not been aware that so many students had this idea
- Through individual interviews with 18 students, we realized that students were confusing the terms *entropy* and *energy*. They had previously learned that "energy is conserved" (total energy can not change in an isolated system)
- We developed instructional materials to help students understand why entropy would increase in this process

“Two-blocks” Instructional Worksheet (“Tutorial”)



Consider a slow heat transfer process between two large metal blocks at different temperatures, connected by a thin metal pipe.

- Does total energy change during the process? *[No]*
- Does total entropy change during the process? *[Yes]*

Students are guided to apply this entropy equation:

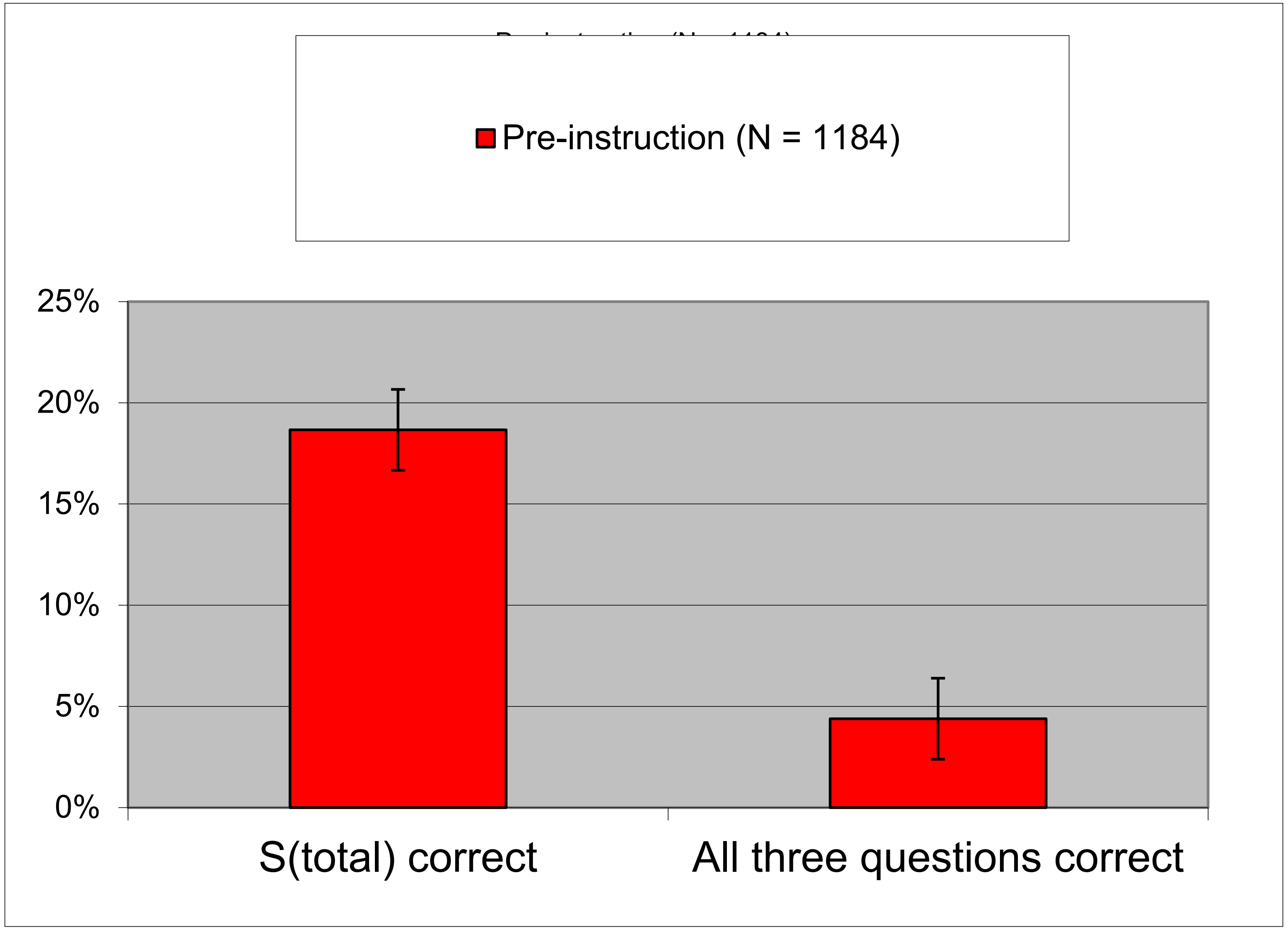
$$\Delta S = Q/T$$

ΔS = change in entropy
Q = thermal energy transfer
T = temperature

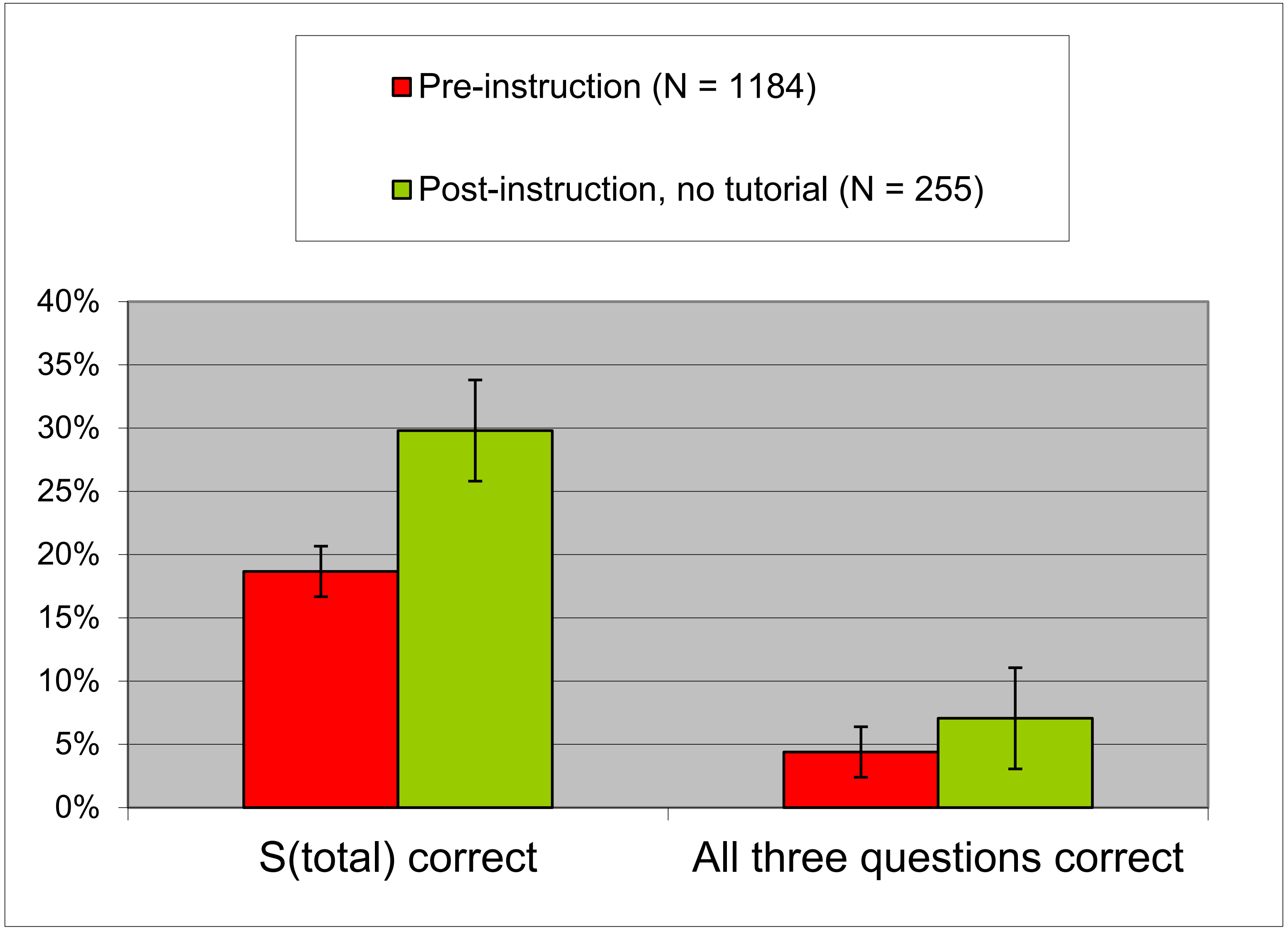
Students find that the entropy gain of the low-temperature block is *larger* than the entropy loss of high-temperature block, so:

→ *total entropy increases*

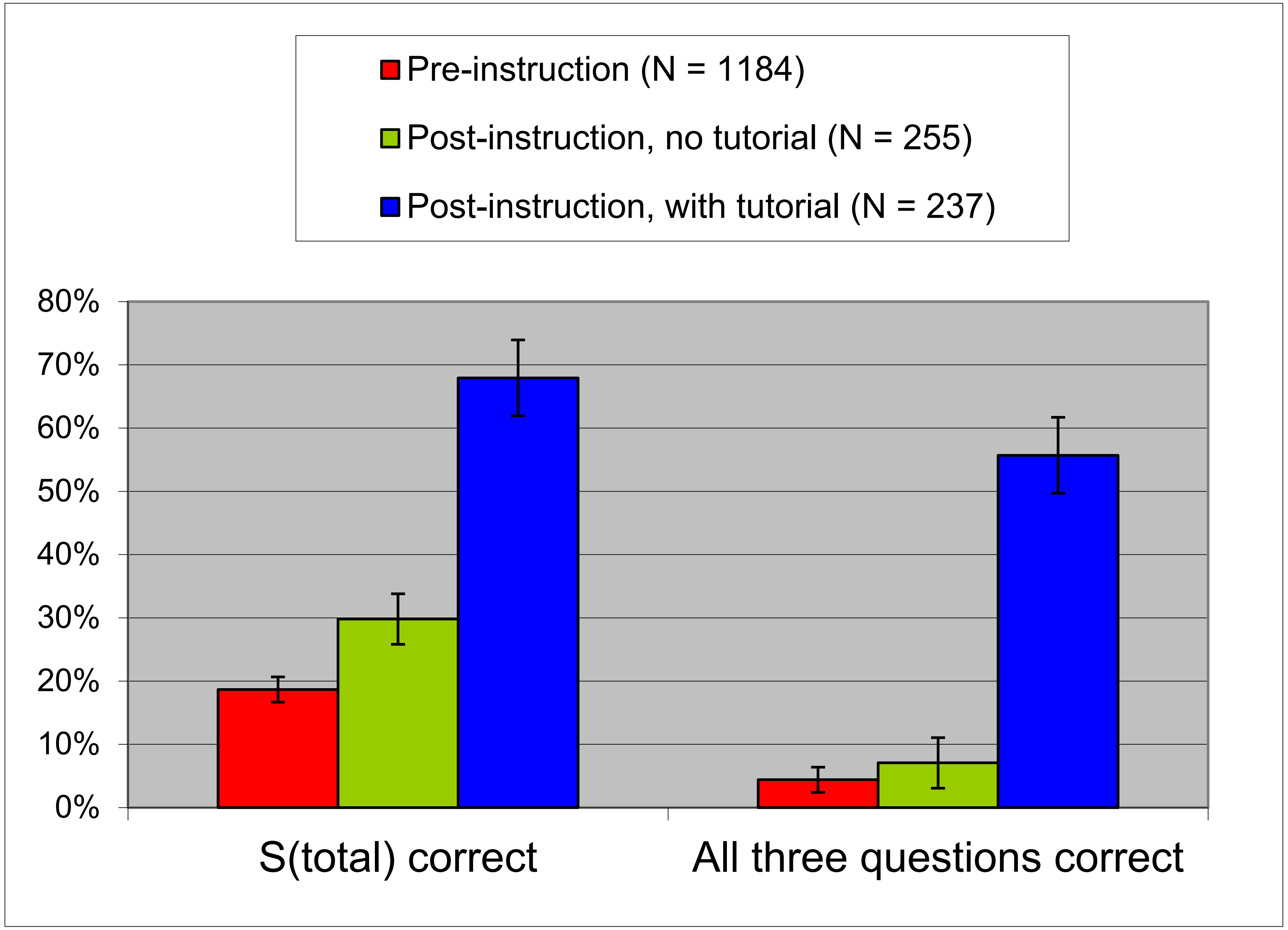
Correct responses, pre- and post-instruction



Correct responses, pre- and post-instruction



Correct responses, pre- and post-instruction



What do we gain from research on student learning?

- We learn *why* students give certain specific responses to our questions, that is, the method by which they arrive at their answers.
- We learn the precise nature of students' ideas related to specific science concepts, both potentially productive ideas and potentially *misleading* or unproductive ideas.
- We learn the *prevalence* of specific student ideas within broad categories of student populations: how widespread are they?

How do we apply research on student learning?

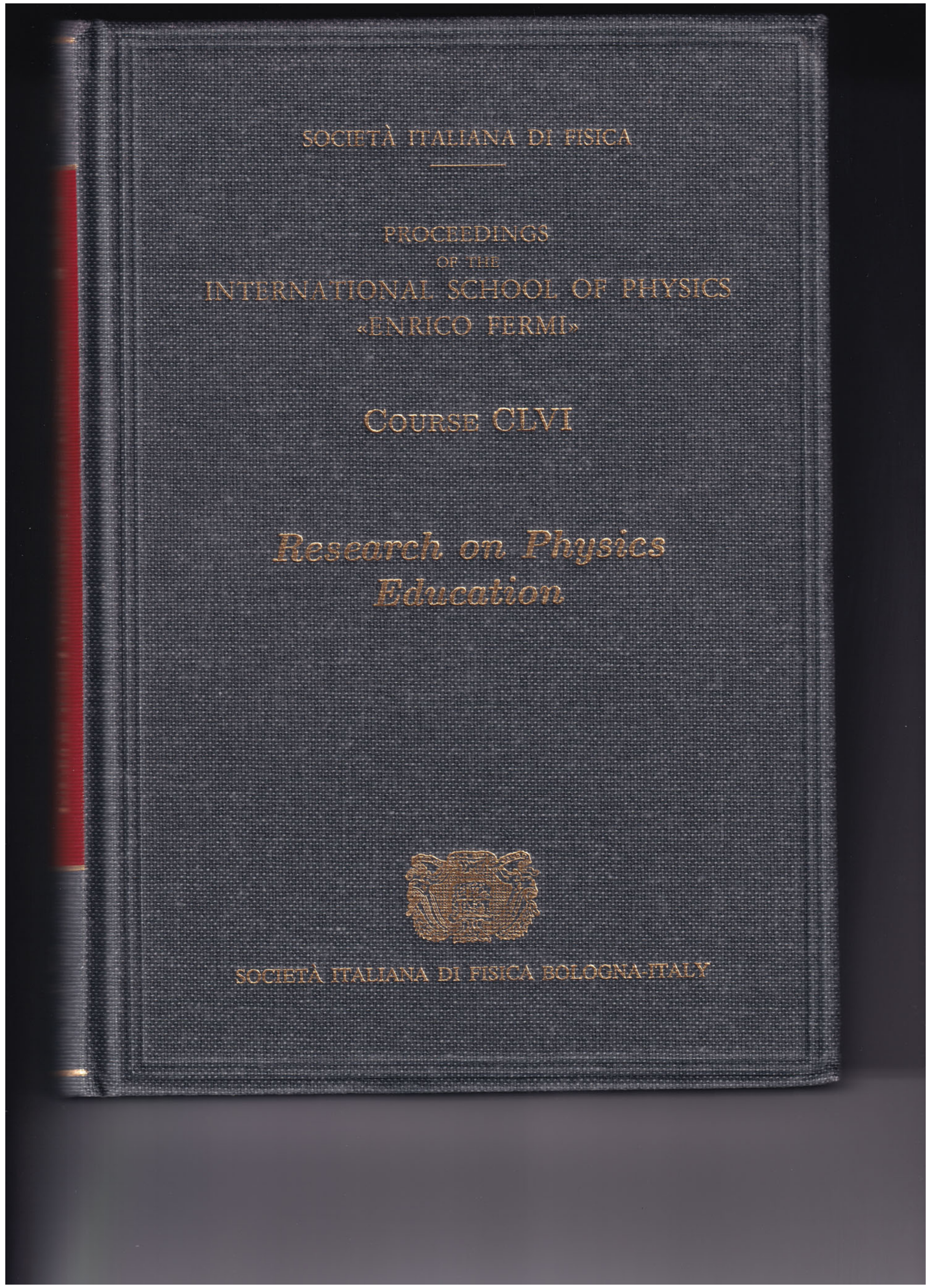
- We design sequences of questions that help students reason effectively about specific difficult concepts.
- We *monitor and test* the reactions of students to see whether their reasoning is proceeding along productive lines.
- We continually assess effectiveness of our instructional materials, and revise and re-assess to improve their utility.

Examples of research-based curriculum development:

1. Thermodynamics
2. Buoyancy

Examples of research-based curriculum development:

2. Buoyancy



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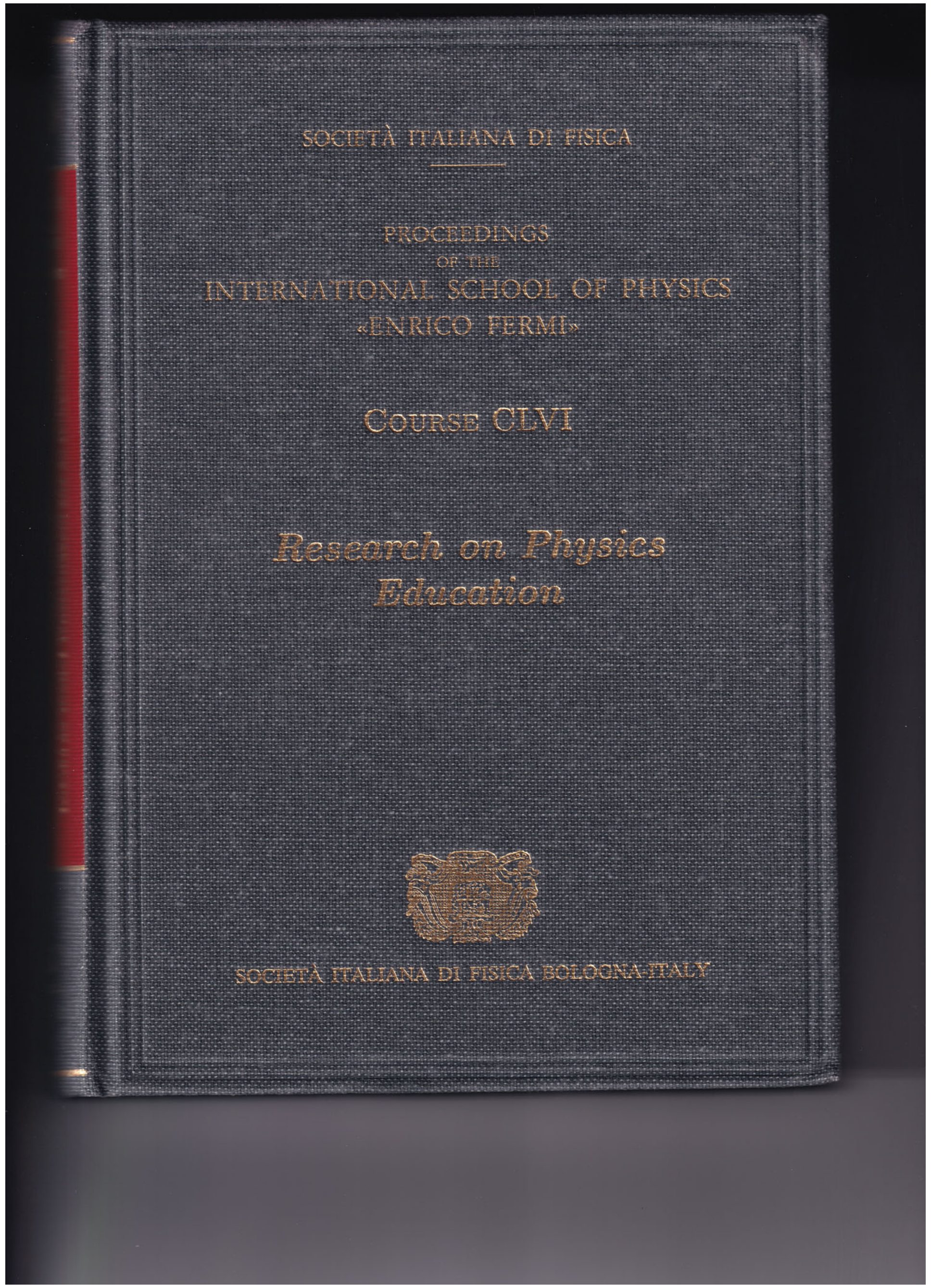

Empirical investigations of learning and teaching, part II: Developing research-based instructional materials

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1. – Introduction

This article is the second of two that are based on lectures that described the empirical approach to physics education research of the Physics Education Group (PEG) at the University of Washington (UW). A secondary goal of the lectures was to provide an experimentalist's perspective on the development of theories of student learning and on some general issues related to experimental research. A general framework for our study of student understanding was described in the first article [1]. In this second article, the emphasis is on the role of research in developing instructional materials. An ongoing, multi-year investigation of student understanding of Archimedes' Principle provides an example. The initial investigation of student understanding is described in sect. **2**; the subsequent process of designing materials that take research findings into account is described in sect. **3**. General issues for assessing the effectiveness of instructional interventions are discussed in sect. **4**.

2. – Investigating student understanding

Our investigation began with interviews based on the behavior of a "Cartesian diver", an object whose average density, and hence its tendency to sink or float, can be varied by changing the pressure of the container in which it is sealed. The inability of students to account for the diver's behavior, despite having seen similar demonstrations in class,

[This example is based on a published paper:]

Helping students develop an understanding of Archimedes' principle. I. Research on student understanding

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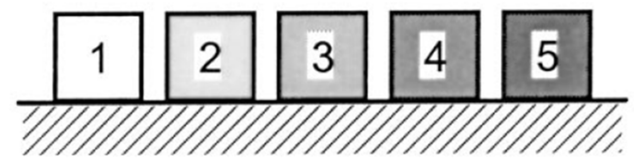
Blocks of equal volume, different mass

$$m_1 < m_2 < m_3 < m_4 < m_5$$



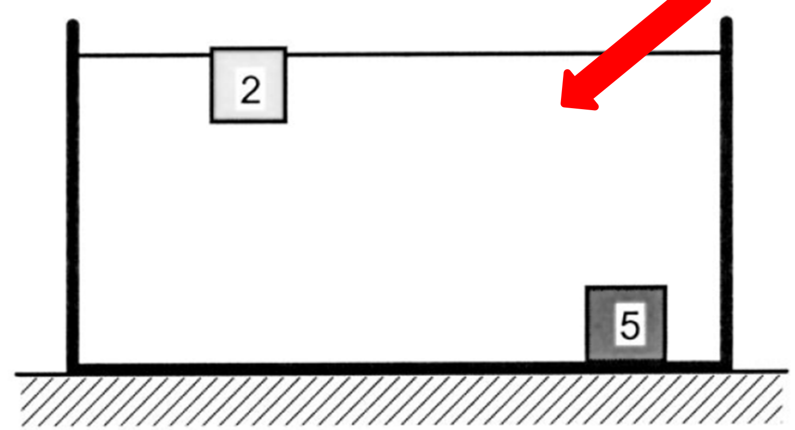
Five blocks of the same size and shape but different masses are shown at right. The blocks are numbered in order of increasing mass *(i.e. $m_1 < m_2 < m_3 < m_4 < m_5$).*

All the blocks are held approximately halfway down in an aquarium filled with water and then released. The final positions of blocks 2 and 5 are shown.

On the diagram, sketch the final positions of blocks 1, 3, and 4. Explain your reasoning.

(Assume that the water is incompressible.)

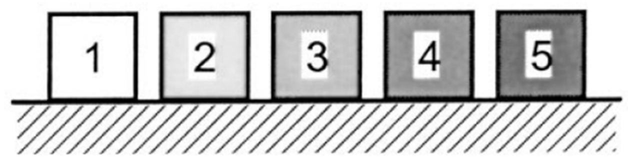
water

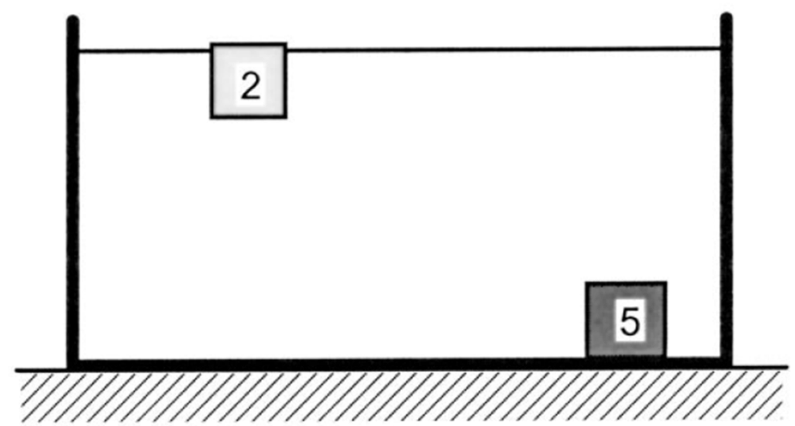


Blocks are held underneath water surface and released

On the diagram, sketch the final positions of blocks 1, 3, and 4. Explain your reasoning.

$$m_1 < m_2 < m_3 < m_4 < m_5$$

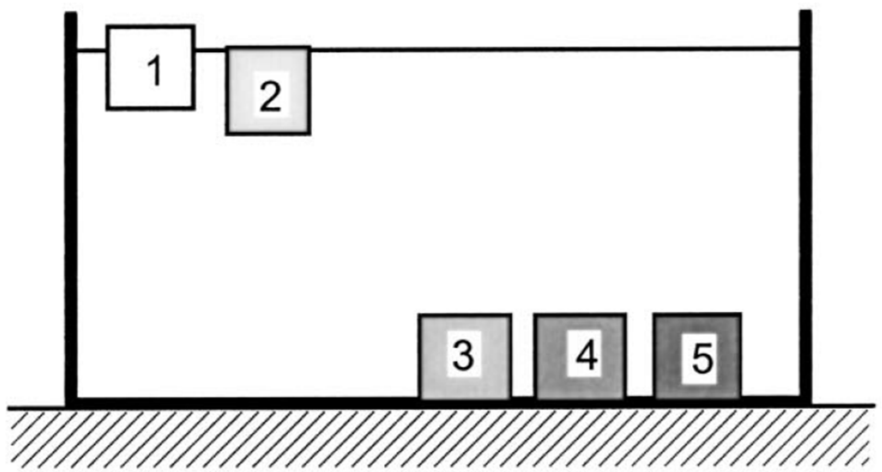


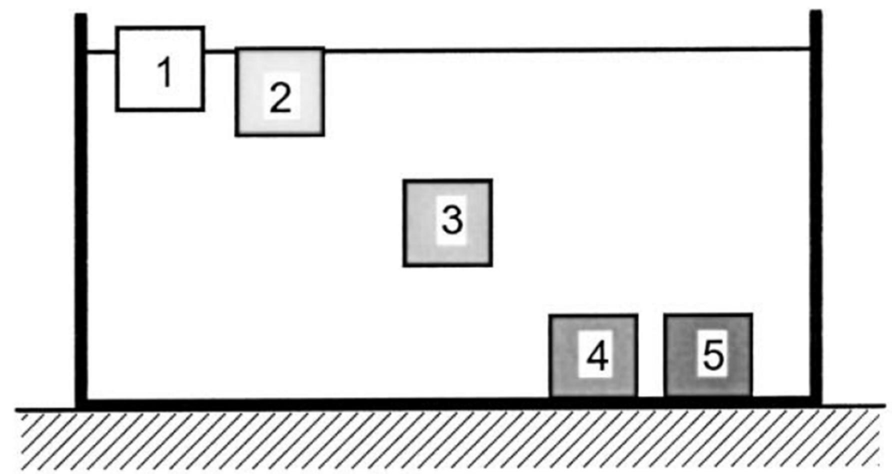


Explanation:

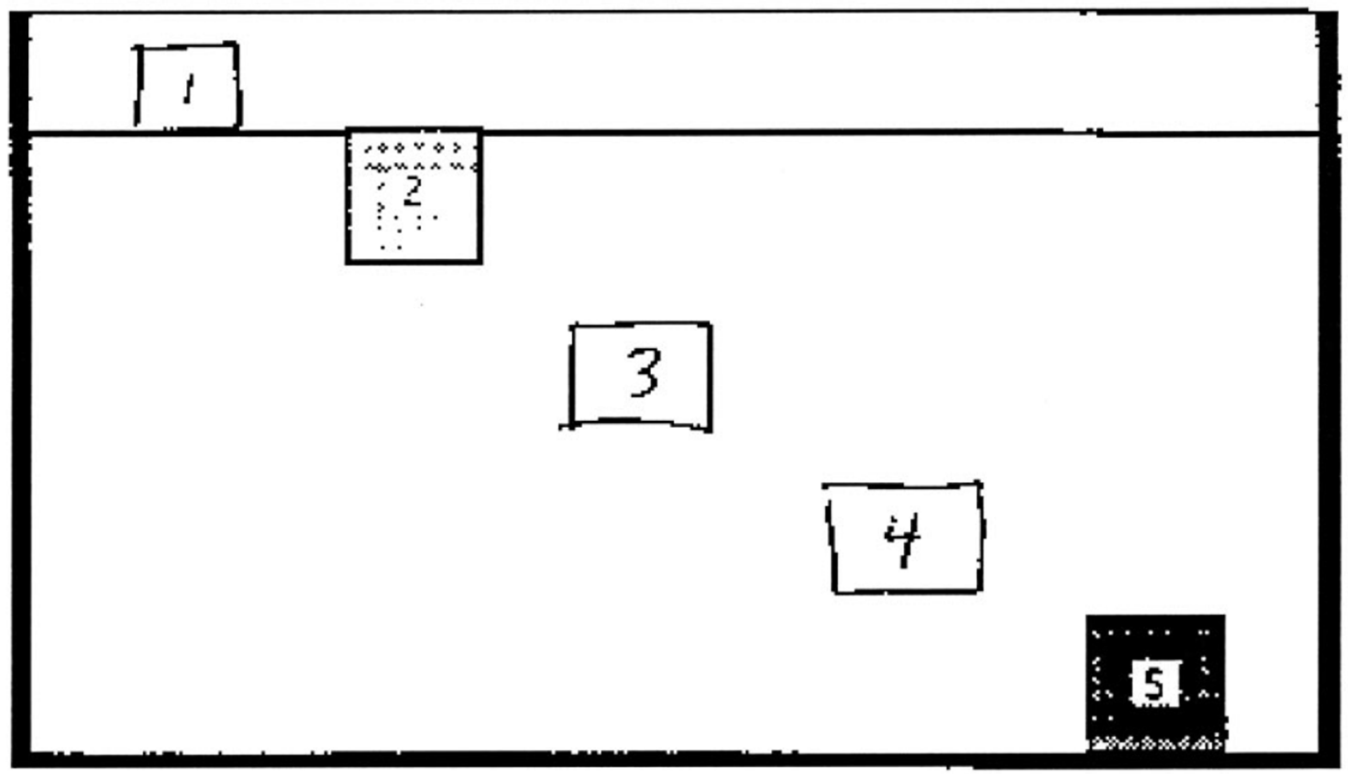
- The blocks all have the same volume, but different densities
- Blocks will either sink to bottom or float to top, depending on whether their density is larger or smaller than that of water
- A <u>maximum</u> of only one single block can be suspended in the water without sinking or floating (if its density is exactly equal to that of water)

Possible correct responses:





Common student incorrect response:



Students’ written explanations indicate conceptual difficulties

- Many students think incorrectly that the upward (buoyant) force on the submerged object is proportional to the object’s *mass*, instead of its volume
- Students often apply Newton’s laws incorrectly, not realizing that unless the upward buoyant force and the downward weight force are *exactly* equal, the object must float upward *or* sink down.

“Tutorials in Introductory Physics”:
Research-based instructional materials for classroom use

- Tutorials are printed worksheets, developed through research on students’ specific ideas and reasoning patterns
- Students work in groups of 3-4 on worksheets that pose a series of carefully sequenced questions; experiments are sometimes done
- Tutorial instructors ask additional questions intended to help students arrive at the answers themselves
- The overall goal is to guide students through the reasoning needed to construct and apply fundamental concept and principles

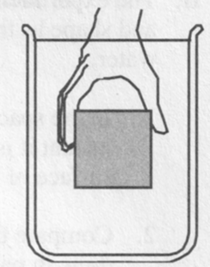
Tutorial in Introductory Physics at the University of Colorado

Tutorial on buoyancy, developed, assessed, and revised through research on students' reasoning.

Guides students through a careful analysis of the forces acting on a submerged object, and its resulting motion.

I. Buoyant force

A. A cubical block is observed to float in a beaker of water. The block is then held near the center of the beaker as shown and released.



1. Describe the motion of the block after it is released.

2. In the space provided, draw a free-body diagram for the block at the instant that it is released. Show the forces that the water exerts on each of the surfaces of the block separately.

   Make sure the label for each force indicates:

   - the type of force,
   - the object on which the force is exerted, and
   - the object exerting the force.

Free-body diagram for block at instant it is released

3. Rank the magnitudes of the vertical forces in your free-body diagram. If you cannot completely rank the forces, explain why you cannot.

   Did you use the relationship between pressure and depth to compare the magnitudes of any of the vertical forces? If so, how?

   Did you use information about the motion of the block to compare the magnitudes of any of the vertical forces? If so, how?

4. In the box at right, draw an arrow to represent the vector sum of the forces exerted on the block by the surrounding water. How did you determine the direction?

Sum of forces on block by water

Testing and revision of instructional materials

- After using preliminary version of tutorial, students' score on assessment questions is improved (55% correct compared to 35% correct); however:
- Further research indicates that students are confused about Archimedes' principle relating upward buoyant force to weight of "displaced" water
- Tutorial is revised with additional demonstration relating volume of displaced water to volume of the object
- Revised tutorial yields improved student scores (75% correct) on assessment problem

Iterative process of instructional materials development

1. Carry out research on students’ ideas about physical phenomena
2. Develop preliminary instructional materials based on the research
3. Assess effectiveness of instructional materials
4. Carry out further research to examine students’ thinking in greater depth

Pretest and post-test questions for assessment of student learning

Examples from research on Mechanics

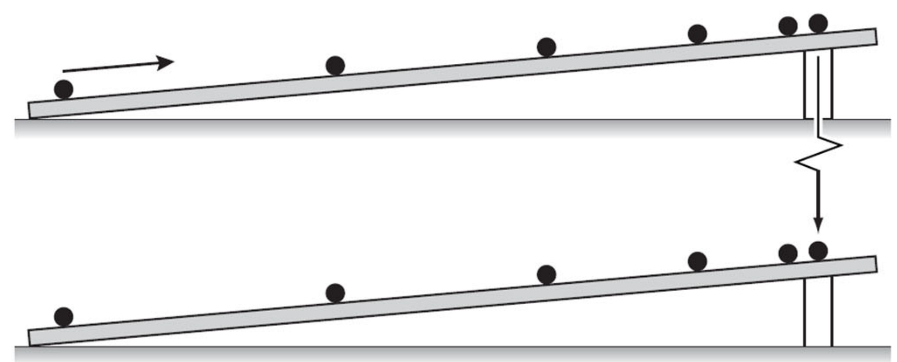
Physics Education Group
Research · Curriculum · Instruction

Physics Education Group
University of Washington
Seattle, WA

Assessment questions require students to explain their reasoning

The diagram below represents a strobe photograph of the motion of a ball as it rolls up and then down a track. (In a strobe photograph, the position of an object is shown at instants that are separated by equal time intervals.)

A. The arrow on the diagram represents the velocity of the ball at the first location. At each of the other locations shown, draw vectors to represent the *velocity* of the ball at those locations. If the velocity is zero at any of the locations, indicate that explicitly. Briefly explain why you drew the arrows as you did.



Highest point is same instant on uphill and downhill figures.

2	Ball on incline	1-d Kinematics	AJP **73** (10) 2005

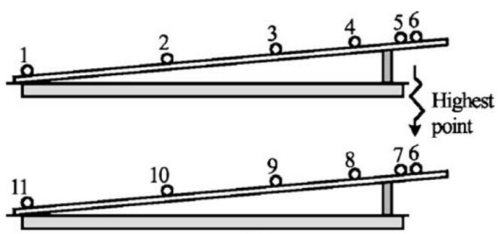
A research-based approach to improving student understanding of the vector nature of kinematical concepts

Peter S. Shaffer and Lillian C. McDermott
Department of Physics, University of Washington, Seattle, Washington 98195-1560

(Received 6 April 2005; accepted 26 June 2005)

In this paper we describe a long-term, large-scale investigation of the ability of university students to treat velocity and acceleration as vectors in one and two dimensions. Some serious conceptual

Research results are published in professional journals



(a)

Fig. 3. Examples of pretests administered to large numbers of students. Students were asked to draw velocity and acceleration vectors at various points during each motion. (a) 1D pretest on ball moving up and down a ramp. (b) 2D pretest on object moving at constant speed along a closed, horizontal track. Some students were also asked about the case that the object speeds up from rest.

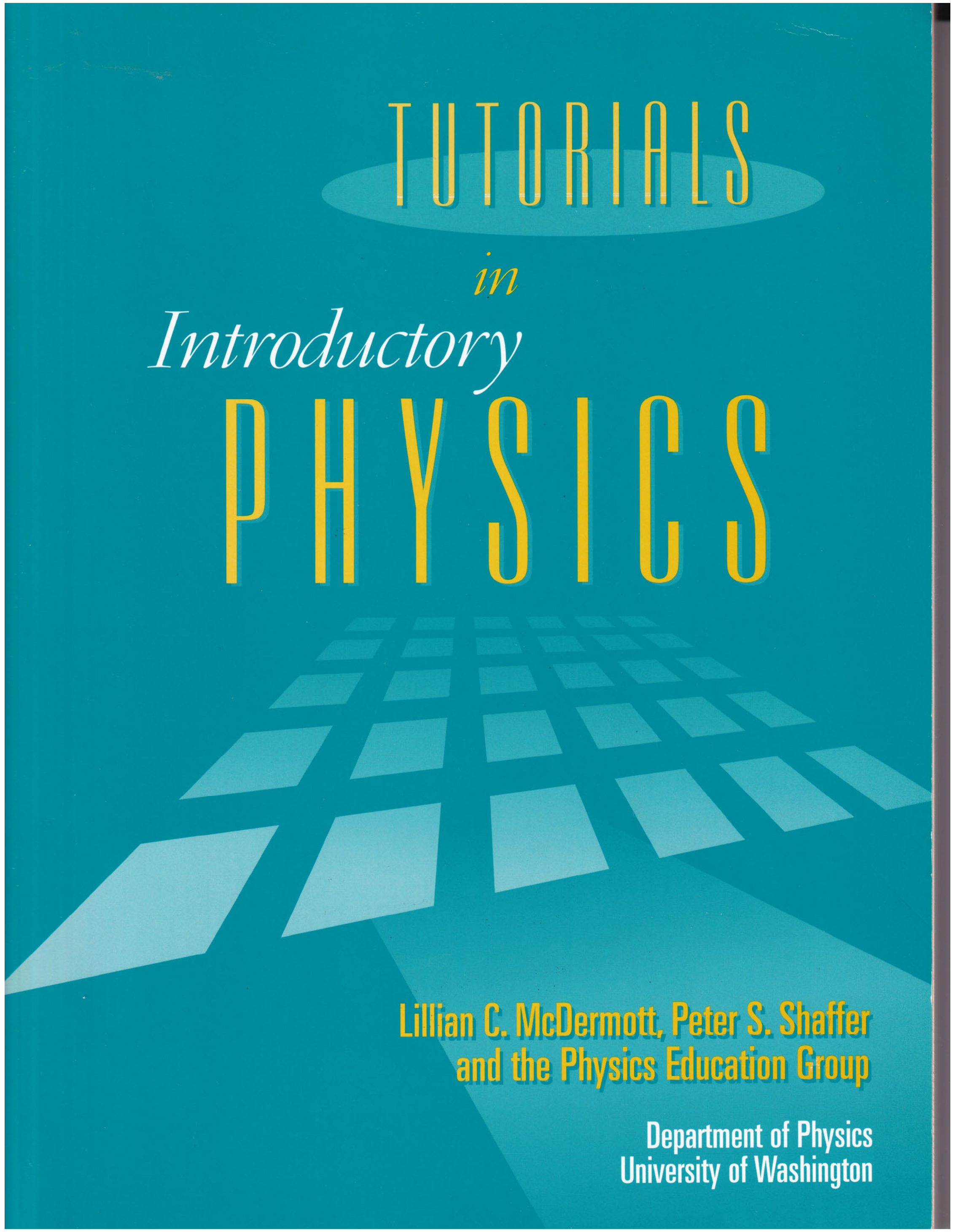
Table II. Results from 1D pretest on the ball on ramp [Fig. 3(a)] and 1D post-test on the motion of two blocks [Fig. 4(b)]. Not all students were asked about both the velocity and the acceleration.

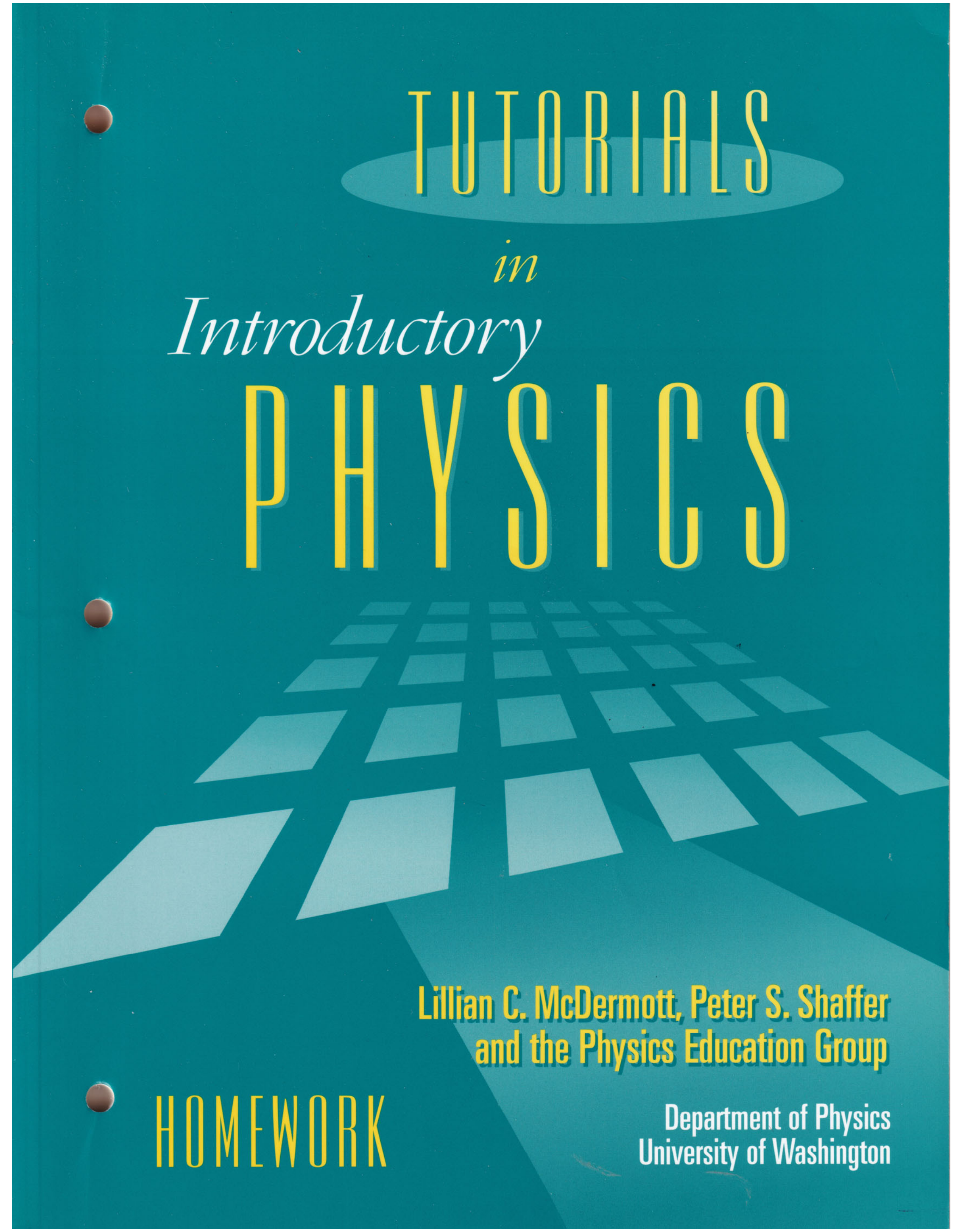
	Pretest		Post-test
	Undergraduates[a]	TAs	Undergraduates[a]
Velocity	$N\sim 715$	…	…
Correct (up along ramp, zero, down along ramp)	80%	…	…
Incorrect			
Nonzero vector drawn at point where $v=0$	15%	…	…
Acceleration	$\boxed{N\sim 20\,110}$	$N\sim 285$	$N\sim 575$
Correct (down along ramp at all points)	20%	75%	75% (top only)
Incorrect[b]			
acceleration mimics velocity	20%	5%	…
acceleration straight down (at one or more points)	20%	10%	10%
acceleration zero at top	50%	15%	10%

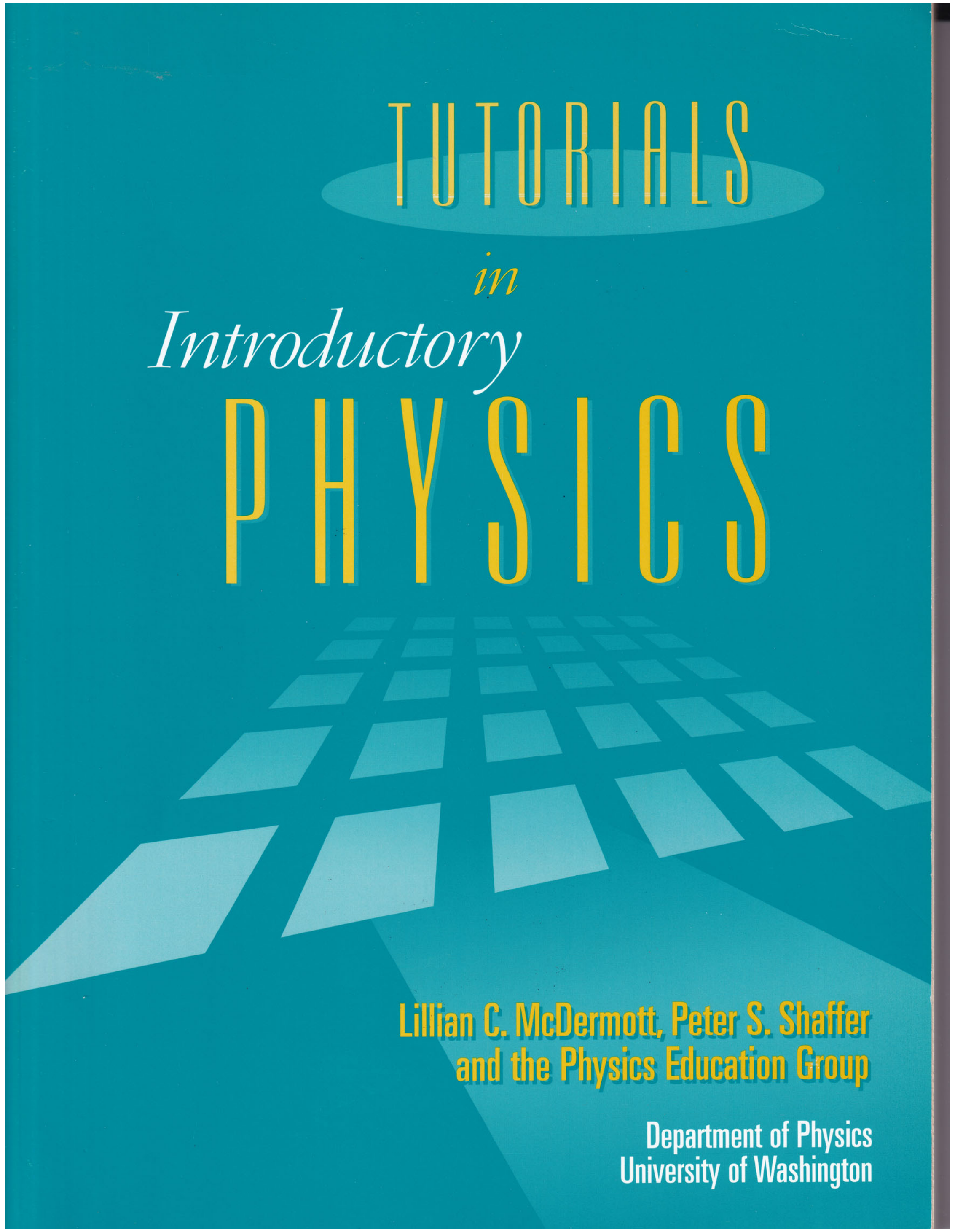
[a]Includes results from most of the Ph.D. granting universities, which had very similar results. About 35% of the students [$N\sim 500$] at Harvard University and in the UW honors section of calculus-based physics answered the question about acceleration correctly. These data are not included.
[b]Categories not mutually exclusive.

Iterative process of instructional materials development

1. Carry out research on students' ideas about physical phenomena
2. Develop preliminary instructional materials based on the research
3. Assess effectiveness of instructional materials
4. Carry out further research to examine students' thinking in greater depth
5. Develop revised and updated instructional materials to reflect additional research
6. Further assess the effectiveness of revised instructional materials
7. Publish materials; disseminate to other instructors and schools

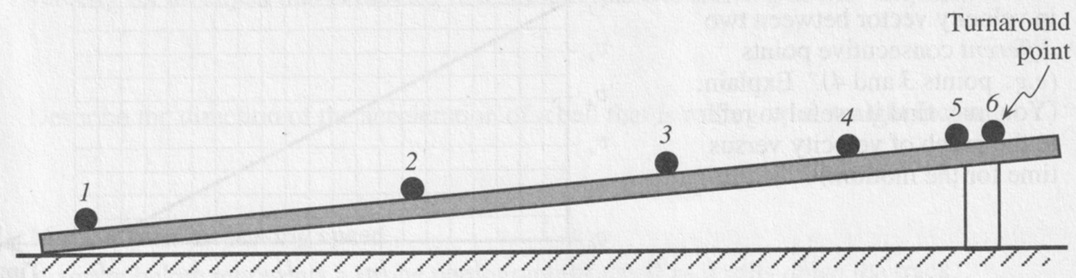

TUTORIALS
in
Introductory
PHYSICS
Lillian C. McDermott, Peter S. Shaffer
and the Physics Education Group
Department of Physics
University of Washington


TUTORIALS
in
Introductory
PHYSICS
Lillian C. McDermott, Peter S. Shaffer
and the Physics Education Group
HOMEWORK
Department of Physics
University of Washington



I. Motion with decreasing speed

The diagram below represents a strobe photograph of a ball as it rolls *up* a track. (In a strobe photograph, the position of an object is shown at instants separated by *equal time intervals*.)



A. Draw vectors on your diagram that represent the instantaneous velocity of the ball at each of the labeled locations. If the velocity is zero at any point, indicate that explicitly. Explain why you drew the vectors as you did.

We will call diagrams like the one you drew above *velocity diagrams*. Unless otherwise specified, a velocity diagram shows both the location and the velocity of an object at instants in time that are separated by equal time intervals.

Longitudinal study: Long-term impacts of Tutorials

- Students in a upper-level electricity and magnetism course who had used Tutorials in Introductory Physics in their freshman introductory course had *better course grades and higher scores on a conceptual test* than students who had taken introductory courses that did not use Tutorials.

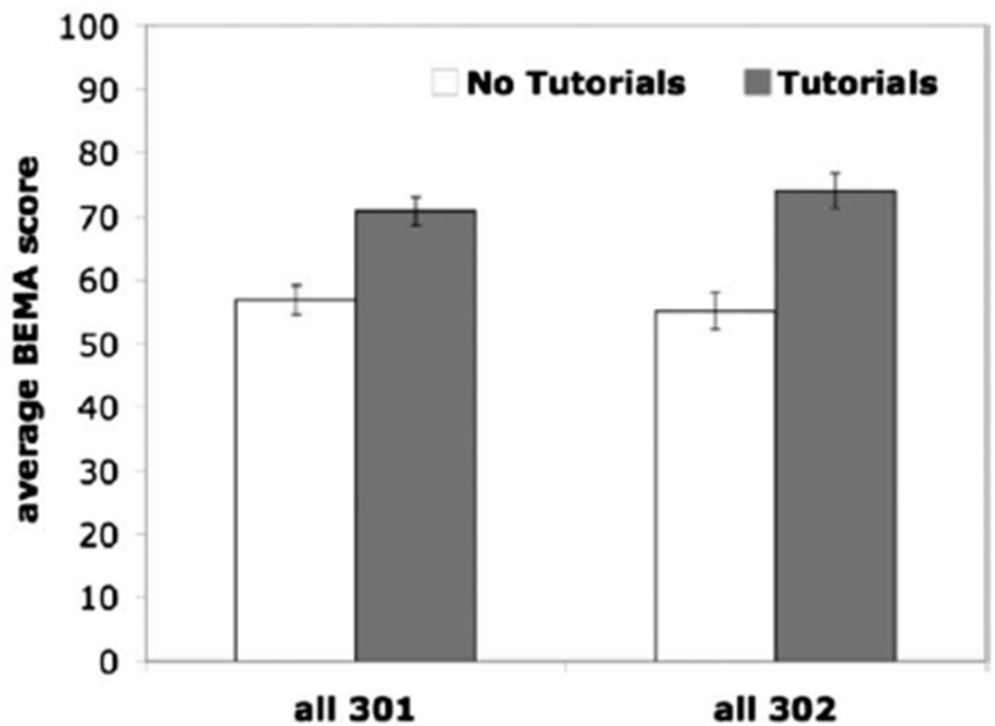
PHYSICAL REVIEW SPECIAL TOPICS - PHYSICS EDUCATION RESEARCH **5**, 020110 (2009)

Longitudinal study of student conceptual understanding in electricity and magnetism

S. J. Pollock
Department of Physics, University of Colorado, Boulder, Colorado 80309-0390, USA
(Received 20 July 2009; published 15 December 2009)

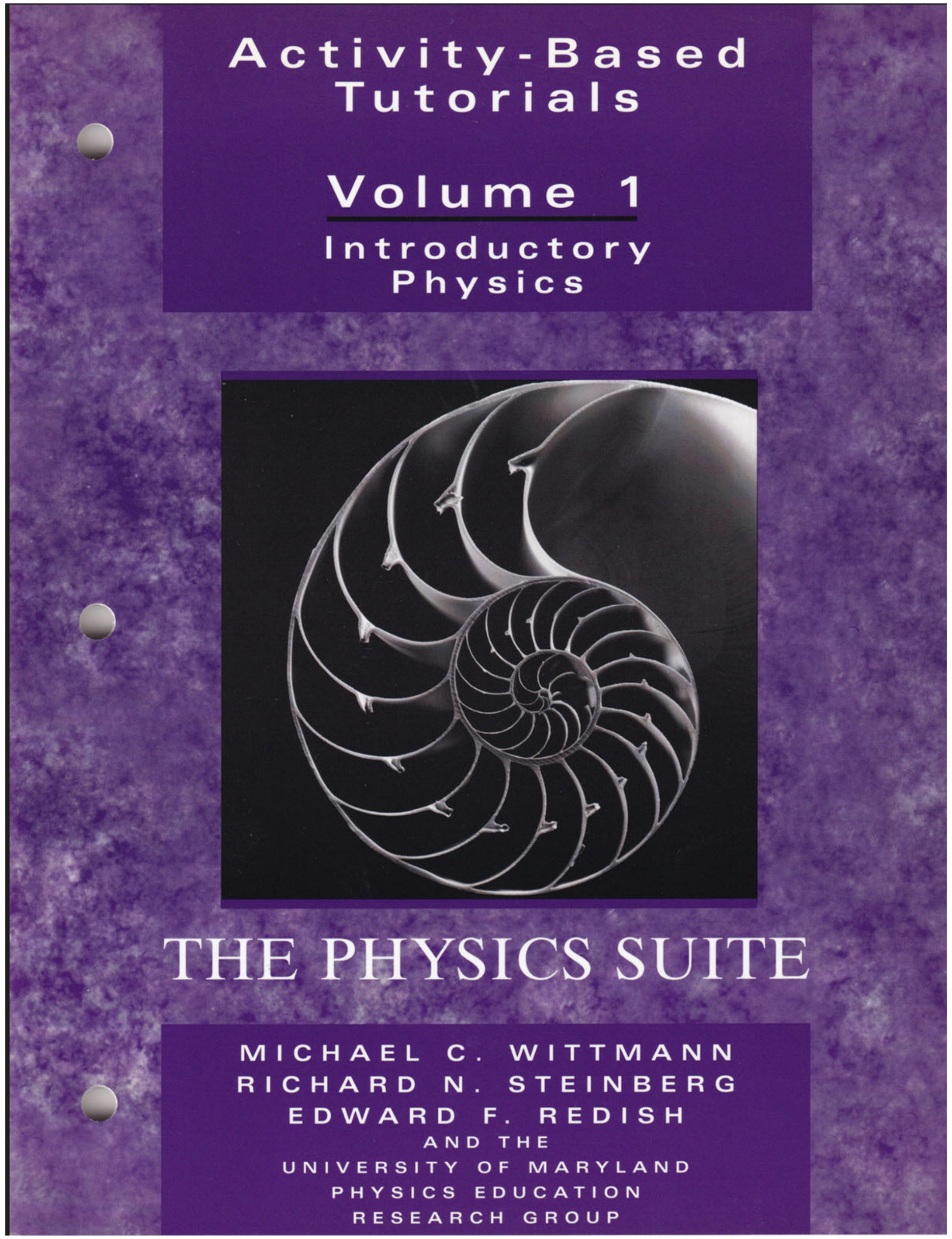
We have investigated the long-term effect of student-centered instruction at the freshman level on juniors' performance on a conceptual survey of Electricity and Magnetism (E&M). We measured student performance on a research-based conceptual instrument—the Brief Electricity & Magnetism Assessment (BEMA)–over a

S. Pollock (2009), Phys. Rev. PER

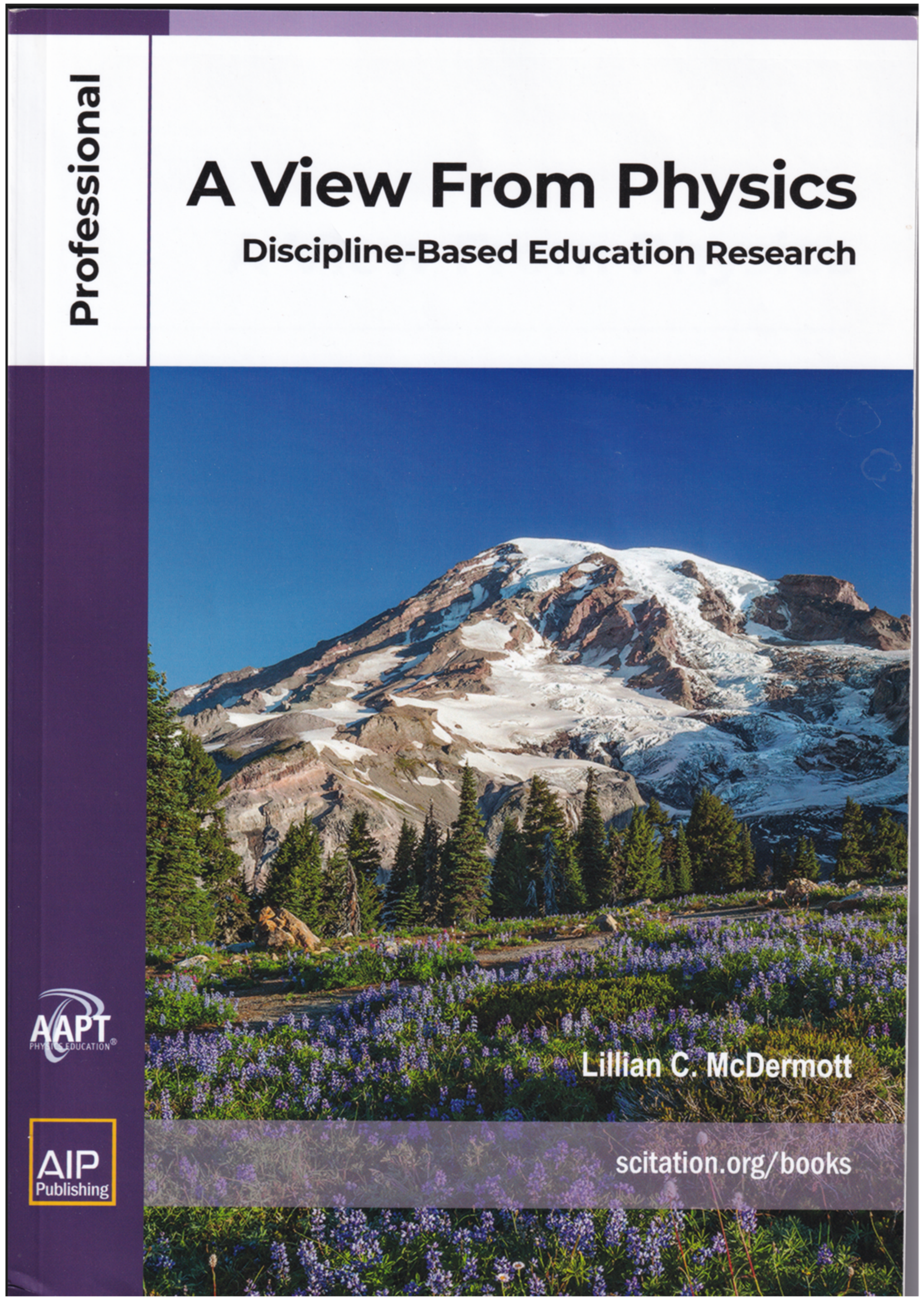


Scores on “BEMA” diagnostic assessment test after taking upper-level Electricity and Magnetism: Scores *higher* for “Tutorials” group. (Final course grades were *equal or better* in Tutorials group.)

[“Tutorials” group experienced University of Washington Tutorials during their freshman physics course; the “No Tutorials” group did *not* experience Tutorials.]

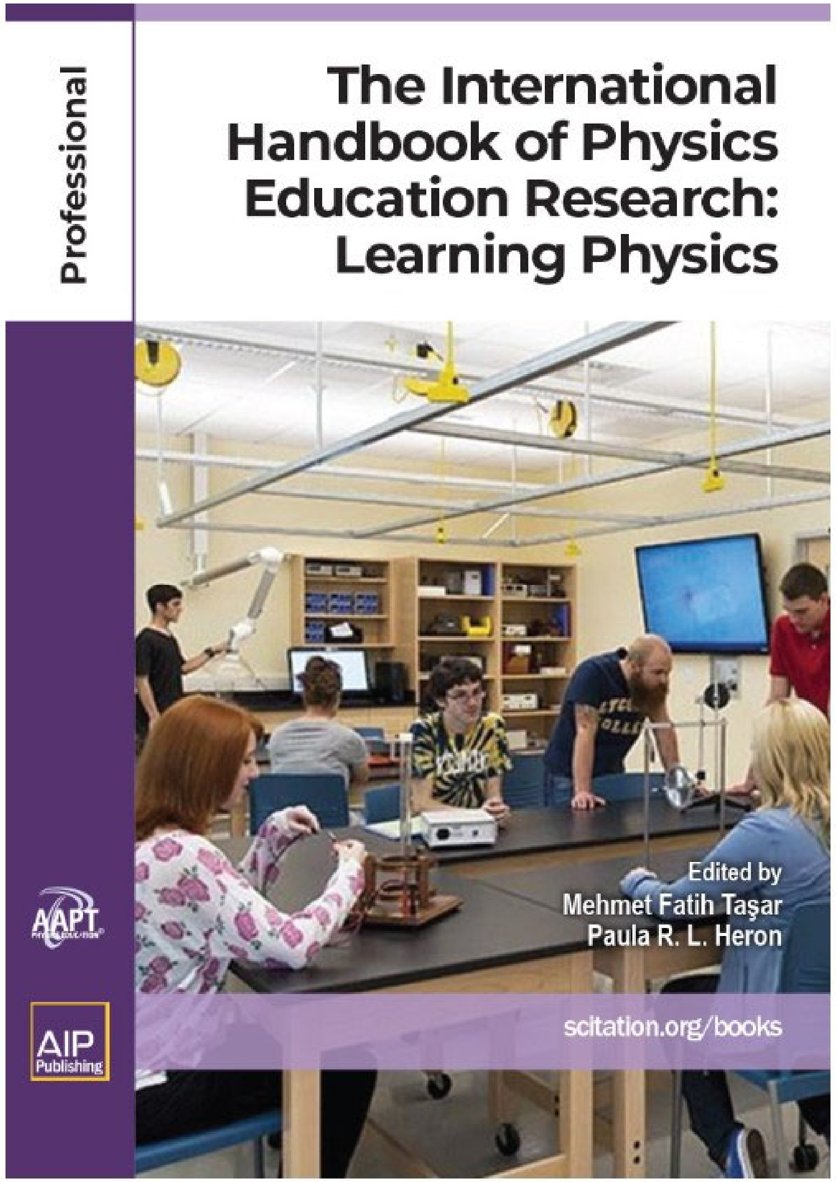


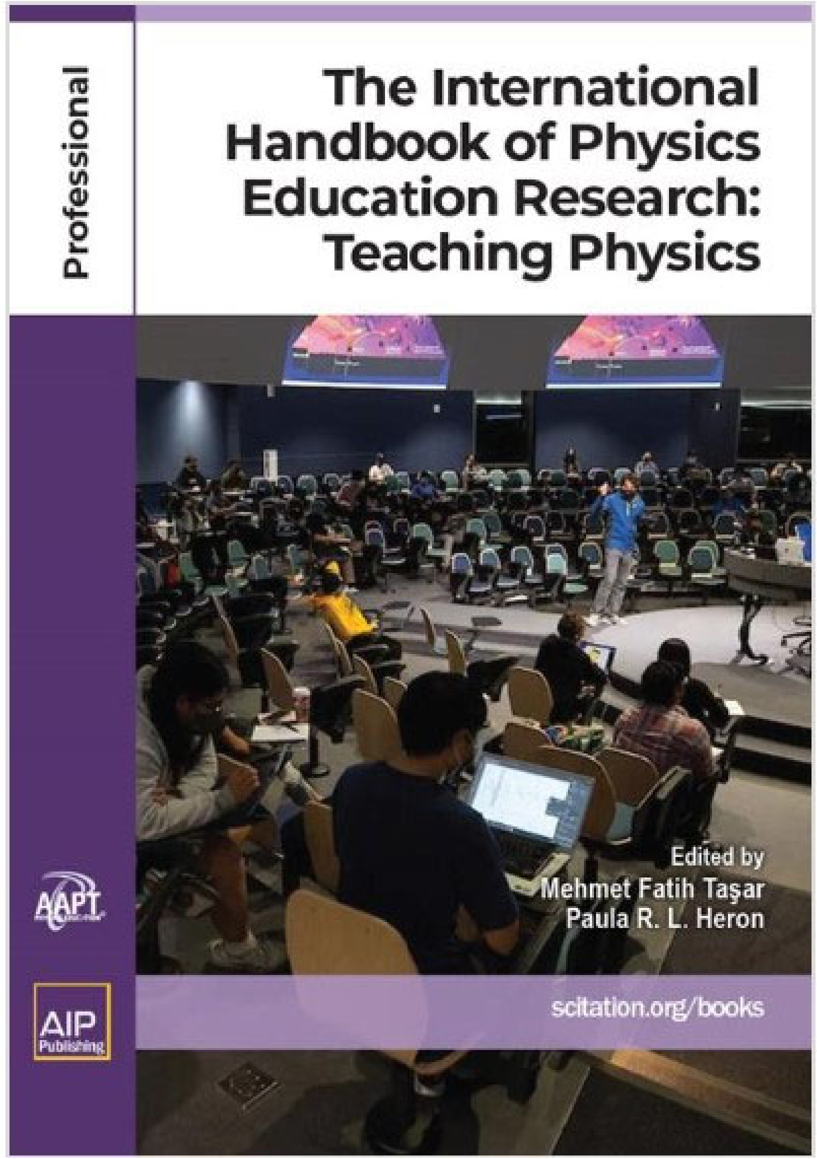
Research-based tutorials developed by the University of Maryland



McDermott's final work—the 2021 book "A View From Physics."

More recently, an international handbook on all aspects of physics education research and research-based instruction has been released by AIP Publishing:


Professional
The International Handbook of Physics Education Research: Learning Physics
Edited by
Mehmet Fatih Taşar
Paula R. L. Heron
scitation.org/books


Professional
The International Handbook of Physics Education Research: Teaching Physics
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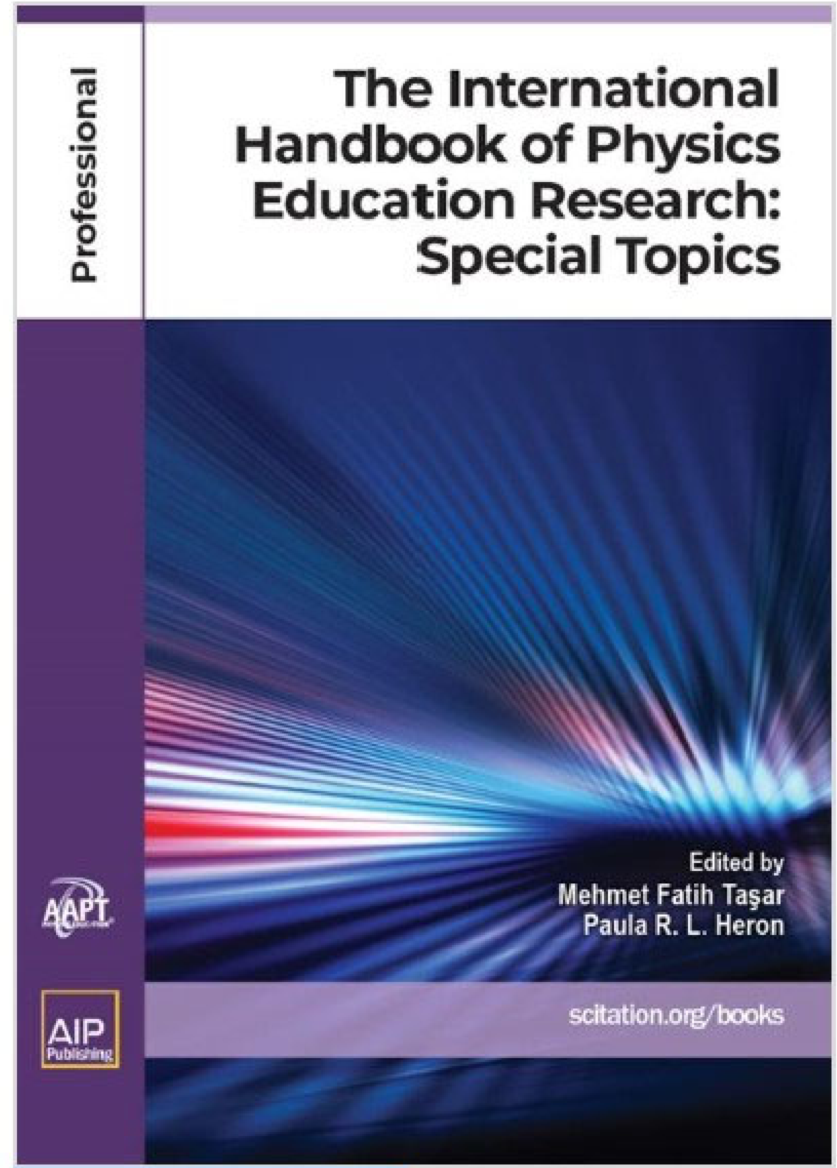
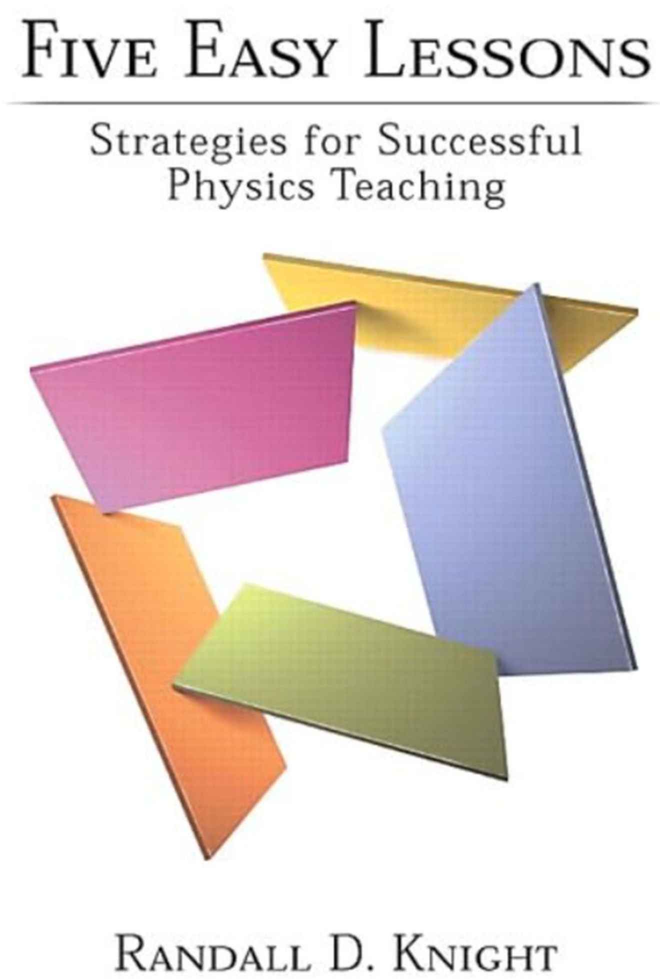
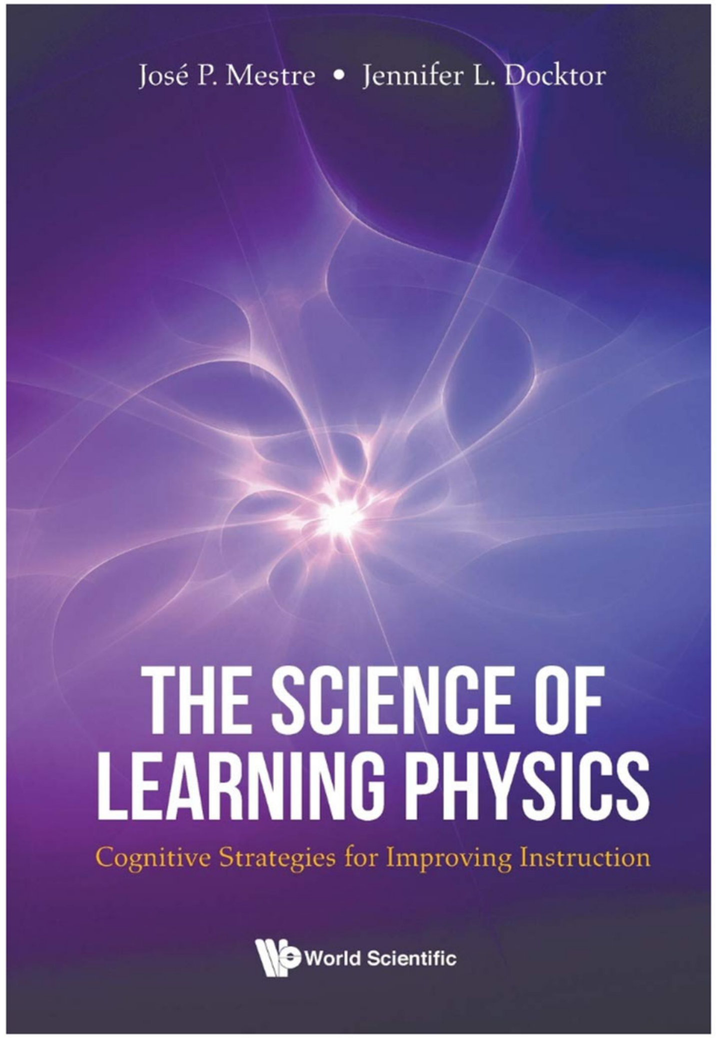
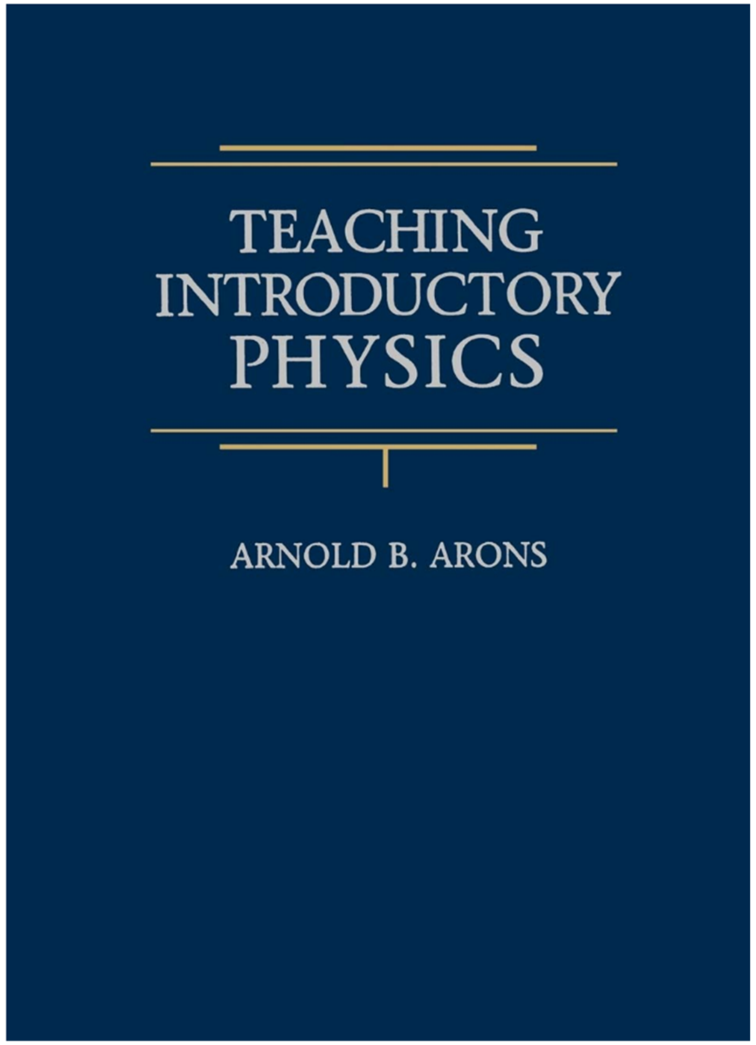
scitation.org/books


Professional
The International Handbook of Physics Education Research: Special Topics
Edited by
Mehmet Fatih Taşar
Paula R. L. Heron
scitation.org/books







Several valuable books on research-based instruction in physics

Other models of research-based active learning in physics

- The research model developed and implemented by Lillian McDermott at the University of Washington has been extremely successful. However, it is relatively slow and resource-intensive, requiring long-term collaboration of research teams of professors, post-doctoral researchers, and graduate students. Many other models have been employed with success over the past 50 years.

- A central feature of all research-based work in physics education is that there must be tools to investigate and assess students’ thinking. So-called “diagnostic assessment instruments” of all types have been developed.

Force Concept Inventory

By David Hestenes, Malcolm Wells, and Gregg Swackhamer

Every student begins physics with a well-established system of commonsense beliefs about how the physical world works derived from years of personal experience. Over the last decade, physics education research has established that these beliefs play a dominant role in introductory physics. Instruction that does not take them into account is almost totally ineffective, at least for the majority of students.

Specifically, it has been established that[1] (1) commonsense beliefs about motion and force are incompatible with Newtonian concepts in most respects, (2) conventional physics instruction produces little change in these beliefs, and (3) this result is independent of the instructor and the mode of instruction. The implications could not be more serious. Since the students have evidently not learned the most basic Newtonian concepts, they must have failed to comprehend most of the material in the course. They have been forced to cope with the subject by rote memorization of isolated fragments and by carrying out meaningless tasks. No wonder so many are repelled! The few who are successful have become so by their own devices, the course and the teacher having supplied only the opportunity and perhaps inspiration.

The authors, David Hestenes, Malcolm Wells, and Gregg Swackhamer are trying to make a point!

David Hestenes *is a professor of theoretical physics at Arizona State University. He has been active in physics education research for more than a decade. He also has current research in relativistic electron theory and neural network modeling of the brain (Department of Physics and Astronomy, Arizona State University, Tempe, AZ 85287).*

Malcolm Wells *has been a high-school physics teacher for three decades. In 1986 he received the Presidential Award for Excellence in Science Education. In 1987 he completed a doctorate in physics education research. He is currently collaborating with Hestenes on an NSF grant for educational research and teacher enhancement (Marcos de Niza High School, Tempe, AZ 85283).*

Gregg Swackhamer *has taught high-school physics for 13 years. He has B.S. and M.A.T. degrees from Indiana University. He is currently teaching physics at Glenbrook North High School (Northbrook, IL 60062) from which he took sabbatical leave in 1989–90 to study at Arizona State University and work on this project.*

One of the most widely used and influential assessments of physics concept knowledge has been the "Force Concept Inventory" (FCI), published in 1992

The FCI was based on research on students' ideas by Halloun and Hestenes (1985):

The initial knowledge state of college physics students

Ibrahim Abou Halloun[a] and David Hestenes
Department of Physics, Arizona State University, Tempe, Arizona 85287

(Received 1 August 1984; accepted for publication 28 January 1985)

An instrument to assess the basic knowledge state of students taking a first course in physics has been designed and validated. Measurements with the instrument show that the student's initial qualitative, common sense beliefs about motion and causes has a large effect on performance in physics, but conventional instruction induces only a small change in those beliefs.

Common sense concepts about motion

Ibrahim Abou Halloun[a] and David Hestenes
Department of Physics, Arizona State University, Tempe, Arizona 85287

(Received 1 August 1984; accepted for publication 28 January 1985)

Common sense beliefs of college students about motion and its causes are surveyed and analyzed. A taxonomy of common sense concepts which conflict with Newtonian theory is developed as a guide to instruction.

The current version contains 30 “multiple-choice” questions

FCI- Questionario sul Concetto di Forza

Versione originale in *The Physics Teacher*, marzo1992
ad opera di
David Hestenes, Malcolm Wells, and Gregg Swackhamer

Rivisto nell' agosto 1995
da *Ibrahim Halloun, Richard Hake, and Eugene Mosca*

Traduzione in italiano di Leonardo Colletti
(Liceo Classico "Carducci ", Bolzano e Libera Università di Bolzano), settembre 2006

Il Force Concept Inventory (FCI) è un test a risposta multipla predisposto per la valutazione della comprensione da parte degli studenti dei concetti basilari della meccanica newtoniana. Tale test può essere usato per scopi diversi, ma il più importante è quello di valutare l'efficacia dell'insegnamento. Per un quadro completo di ciò che ha indirizzato lo sviluppo di questo strumento e sui modi in cui può essere utilizzato, si possono consultare alcuni articoli che lo riguardano (1,2), così come (a) gli articoli sul Mechanics Diagnostic Test (3,4), il predecessore del FCI, (b) l'articolo sul Mechanics Baseline Test, uno stumento che raccomandiamo come parallelo al FCI per la valutazione delle abilità quantitative di problem-solving, e (c) la collezione di dati (6) di Richard Hake sull' insegnamento della fisica nelle scuole superiori e all'università da parte di molti insegnanti e con metodi diversi negli Stati Uniti.

I riferimenti bibliografici 1-5 sono online a <http://modeling.asu.edu/R&E/Research.html> Il rif. 6 è online come ref. 24 at <http://www.physics.indiana.edu/~hake>.

Bibliografia:

1. D. Hestenes, M. Wells, and G. Swackhamer (1992). Force Concept Inventory, *The Physics Teacher* **30**, 141-151.
2. D. Hestenes and I. Halloun (1995). Interpreting the Force Concept Inventory, *The Physics Teacher* **33**, 502-506.
3. I. Halloun and D. Hestenes (1985). The initial knowledge state of college physics students. *Am. J. Phys*. **53**, 1043-1055.
4. I. Halloun and D. Hestenes (1985). Common sense concepts about motion. *Am. J. Phys*. **53**, 1056-1065.
5. D. Hestenes and M. Wells (1992). A Mechanics Baseline Test. *The Physics Teacher* **30**, 159-166.
6. R. Hake (1998). Interactive-engagement vs. traditional methods: A six thousand-student survey of mechanics test data for introductory physics courses. *Am. J. Phys.***66**, 64-74.

17. Un'ascensore (vedi pagina seguente) viene sollevato lungo il vano ascensore a velocità costante da un cavo d'acciaio, come mostato nella figura sottostante. Tutti gli attriti sono trascurabili. In questa situazione, le forze sull'ascensore sono tali che:

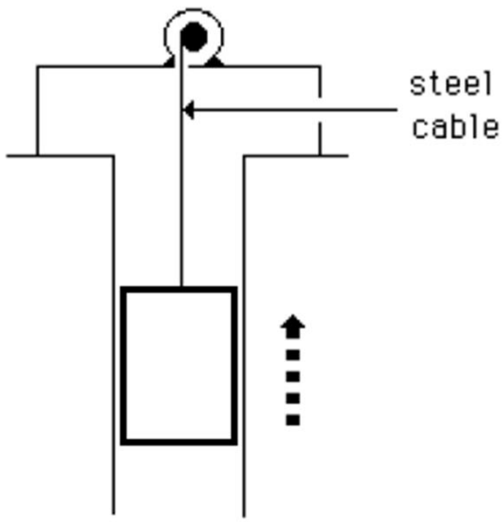
(A) la forza verso l'alto esercitata dal cavo è maggiore della forza di gravità verso il basso.

✓ (B) la forza verso l'alto esercitata dal cavo è uguale alla forza di gravità verso il basso.

(C) la forza verso l'alto esercitata dal cavo è minore della forza di gravità verso il basso.

(D) la forza verso l'alto esercitata dal cavo è maggiore della somma della forza di gravità verso il basso e di una forza verso il basso dovuta all'aria.

(E) nessuna delle precedenti. (L'ascensore sale perché il cavo viene accorciato, e non perché una forza verso l'alto viene esercitata dal cavo sull'ascensore)..



L'ascensore sta salendo a velocità costante.

17. Un'ascensore (vedi pagina seguente) viene sollevato lungo il vano ascensore a velocità costante da un cavo d'acciaio, come mostato nella figura sottostante. Tutti gli attriti sono trascurabili. In questa situazione, le forze sull'ascensore sono tali che:

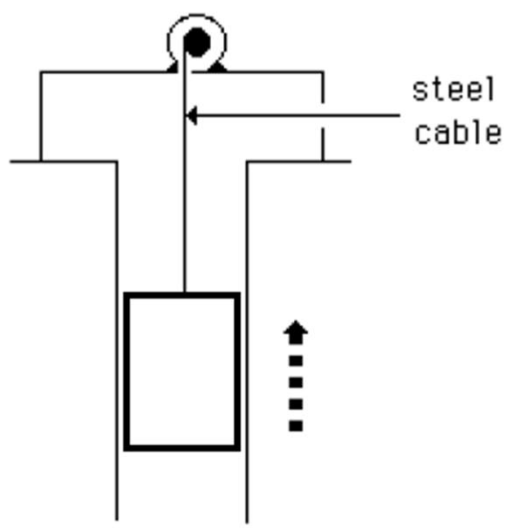
(A) la forza verso l'alto esercitata dal cavo è maggiore della forza di gravità verso il basso.

(B) la forza verso l'alto esercitata dal cavo è uguale alla forza di gravità verso il basso.

(C) la forza verso l'alto esercitata dal cavo è minore della forza di gravità verso il basso.

(D) la forza verso l'alto esercitata dal cavo è maggiore della somma della forza di gravità verso il basso e di una forza verso il basso dovuta all'aria.

(E) nessuna delle precedenti. (L'ascensore sale perché il cavo viene accorciato, e non perché una forza verso l'alto viene esercitata dal cavo sull'ascensore)..



L'ascensore sta salendo a velocità costante.

Am. J. Phys. **66** (1), January 1998

Interactive-engagement versus traditional methods: A six-thousand-student survey of mechanics test data for introductory physics courses

Richard R. Hake[a)]
Department of Physics, Indiana University, Bloomington, Indiana 47405

(Received 6 May 1996; accepted 4 May 1997)

A survey of pre/post-test data using the Halloun–Hestenes Mechanics Diagnostic test or more recent Force Concept Inventory is reported for 62 introductory physics courses enrolling a total number of

Traditional lecture-based courses

Courses using research-based active-learning instruction

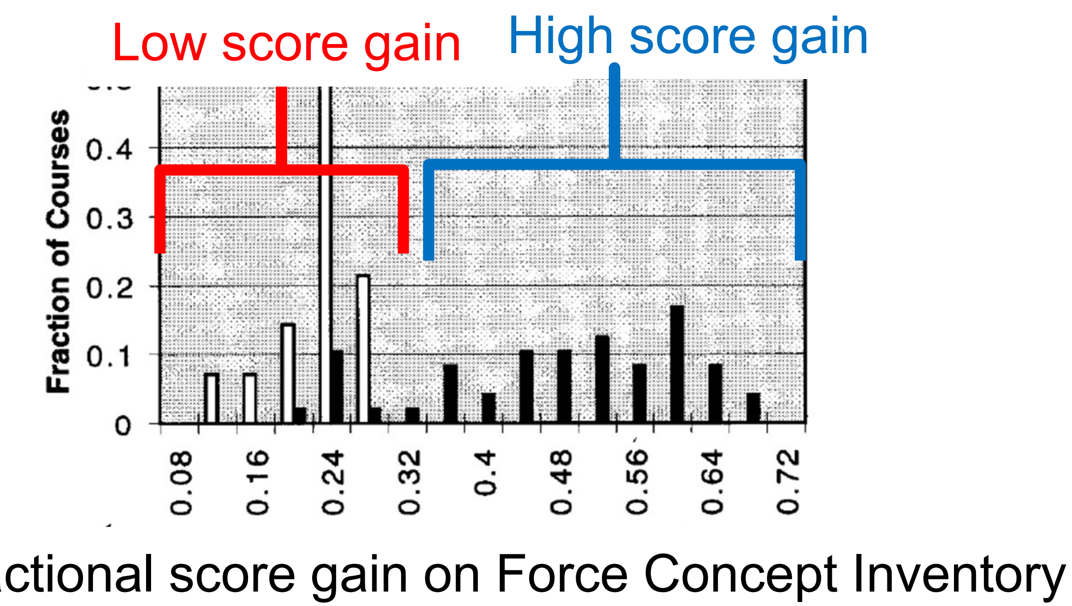


Fig. 2. Histogram of the average normalized gain $\langle g \rangle$: white bars show the *fraction* of 14 traditional courses ($N=2084$), and black bars show the *fraction* of 48 interactive engagement courses ($N=4458$), both within bins of width $\delta\langle g \rangle = 0.04$ centered on the $\langle g \rangle$ values shown.

Interactive-engagement versus traditional methods: A six-thousand-student survey of mechanics test data for introductory physics courses

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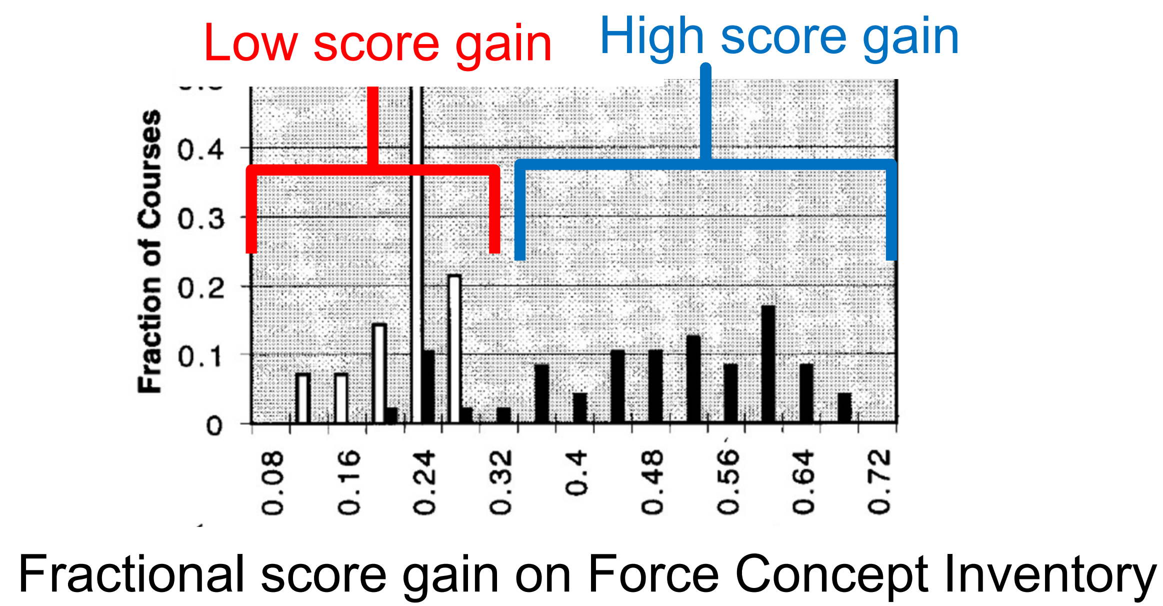

Much higher gains on assessment test for courses that used active-learning instruction

Interactive-engagement versus traditional methods: A six-thousand-student survey of mechanics test data for introductory physics courses

Richard R. Hake[a)]
Department of Physics, Indiana University, Bloomington, Indiana 47405

(Received 6 May 1996; accepted 4 May 1997)

Google Scholar

Richard R. Hake

Indiana University Emeritus
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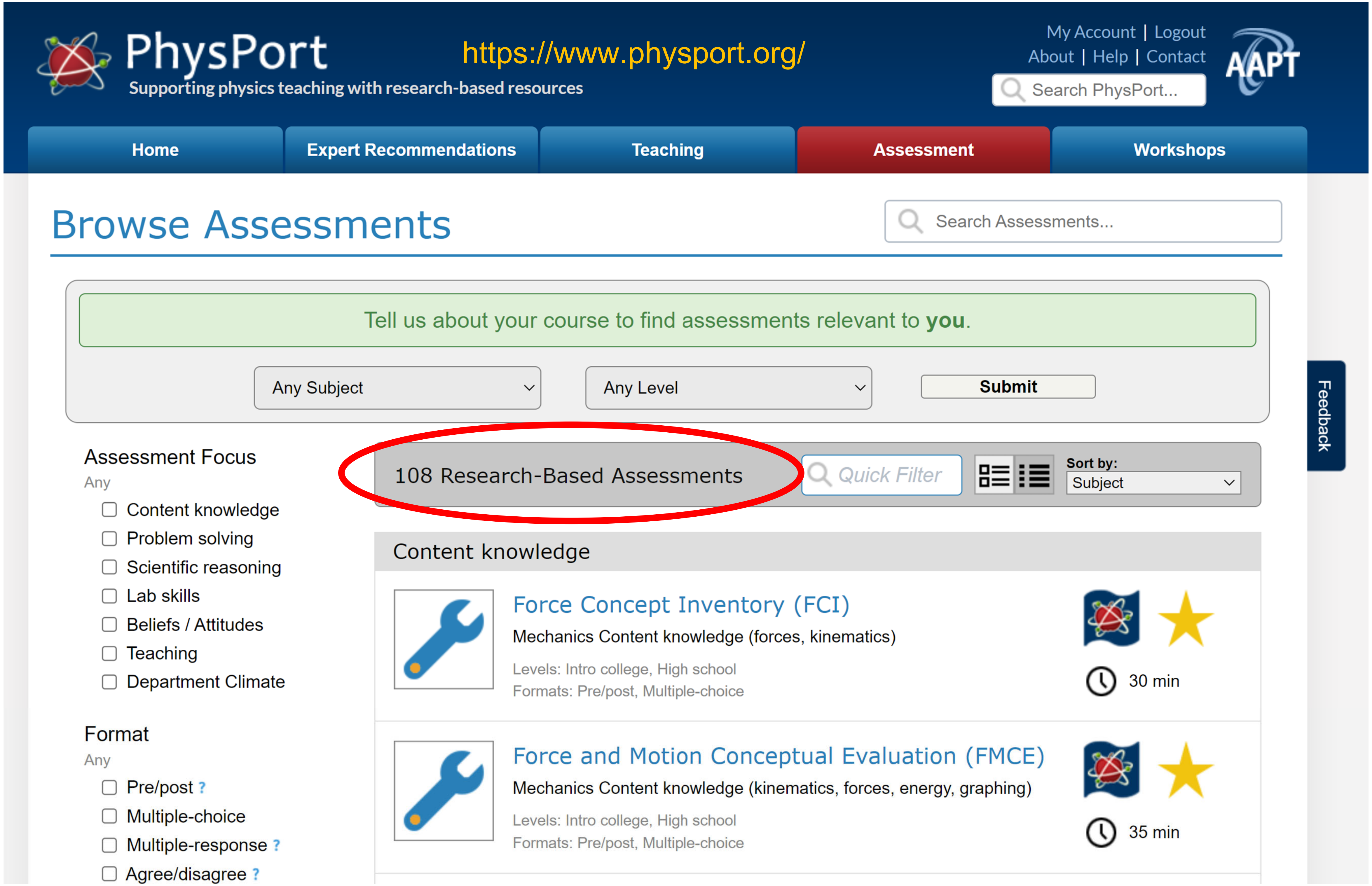
TITLE	CITED BY	YEAR
Interactive-engagement versus traditional methods: A six-thousand-student survey of mechanics test data for introductory physics courses RR Hake American journal of Physics 66 (1), 64-74	10040	1998


PhysPort
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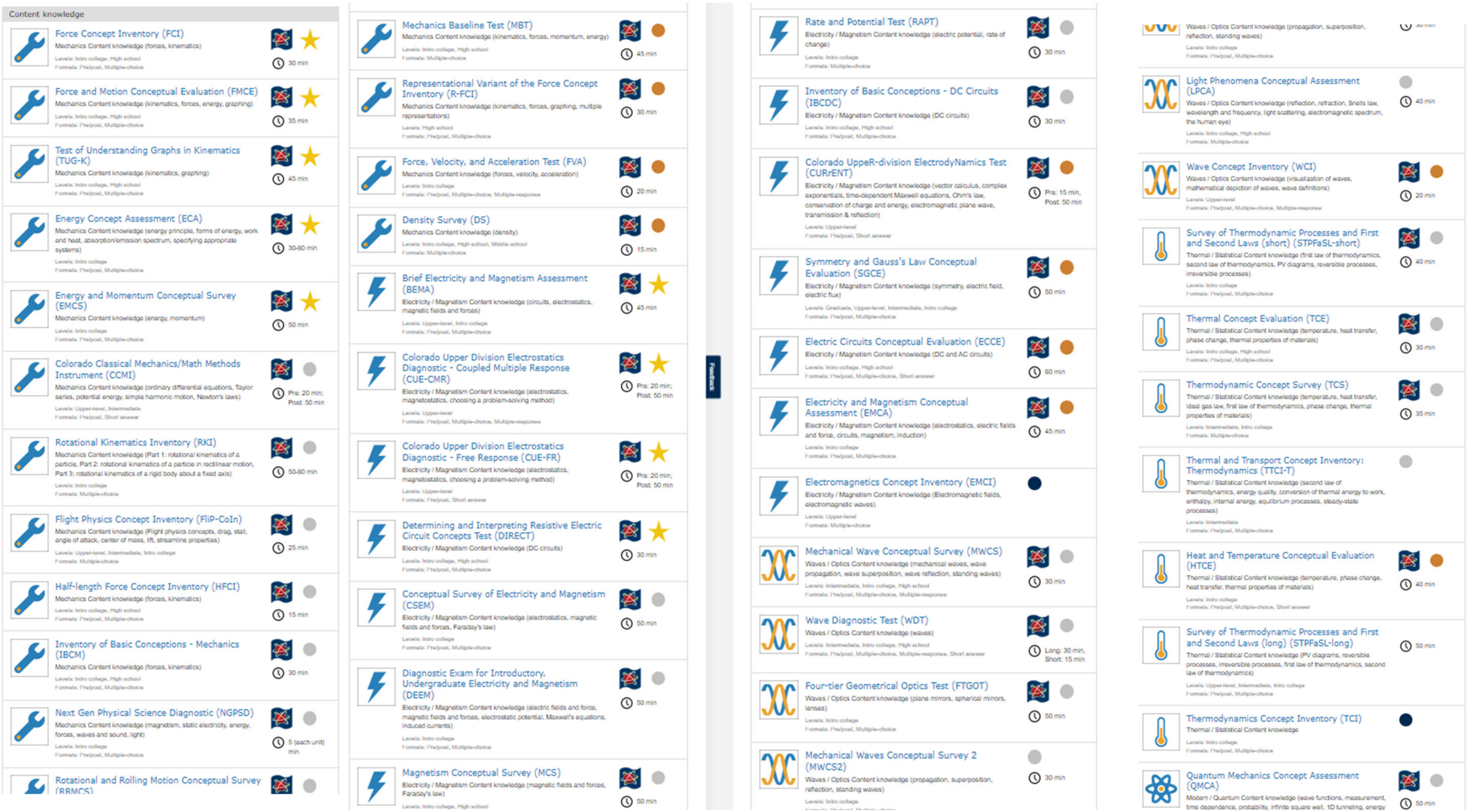
Teaching
Assessment
Workshops
Browse Assessments
Search Assessments...
Tell us about your course to find assessments relevant to you.
Any Subject
Any Level
Submit
Feedback
Assessment Focus
Any
Content knowledge
Problem solving
Scientific reasoning
Lab skills
Beliefs / Attitudes
Teaching
Department Climate
Format
Any
Pre/post ?
Multiple-choice
Multiple-response ?
Agree/disagree ?
108 Research-Based Assessments
Quick Filter
Sort by:
Subject
Content knowledge
Force Concept Inventory (FCI)
Mechanics Content knowledge (forces, kinematics)
Levels: Intro college, High school
Formats: Pre/post, Multiple-choice
30 min
Force and Motion Conceptual Evaluation (FMCE)
Mechanics Content knowledge (kinematics, forces, energy, graphing)
Levels: Intro college, High school
Formats: Pre/post, Multiple-choice
35 min



Content knowledge
Force Concept Inventory (FCI)
Mechanics Content knowledge (forces, kinematics)
30 min
Force and Motion Conceptual Evaluation (FMCE)
Mechanics Content knowledge (kinematics, forces, energy, graphing)
35 min
Test of Understanding Graphs in Kinematics (TUG-K)
Mechanics Content knowledge (kinematics, graphing)
45 min
Energy Concept Assessment (ECA)
Mechanics Content knowledge (energy principle, forms of energy, work and heat, absorption/emission spectrum, specifying appropriate systems)
30-60 min
Energy and Momentum Conceptual Survey (EMCS)
Mechanics Content knowledge (energy, momentum)
50 min
Colorado Classical Mechanics/Math Methods Instrument (CCMI)
Mechanics Content knowledge (ordinary differential equations, Taylor series, potential energy, simple harmonic motion, Newton's laws)
Pre: 20 min; Post: 50 min
Rotational Kinematics Inventory (RKI)
Mechanics Content knowledge (Part 1: rotational kinematics of a particle, Part 2: rotational kinematics of a particle in rectilinear motion, Part 3: rotational kinematics of a rigid body about a fixed axis)
50-60 min
Flight Physics Concept Inventory (FliP-CoIn)
Mechanics Content knowledge (Flight physics concepts, drag, stall, angle of attack, center of mass, lift, streamline properties)
25 min
Half-length Force Concept Inventory (HFCI)
Mechanics Content knowledge (forces, kinematics)
15 min
Inventory of Basic Conceptions - Mechanics (IBCM)
Mechanics Content knowledge (forces, kinematics)
30 min
Next Gen Physical Science Diagnostic (NGPSD)
Mechanics Content knowledge (magnetism, static electricity, energy, forces, waves and sound, light)
5 (each unit) min
Rotational and Rolling Motion Conceptual Survey (RRMCS)
Mechanics Baseline Test (MBT)
Mechanics Content knowledge (kinematics, forces, momentum, energy)
45 min
Representational Variant of the Force Concept Inventory (R-FCI)
Mechanics Content knowledge (kinematics, forces, graphing, multiple representations)
30 min
Force, Velocity, and Acceleration Test (FVA)
Mechanics Content knowledge (forces, velocity, acceleration)
20 min
Density Survey (DS)
Mechanics Content knowledge (density)
15 min
Brief Electricity and Magnetism Assessment (BEMA)
Electricity / Magnetism Content knowledge (circuits, electrostatics, magnetic fields and forces)
45 min
Colorado Upper Division Electrostatics Diagnostic - Coupled Multiple Response (CUE-CMR)
Electricity / Magnetism Content knowledge (electrostatics, magnetostatics, choosing a problem-solving method)
Pre: 20 min; Post: 50 min
Colorado Upper Division Electrostatics Diagnostic - Free Response (CUE-FR)
Electricity / Magnetism Content knowledge (electrostatics, magnetostatics, choosing a problem-solving method)
Pre: 20 min; Post: 50 min
Determining and Interpreting Resistive Electric Circuit Concepts Test (DIRECT)
Electricity / Magnetism Content knowledge (DC circuits)
30 min
Conceptual Survey of Electricity and Magnetism (CSEM)
Electricity / Magnetism Content knowledge (electrostatics, magnetic fields and forces, Faraday's law)
50 min
Diagnostic Exam for Introductory, Undergraduate Electricity and Magnetism (DEEM)
Electricity / Magnetism Content knowledge (electric fields and force, magnetic fields and forces, electrostatic potential, Maxwell's equations, induced currents)
50 min
Magnetism Conceptual Survey (MCS)
Electricity / Magnetism Content knowledge (magnetic fields and forces, Faraday's law)
50 min
Feedback
Rate and Potential Test (RAPT)
Electricity / Magnetism Content knowledge (electric potential, rate of change)
30 min
Inventory of Basic Conceptions - DC Circuits (IBCDC)
Electricity / Magnetism Content knowledge (DC circuits)
30 min
Colorado UppeR-division ElectrodyNamics Test (CURrENT)
Electricity / Magnetism Content knowledge (vector calculus, complex exponentials, time-dependent Maxwell equations, Ohm's law, conservation of charge and energy, electromagnetic plane wave, transmission & reflection)
Pre: 15 min, Post: 50 min
Symmetry and Gauss's Law Conceptual Evaluation (SGCE)
Electricity / Magnetism Content knowledge (symmetry, electric field, electric flux)
50 min
Electric Circuits Conceptual Evaluation (ECCE)
Electricity / Magnetism Content knowledge (DC and AC circuits)
60 min
Electricity and Magnetism Conceptual Assessment (EMCA)
Electricity / Magnetism Content knowledge (electrostatics, electric fields and force, circuits, magnetism, induction)
45 min
Electromagnetics Concept Inventory (EMCI)
Electricity / Magnetism Content knowledge (Electromagnetic fields, electromagnetic waves)
Mechanical Wave Conceptual Survey (MWCS)
Waves / Optics Content knowledge (mechanical waves, wave propagation, wave superposition, wave reflection, standing waves)
30 min
Wave Diagnostic Test (WDT)
Waves / Optics Content knowledge (waves)
Long: 30 min, Short: 15 min
Four-tier Geometrical Optics Test (FTGOT)
Waves / Optics Content knowledge (plane mirrors, spherical mirrors, lenses)
50 min
Mechanical Waves Conceptual Survey 2 (MWCS2)
Waves / Optics Content knowledge (propagation, superposition, reflection, standing waves)
30 min
Waves / Optics Content knowledge (propagation, superposition, reflection, standing waves)
Light Phenomena Conceptual Assessment (LPCA)
Waves / Optics Content knowledge (reflection, refraction, Snells law, wavelength and frequency, light scattering, electromagnetic spectrum, the human eye)
40 min
Wave Concept Inventory (WCI)
Waves / Optics Content knowledge (visualization of waves, mathematical depiction of waves, wave definitions)
20 min
Survey of Thermodynamic Processes and First and Second Laws (short) (STPFaSL-short)
Thermal / Statistical Content knowledge (first law of thermodynamics, second law of thermodynamics, PV diagrams, reversible processes, irreversible processes)
40 min
Thermal Concept Evaluation (TCE)
Thermal / Statistical Content knowledge (temperature, heat transfer, phase change, thermal properties of materials)
30 min
Thermodynamic Concept Survey (TCS)
Thermal / Statistical Content knowledge (temperature, heat transfer, ideal gas law, first law of thermodynamics, phase change, thermal properties of materials)
35 min
Thermal and Transport Concept Inventory: Thermodynamics (TTCI-T)
Thermal / Statistical Content knowledge (second law of thermodynamics, energy quality, conversion of thermal energy to work, enthalpy, internal energy, equilibrium processes, steady-state processes)
Heat and Temperature Conceptual Evaluation (HTCE)
Thermal / Statistical Content knowledge (temperature, phase change, heat transfer, thermal properties of materials)
40 min
Survey of Thermodynamic Processes and First and Second Laws (long) (STPFaSL-long)
Thermal / Statistical Content knowledge (PV diagrams, reversible processes, irreversible processes, first law of thermodynamics, second law of thermodynamics)
50 min
Thermodynamics Concept Inventory (TCI)
Thermal / Statistical Content knowledge
Quantum Mechanics Concept Assessment (QMCA)
Modern / Quantum Content knowledge (wave functions, measurement, time dependence, probability, infinite square well, 1D tunneling, energy
50 min

What are the primary characteristics of research-based active-learning instruction in physics?

RESOURCE LETTER

Am. J. Phys. **80** (6), June 2012

Resource Letter ALIP–1: Active-Learning Instruction in Physics

David E. Meltzer
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(Received 19 September 2011; accepted 30 December 2011)

This Resource Letter provides a guide to the literature on research-based active-learning instruction in physics. These are instructional methods that are based on, assessed by, and validated through research on the teaching and learning of physics. They involve students in their own learning more deeply and more intensely than does traditional instruction, particularly during class time. The instructional methods and supporting body of research reviewed here offer potential for

What is "Research-based Active-Learning Instruction"?

(as defined by Meltzer and Thornton, 2012)

- It is explicitly based on research in teaching and learning of a *specific discipline*
- Incorporates activities that require students to express their thinking through speaking, writing, or other actions
- Tested repeatedly and shows evidence of improved student learning

➢ All examples cited in this paper include published evidence of effectiveness, generally using a variety of diagnostic tests.

VI. ACTIVE-LEARNING INSTRUCTIONAL MATERIALS FOR INTRODUCTORY ALGEBRA- AND CALCULUS-BASED PHYSICS COURSES

We include here selected references to research-validated instructional materials and to papers that provide information regarding implementation and effectiveness of the materials. Materials within each of Secs. VI A–E are organized in chronological order of most recent publication of the primary (first) reference, which in some cases is years or decades after the publication date of the original version of the materials; additional references within subsections are organized chronologically; otherwise, organization is alphabetical.

A. Materials primarily for use in lecture sessions or lecture-based courses

1. Peer Instruction

104. **Peer Instruction: A User's Manual**, E. Mazur (Prentice Hall, Upper Saddle River, NJ, 1997). Peer Instruction is a method of interactive lecturing; short segments of a lecture are interspersed with students working collaboratively to answer qualitative, conceptual multiple-choice questions ("ConcepTests"). Provides an overview of the method and a large collection of ConcepTests. (E)

105. "Peer Instruction: Ten years of experience and results," C. H. Crouch and E. Mazur, Am. J. Phys. **69**, 970–977 (2001). Detailed documentation of improved student learning in physics lecture courses at Harvard that were based on Peer Instruction. (E)

106. "Transforming the lecture-hall environment: The fully interactive physics lecture," D. E. Meltzer and K. Manivannan, Am. J. Phys. **70**, 639–654 (2002). Review of active-learning instruction in physics and description of the "fully" interactive lecture. This variant of Peer

B. Materials primarily for the laboratory

1. Socratic Dialog-Inducing Labs

117. "Socratic pedagogy in the introductory physics laboratory," R. R. Hake, Phys. Teach. **30**, 546–552 (1992). "SDI" labs (Ref. 63) are designed to promote mental construction of concepts through conceptual conflict, analysis using multiple representations, peer discussion, and Socratic dialogue with instructors. Curricular materials are archived at <http://www.physics.indiana.edu/~sdi/>. (E)

2. Tools for Scientific Thinking

118. **Tools for Scientific Thinking: Motion and Force Curriculum and Guide;** and **Heat and Temperature**

C. Hybrid lecture-lab materials

1. Cooperative Group Problem Solving

124. University of Minnesota Physics Education Research and Development, *Cooperative Group Problem Solving*: <http://groups.physics.umn.edu/physed/Research/CGPS/CGPSintro.htm>. Comprehensive approach to restructuring introductory physics courses, based on work

D. Tutorials and problem-solving worksheets

1. Tutorials in Introductory Physics

136. **Tutorials in Introductory Physics; Homework for Tutorials in Introductory Physics; Instructor's Guide**

E. Computer simulations and intelligent tutors

1. MasteringPhysics

143. "What course elements correlate with improvement on tests in introductory Newtonian mechanics?" E.-S. Morote and D. E. Pritchard, Am. J. Phys. **77**, 746–753 (2009). "MasteringPhysics" is an online homework system with self-paced tutorials that incorporate extensive hints and feedback based on physics education research. This study showed that use of an early version correlated more strongly with high performance on both the MIT final course exam and the FCI (Ref. 72) than other course elements such as written homework, group problem solving, and class participation. The system was originally developed by D. E. Pritchard of MIT but is currently owned by Pearson Education; see: <http://www.masteringphysics.com/site/index.html>. (E)

2. Andes

144. "The Andes physics tutoring system: An experiment in freedom," K. VanLehn, B. van de Sande, R. Shelby, and S. Gershman, in **Advances in Intelligent Tutoring Systems [Studies in Computational Intelligence 308]**, edited by R. Nkambou, J. Bourdeau, and R. Mizoguchi (Springer-Verlag, Berlin, 2010), pp. 421–443

VII. ACTIVE-LEARNING INSTRUCTIONAL MATERIALS FOR INTERMEDIATE- AND ADVANCED-LEVEL PHYSICS COURSES

Material following the first reference within subsections is organized chronologically.

A. Mechanics

149. **Intermediate Mechanics Tutorials**: <http://umaine.edu/per/projects/imt/>. Contains a large collection of pretests, tutorials, exam questions, homework, and instructor's guides for a wide variety of topics in upper-level mechanics, modeled after the University of Washington's **Tutorials in Introductory Physics** (Ref. 136). (E)

150. "Investigating student understanding in intermediate mechanics: Identifying the need for a tutorial approach to instruction," B. S. Ambrose, Am. J. Phys. **72**, 453–459 (2004). Discussion of research on which **Intermediate Mechanics Tutorials** are based, along with some student-learning data that demonstrate effectiveness of some of the materials. (E)

B. Electricity and magnetism

151. **University of Colorado, Junior-level Electricity and Magnetism Course Materials**: <http://www.colorado.edu/sei/departments/physics_3310.htm>. Includes tutorials, ConcepTests (Ref. 104) for interactive lectures, homework, lecture notes, and very detailed instructor's notes. (E)

152. "Longer term impacts of transformed courses on student conceptual understanding of E&M," S. J. Pollock and S. V. Chasteen, in **2009 Physics Education Research Conference**, edited by M. Sabella, C. Henderson, and C. Singh, AIP Conference Proceedings **1179** (AIP, Melville, NY, 2009), pp. 237–240. Students in a course using research-based materials (Ref. 151) did significantly better on a diagnostic exam than students in the traditionally taught course. Also see

C. Optics

153. "Active learning in intermediate optics through concept building laboratories," M. F. Masters and T. T. Grove, Am. J. Phys. **78**, 485–491 (2010). Laboratory approach relying on direct confrontation of misconceptions through experimental tests of predictions. Materials available at <http://users.ipfw.edu/masters/Optics%20CCLI%20Project/optics_ccli_project.htm>. (E)

D. Thermal physics

154. **Physics Education Research in Thermal Physics:** <http://thermoper.wikispaces.com/>. Materials targeted at upper-level thermal physics courses; some are also useful for introductory courses. (E)

155. "Student ideas regarding entropy and the second law of thermodynamics in an introductory physics course," W. M. Christensen, D. E. Meltzer, and C. A. Ogilvie, Am. J. Phys. **77**, 907–917 (2009). Provides evidence for effectiveness of some of the materials in introductory and sophomore-level courses. (E)

156. "Student understanding of basic probability concepts in an upper-division thermal physics course," M. E. Loverude, in **2009 Physics Education Research Conference**, edited by M. Sabella, C. Henderson, and C. Singh, AIP Conference Proceedings **1179** (AIP, Melville, NY, 2009), pp. 189–192. This and the following reference provide promising, albeit ambiguous, evidence of student learning gains in upper-level courses using the thermal physics curricular materials. (E)

157. "Investigating student understanding for a statistical analysis of two thermally interacting solids," M. E. Loverude, in **2010 Physics Education Research Conference**, edited by C. Singh, M. Sabella, and S. Rebello, AIP Conference Proceedings **1289** (AIP, Melville, NY, 2010), pp. 213–216. (E)

E. Modern physics and quantum mechanics

These materials are organized chronologically. In addition to the following sources, curricular materials on modern physics and quantum mechanics are included in Volume 2 of **Activity-Based Tutorials** (Ref. 140).

158. **Physlet® Quantum Physics: An Interactive Introduction to Quantum Theory**, M. Belloni, W. Chris-

VIII. ACTIVE-LEARNING INSTRUCTIONAL MATERIALS FOR PRESERVICE TEACHERS AND NONSCIENCE STUDENTS

Materials in this section are primarily targeted at courses for nontechnical students who take physics to fulfill general-education requirements or as part of an elementary-teacher-education program. However, the materials are generally quite useful as supplements for many other types of courses as well. Subsections are organized chronologically according to most recent publication date of the first reference within each section; references within subsections are organized chronologically.

A. Physics by Inquiry

164. **Physics by Inquiry**, L. C. McDermott and the Physics Education Group at the University of Washington (Wiley, New York, 1996), Vols. I and II. Detailed activity guide that integrates quantitative and qualitative problem-solving exercises, hands-on laboratory activities, and expository text. A broad range of physical-science topics is included. Development of these

B. Constructing Physics Understanding

167. "Using computers to create constructivist learning environments: Impact on pedagogy and achievement," D. Huffman, F. Goldberg, and M. Michlin, J. Comput. Math. Sci. Teach. **22**(2), 151–168 (2003). Describes an implementation and assessment of the Constructing Physics Understanding (CPU) curriculum, targeted at nontechnical students. On-screen prompts guide students to make and test predictions with both real and simulated experiments. Description and sample activities are at <http://cpucips.sdsu.edu/web/cpu/>. (E)

C. Intuitive Quantum Physics

168. "Laboratory-tutorial activities for teaching probability," M. C. Wittmann, J. T. Morgan, and R. E. Feeley, Phys. Rev. ST Phys. Educ. Res. **2**, 020104 (2006). Documents improved student learning of some probability concepts after use of the relevant tutorial from the "Intuitive Quantum Physics" project, archived at <http://umaine.edu/per/projects/iqp/>. (E)

D. Inquiry into Physical Science

169. **Inquiry into Physical Science: A Contextual Approach, Second Edition; Vol. 1, Global Warming; Vol. 2, Kitchen Science; Vol. 3, The Automobile**, R. Nanes (Kendall Hunt, Dubuque, IA, 2008). An inquiry-based activity guide that uses everyday contexts to initiate explorations into fundamental concepts in physics and chemistry. Targeted at preservice elementary

E. Physics & Everyday Thinking

171. **Physics & Everyday Thinking**, F. Goldberg, S. Robinson, and V. Otero (It's About Time, Armonk, NY, 2008). Detailed activity guide targeted especially at prospective elementary-school teachers and other nonscience students; makes heavy use of computer-assisted tools and computer simulations. Puts strong emphasis on students expressing and reflecting on their own ideas, and explicitly comparing and contrasting their thinking with that of scientists and other students. (E)

172. "Attitudinal gains across multiple universities using the Physics and Everyday Thinking curriculum," V. K. Otero and K. E. Gray, Phys. Rev. ST Phys. Educ. Res. **4**, 020104 (2008). In surveys of 182 students in nine courses at multiple institutions that used the **Physics & Everyday Thinking** curriculum (or a variant of it), "expert-like" attitudes on the CLASS instrument (Ref. 89) showed significant increases from pre- to post-instruction. This was in striking contrast to the findings of most other courses previously surveyed with the CLASS or similar instruments. (E)

173. "Design principles for effective physics instruction: A case from physics and everyday thinking," F. Goldberg, V. Otero, and S. Robinson, Am. J. Phys. **78**, 1265–1277 (2010). Detailed description of the design principles of **Physics & Everyday Thinking** with evidence for student learning gains; includes extensive analysis of actual student classroom transcripts to illustrate the principles in action. (E)

Some common characteristics of research-based active-learning instruction (Meltzer and Thornton, 2012)

A. Instruction is informed and explicitly guided by research on student learning

- Various diagnostic instruments are used to explore and assess students’ thinking
- Curriculum development is guided and assessed by continuing research

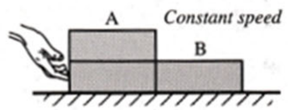
B. Specific student ideas are elicited and addressed

- A wide variety of methods has been used to draw out students' ideas and build curriculum and instruction around those ideas
- One example: University of Washington Tutorials

I. Applying Newton's laws to interacting objects: constant speed

Three identical bricks are pushed across a table at *constant speed* as shown. The hand pushes horizontally. (*Note:* There is friction between the bricks and the table.)

Call the stack of two bricks system A and the single brick system B.



A. Compare the *net force* (magnitude and direction) on system A to that on system B. Explain how you arrived at your comparison.

B. Draw separate free-body diagrams for system A and system B. Label each of the forces in your diagrams by identifying: the type of force, the object on which the force is exerted, and the object exerting the force.

Free-body diagram for system A	Free-body diagram for system B

C. Is the magnitude of the force exerted on system A by system B *greater than, less than*, or *equal to* the magnitude of the force exerted on system B by system A? Explain.

Would your answer change if the hand were pushing system B to the left instead of pushing system A to the right? If so, how? If not, why not?

D. Identify all the *Newton's third law (action-reaction)* force pairs in your diagrams by placing one or more small "×" symbols through each member of the pair (*i.e.*, mark each member of the first pair as —×→, each member of the second pair as —××→, *etc.*).

What criteria did you use to identify the force pair(s)?

Is your answer to part C consistent with your identification of Newton's third law (or action-reaction) force pairs? If so, explain how it is consistent. If not, resolve the inconsistency.

B. Draw separate free-body diagrams for system A and system B. Label each of the forces in your diagrams by identifying: the type of force, the object on which the force is exerted, and the object exerting the force.

Free-body diagram for system A

Free-body diagram for system B

C. Is the magnitude of the force exerted on system A by system B *greater than, less than*, or *equal to* the magnitude of the force exerted on system B by system A? Explain.

We know from research that students have great difficulty with Newton's third law—that the forces that A and B exert on each other are *equal* and opposite—so students are asked to state their answer explicitly *and explain their reasoning*.

Tutorials in Introductory Physics at CU-Boulder

Learning Assistant Alliance

30 subscribers

Subscribe

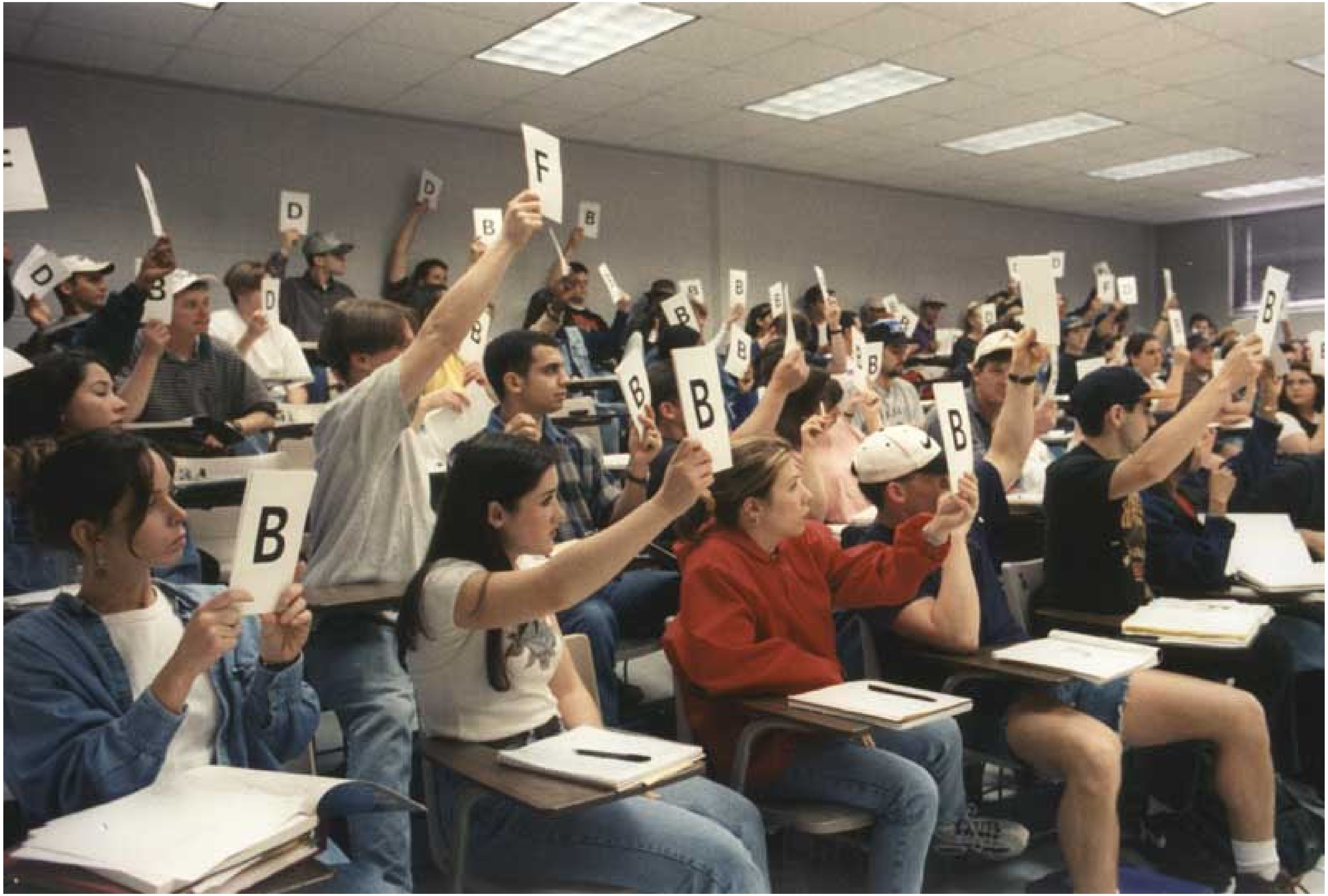
Click for YouTube video

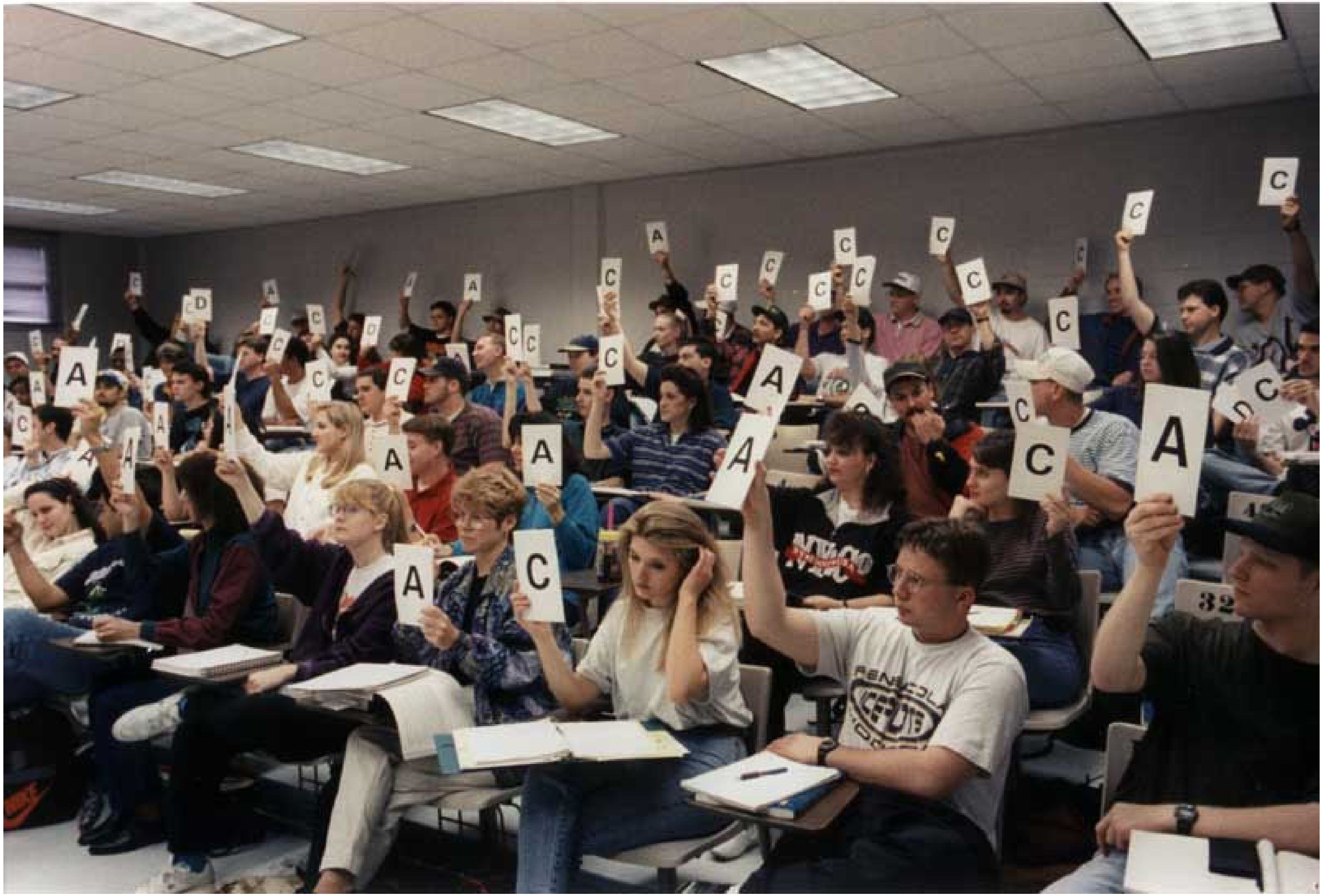
C. Students are encouraged to “figure things out for themselves”

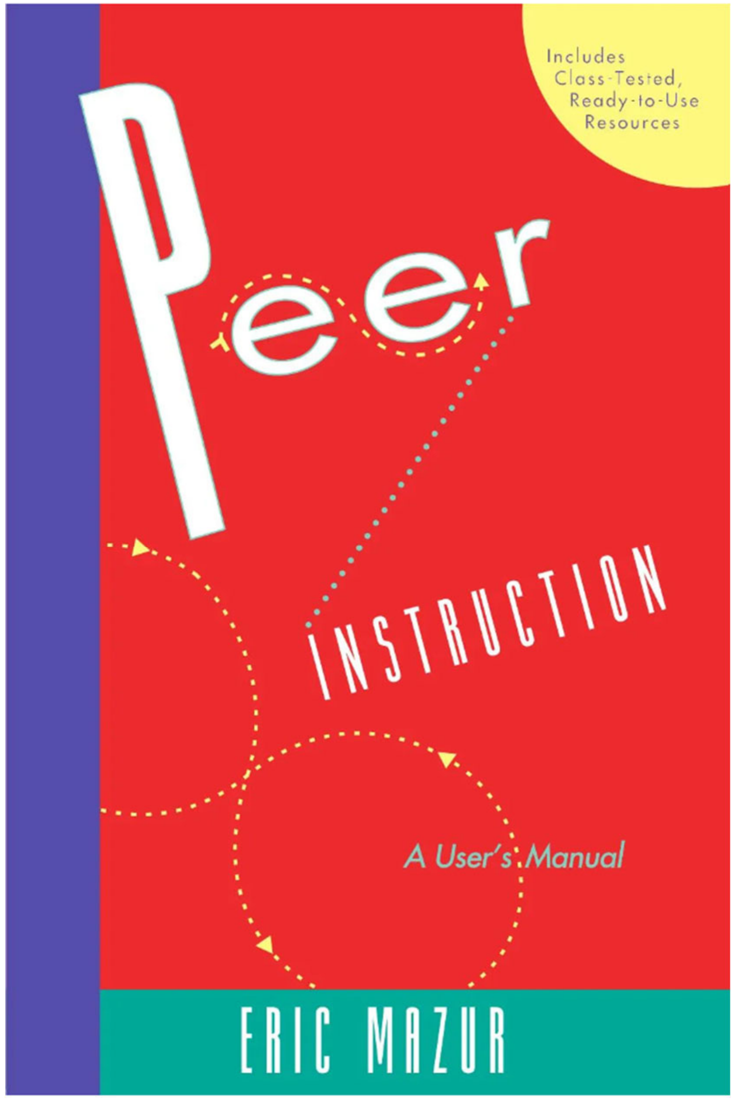
- Ask “leading questions” to guide students in a certain direction, *before* providing detailed formulations of generalized principles
- Ask students to offer predictions regarding the outcome of experiments, to debate various hypotheses, and to test them through experimentation

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

- Hands-on experiments
- Questions requiring quantitative and/or qualitative responses
- Multiple-choice conceptual questions answered with a classroom communication system

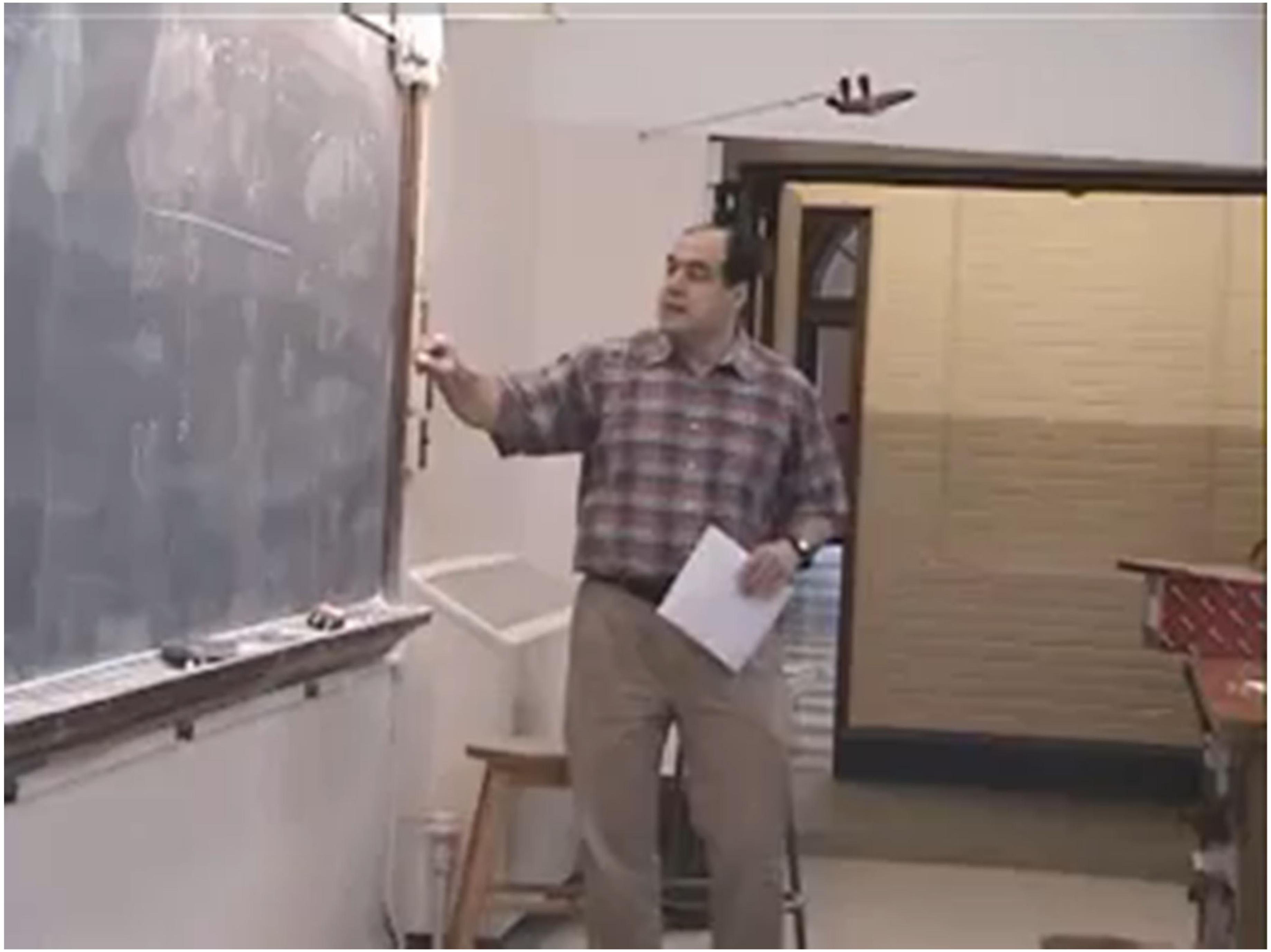






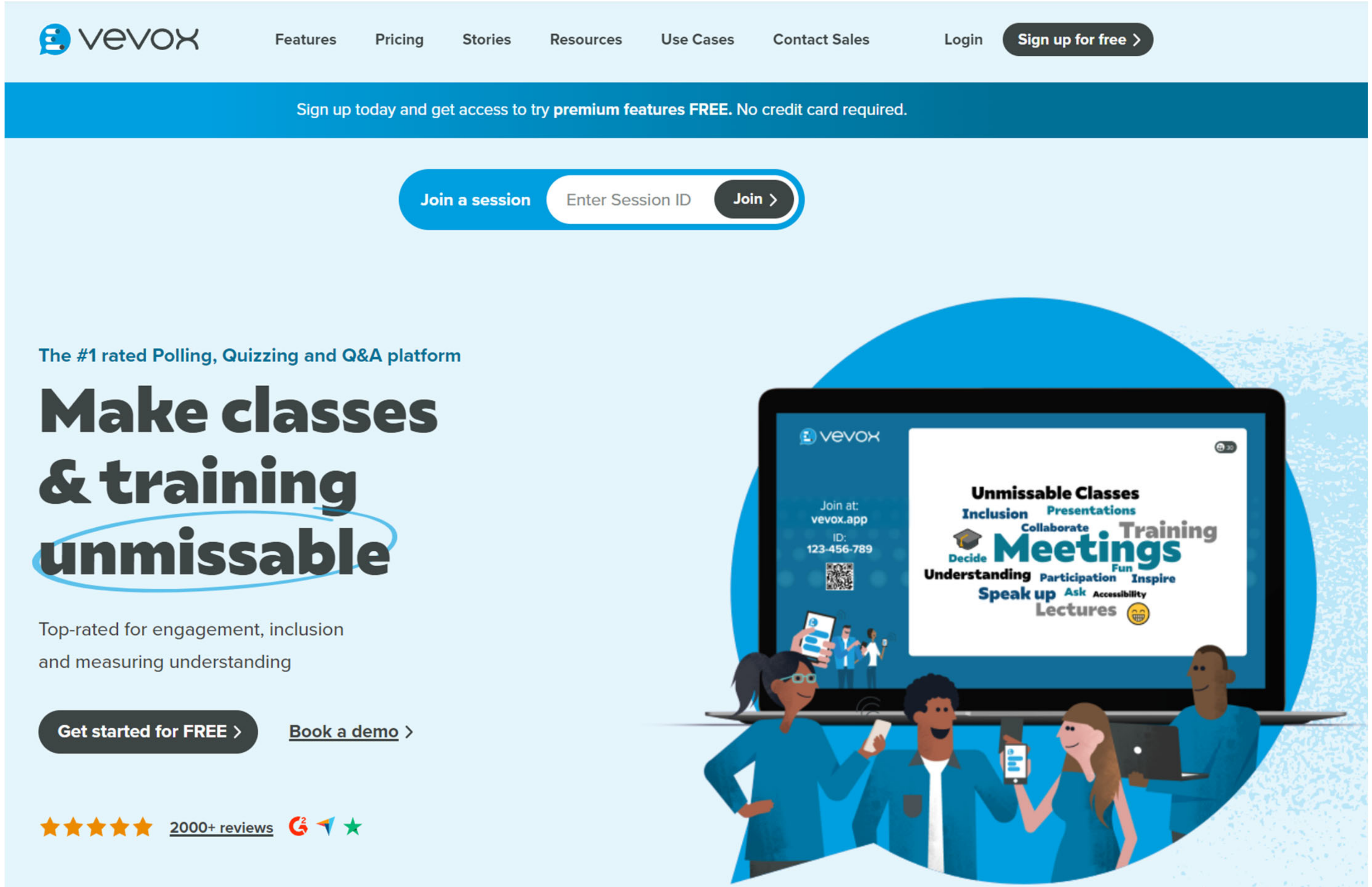
(E. Mazur, 1997)

Pioneering, extremely influential work: described method for interactive lectures accompanied by large number of conceptual, non-quantitative questions



Click for YouTube video

Free, easy-to-use classroom communication interface (students log in on phones or laptops): https://www.vevox.com/

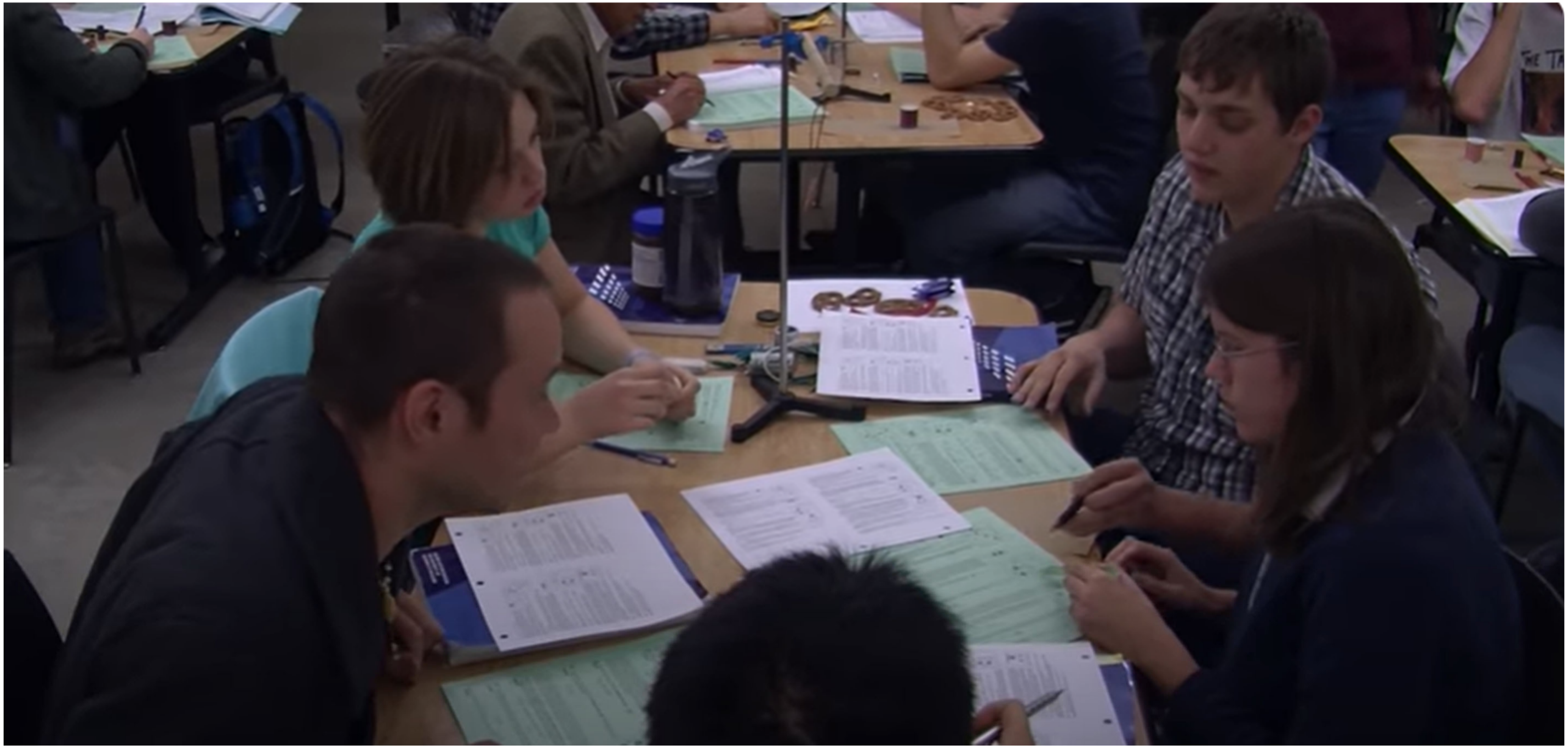


E. Students express their reasoning explicitly

- Students can express their reasoning:
  - Verbally, with instructors and other students
  - In writing (or electronically), on worksheets and homework

F. Students often work together in small groups

- Group work helps students express their own thinking, and comment on and critique each other’s thinking



Tutorial in Introductory Physics at the University of Colorado

G. Students receive *rapid* feedback

- "Rapid" may mean minute-to-minute, or even faster
- Feedback from instructors through *frequent* questions and answers
- Feedback from fellow students through small-group interactions

Tutorial in Introductory Physics at the University of Colorado

H. Qualitative reasoning and conceptual thinking is emphasized

- Non-quantitative means of problem solving are emphasized to strengthen students’ understanding of fundamental concepts

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

- Problem-solving and investigative activities are expressly designed to incorporate diagrammatic, graphical, pictorial, verbal, and other means of representing ideas and posing questions, and they are deliberately set in widely diverse physical contexts.

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

- Whenever practical, students are guided to answer questions and solve problems by engaging in hands-on activities with real objects

K. Instruction emphasizes the need to reflect on one’s own problem-solving practice

- checking results frequently during the problem-solving process;
- considering alternative solution methods;
- performing final checks of the reasonableness and consistency of results;
- searching for coherent patterns;

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

- Expert-like thinking requires both links among concepts and ready access to appropriate concepts through a well-organized hierarchical “filing system”

Millikan Lecture 1994: Understanding and teaching important scientific thought processes

Frederick Reif
Center for Innovation in Learning, and Departments of Physics & Psychology, Carnegie-Mellon University, Pittsburgh, Pennsylvania 15213

17 Am. J. Phys. **63** (1), January 1995

Disconnected, incoherent knowledge elements

Well-organized hierarchical knowledge organization

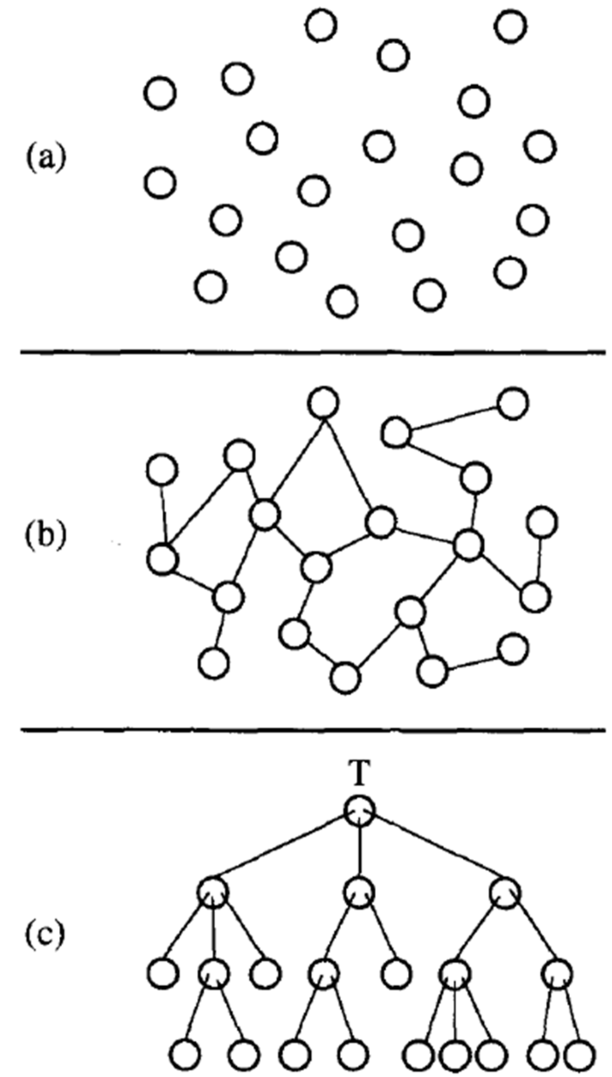
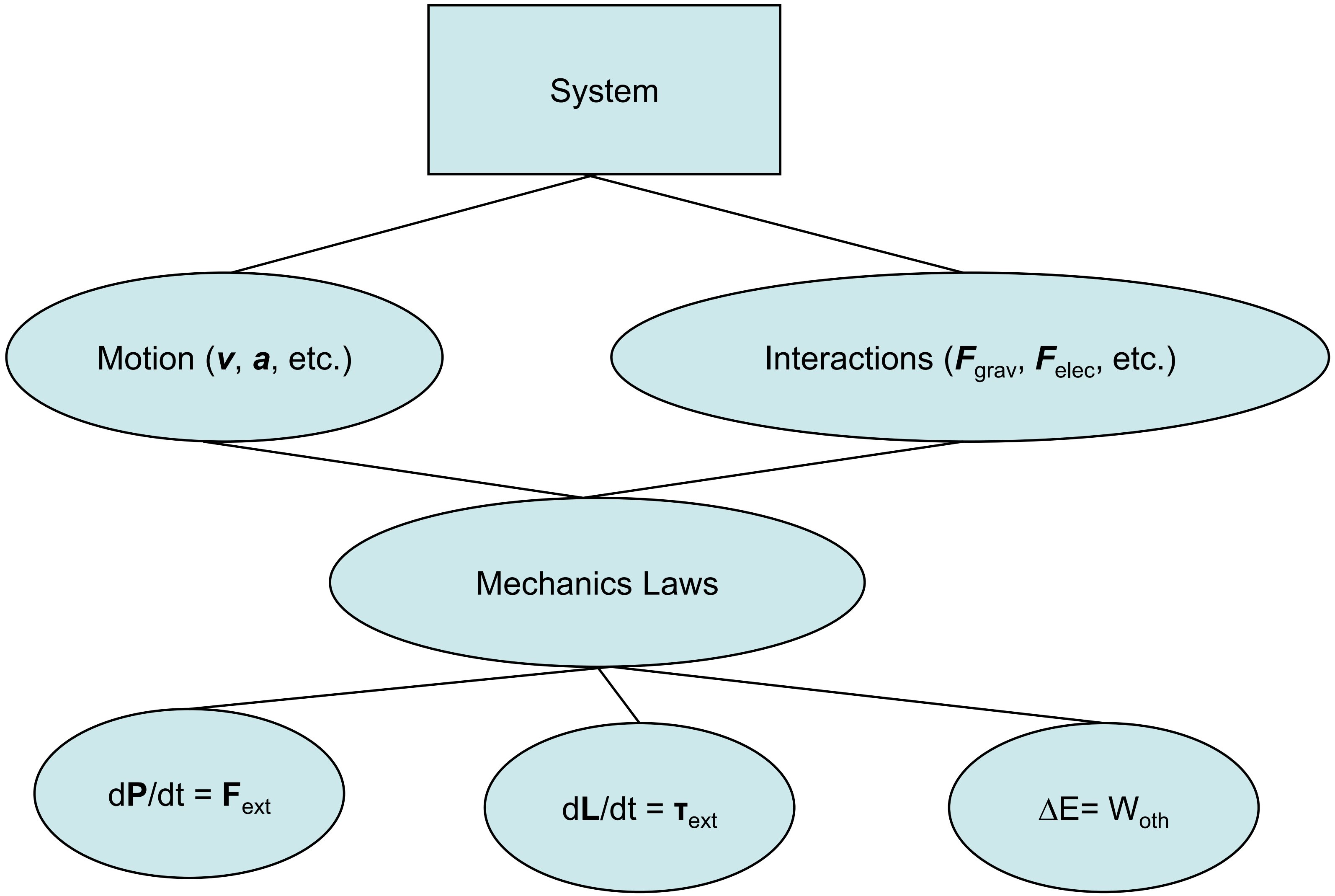


Fig. 9. Schematic representations of various knowledge organizations. (a) Incoherent knowledge consisting of largely disconnected knowledge elements. (b) Knowledge elements linked to form a network. (c) Hierarchical knowledge organization.

Example (F. Reif): Mechanics Overview



M. Instruction integrates both appropriate content and appropriate behaviors

- “Content” refers to instructional materials and activities that are explicitly guided by knowledge of students’ specific thinking patterns and learning behaviors
- “Behaviors” refer to in-class problem-solving activities based on collaborative learning and rapid feedback

Upper-level instruction: University of Colorado model

PHYSICAL REVIEW SPECIAL TOPICS - PHYSICS EDUCATION RESEARCH **8**, 020107 (2012)

Transforming the junior level: Outcomes from instruction and research in E&M

Stephanie V. Chasteen,[1] Steven J. Pollock,[1] Rachel E. Pepper,[2] and Katherine K. Perkins[1]

[1] *Science Education Initiative, Physics Department, University of Colorado at Boulder, UCB 390, Boulder, Colorado 80301, USA*

[2] *Department of Integrative Biology and Department of Civil and Environmental Engineering, University of California, Berkeley, California 94720, USA*

(Received 28 December 2011; published 29 August 2012)

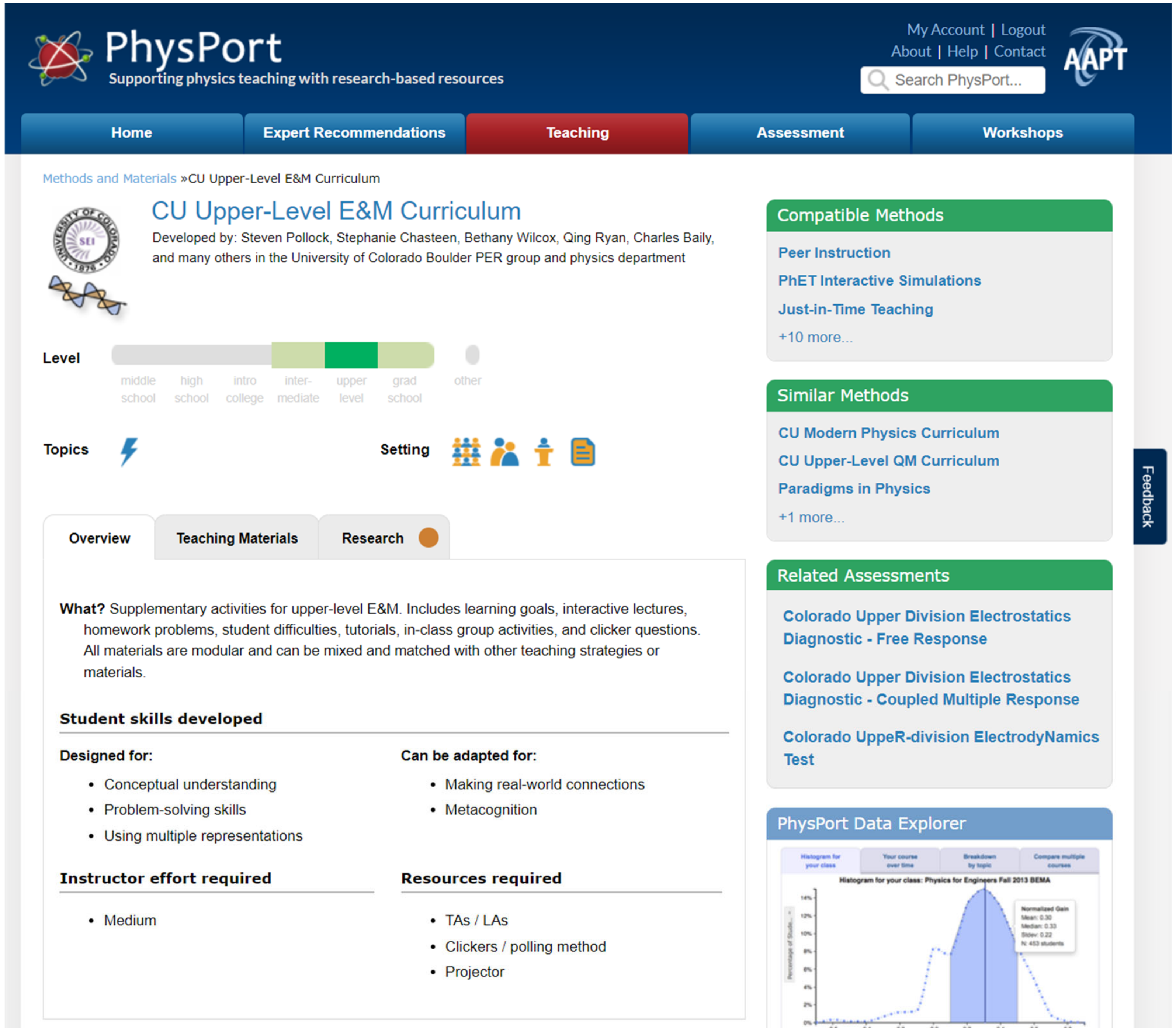
Over the course of four years, we have researched and transformed a key course in the career of an undergraduate physics major—junior-level electricity and magnetism. With the aim of educating our majors based on a more complete understanding of the cognitive and conceptual challenges of upper-division courses, we used principles of active engagement and learning theory to develop course materials and conceptual assessments. Our research results from student and faculty interviews and observations also informed our approach. We present several measures of the outcomes of this work at the University of Colorado at Boulder and external institutions. Students in the transformed courses achieved higher learning gains compared to those in the traditionally taught courses, particularly in the areas of conceptual understanding and ability to articulate their reasoning about a problem. The course transformations appear to close a gender gap, improving female students' scores on conceptual and traditional assessments so that they are more similar to those of male students. Students enthusiastically support the transformations, and indicate that several course elements provide useful scaffolding in conceptual understanding, as well as physicists' "habits of mind" such as problem-solving approaches and work habits. Despite these positive outcomes, student conceptual learning gains do not fully meet faculty expectations, suggesting that it is valuable to further investigate how the content and skills indicative of "thinking like a physicist" can be most usefully taught at the upper division.

DOI: 10.1103/PhysRevSTPER.8.020107 PACS numbers: 01.40.Di, 01.40.Fk, 01.40.G−, 01.40.gb

I. INTRODUCTION

In studying upper-division courses (primarily classical mechanics, thermodynamics, and quantum mechanics) [1,2], researchers have started to document a variety of student conceptual difficulties, allowing researchers and

determined that juniors' scores on the Basic Electricity and Magnetism Assessment (BEMA) do not improve from the freshman to the junior year, or over the course of the first semester of upper-division E&M (E&MI). Bing and Redish [8], studying upper-division students in a variety of courses, found that these students often do not use https://www.physport.org/


PhysPort
Supporting physics teaching with research-based resources
My Account | Logout
About | Help | Contact
Search PhysPort...
AAPT
Home | Expert Recommendations | Teaching | Assessment | Workshops

Methods and Materials »CU Upper-Level E&M Curriculum

CU Upper-Level E&M Curriculum

Developed by: Steven Pollock, Stephanie Chasteen, Bethany Wilcox, Qing Ryan, Charles Baily, and many others in the University of Colorado Boulder PER group and physics department

Level — middle school, high school, intro college, inter-mediate, upper level, grad school, other

Topics **Setting**

Overview | Teaching Materials | Research

What? Supplementary activities for upper-level E&M. Includes learning goals, interactive lectures, homework problems, student difficulties, tutorials, in-class group activities, and clicker questions. All materials are modular and can be mixed and matched with other teaching strategies or materials.

Student skills developed

Designed for:

- Conceptual understanding
- Problem-solving skills
- Using multiple representations

Can be adapted for:

- Making real-world connections
- Metacognition

Instructor effort required

- Medium

Resources required

- TAs / LAs
- Clickers / polling method
- Projector

Compatible Methods

- Peer Instruction
- PhET Interactive Simulations
- Just-in-Time Teaching
- +10 more...

Similar Methods

- CU Modern Physics Curriculum
- CU Upper-Level QM Curriculum
- Paradigms in Physics
- +1 more...

Related Assessments

- Colorado Upper Division Electrostatics Diagnostic - Free Response
- Colorado Upper Division Electrostatics Diagnostic - Coupled Multiple Response
- Colorado UppeR-division ElectrodyNamics Test

PhysPort Data Explorer

Feedback

Upper-level instruction: University of Colorado model

Transformation of intermediate course on Electricity and Magnetism

- Primary aspects of the transformation:
  - Instruction guided by previous research on student learning of course topics
  - Interactive elements introduced during lectures
  - Redesign of homework to emphasize qualitative elements
  - Optional weekly tutorial sessions (group work on research-based worksheets)
- Observed outcomes:
  - Improved performance on concept-focused exam
  - Equal or better performance on traditional quantitative/calculational problems

Upper-level instruction: University of Colorado model

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Research on Student Learning of E&M

- S. Chasteen, R. Pepper, M. Caballero, S. Pollock, and K. Perkins, Colorado Upper-Division Electrostatics diagnostic: A conceptual assessment for the junior level, Phys. Rev. ST Phys. Educ. Res. **8** (2), 020108 (2012).
- R. Pepper, S. Chasteen, S. Pollock, and K. Perkins, Observations on student difficulties with mathematics in upper-division electricity and magnetism, Phys. Rev. ST Phys. Educ. Res. **8** (1), 010111 (2012).
- S. Pollock and B. Wilcox, Upper-Division Students' Use of Separation of Variables, presented at the Physics Education Research Conference 2015, College Park, MD, 2015.
- C. Wallace and S. Chasteen, Upper-division students' difficulties with Ampère's law, Phys. Rev. ST Phys. Educ. Res. **6** (2), 020115 (2010).
- B. Wilcox, M. Caballero, R. Pepper, and S. Pollock, Upper-division student understanding of Coulomb's law: Difficulties with continuous charge distributions, presented at the Physics Education Research Conference 2012, Philadelphia, PA, 2012.
- B. Wilcox and S. Pollock, Upper-division student difficulties with the Dirac delta function, Phys. Rev. ST Phys. Educ. Res. **11** (1), 010108 (2015).

Upper-level instruction: University of Colorado model

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Interactive elements introduced during lectures

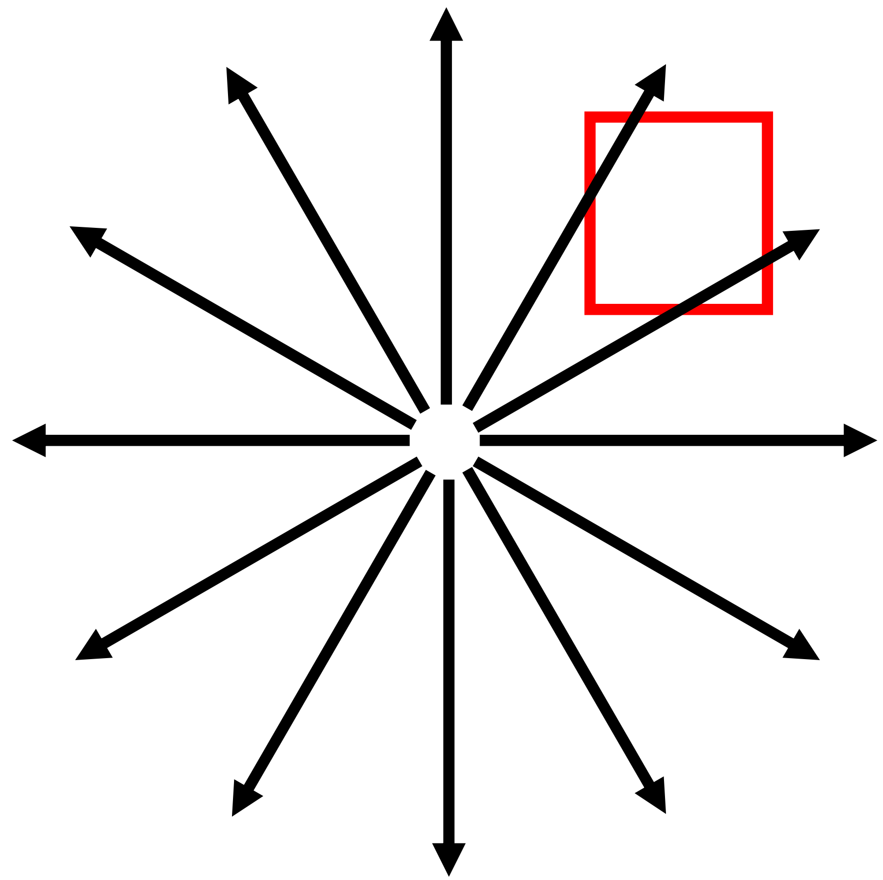
- “Clickers” [classroom communication system; students respond to instructor questions]
- Student work on small whiteboards
- Computer simulations accessed by students

Examples of “Clicker” questions

1.
5

What is the divergence of this vector field *in the boxed region?*

A) Zero
B) Not zero
C) ???



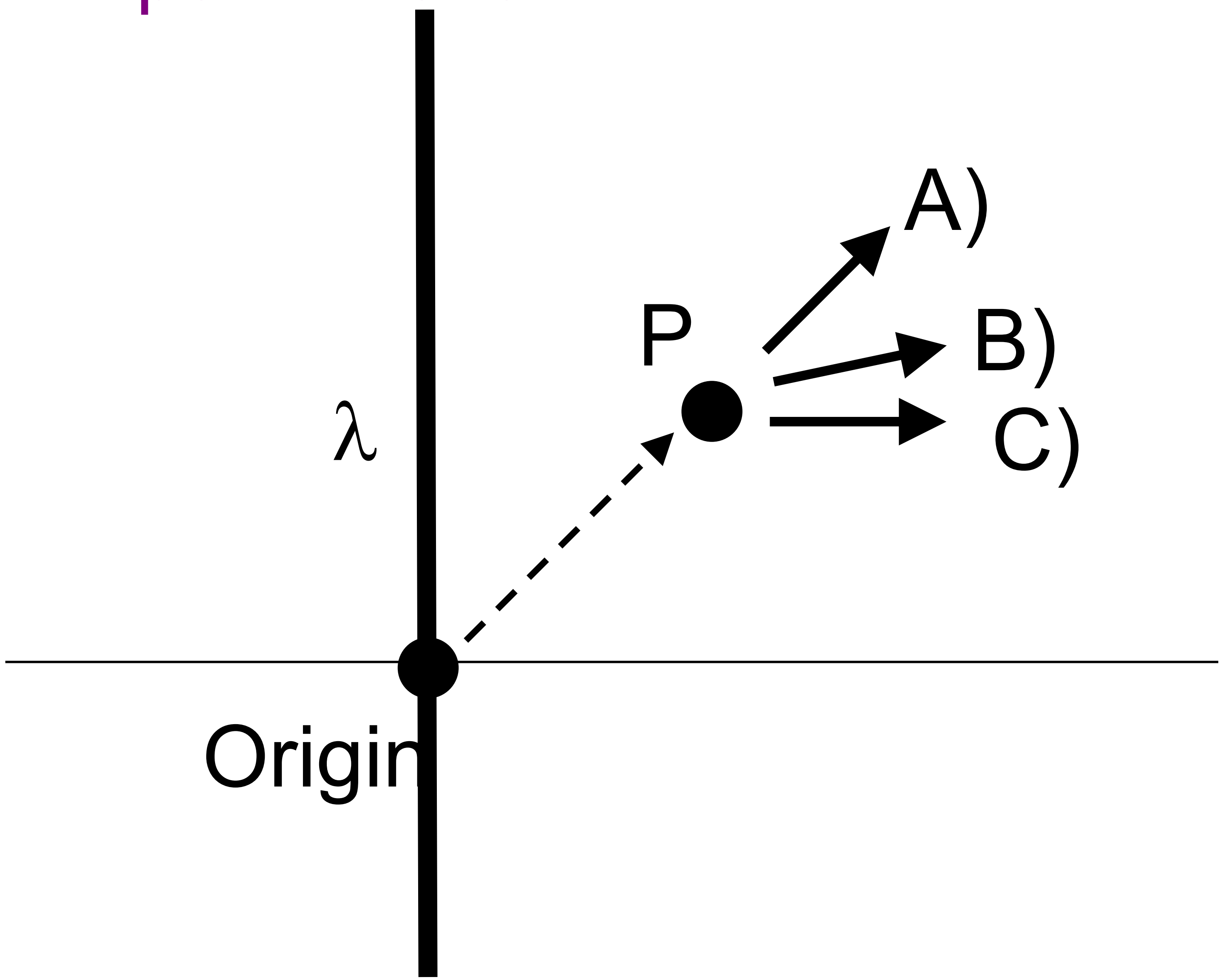
A Gaussian surface which is *not* a sphere has a single charge (q) inside it, *not* at the center. There are more charges outside. What can we say about total electric flux through this surface $\oint \vec{E} \bullet d\vec{a}$?

A) It is q/ε0

B) We know what it is, but it is NOT q/ε0

C) Need more info/details to figure it out.

2.17 An infinite rod has uniform charge density λ. What is the direction of the E field at the point P shown?



Upper-level instruction: University of Colorado model

Transformation of intermediate course on Electricity and Magnetism

- Primary aspects of the transformation:
  - Instruction guided by previous research on student learning of course topics
  - Interactive elements introduced during lectures
  - **Redesign of homework to emphasize qualitative elements**
  - Optional weekly tutorial sessions (group work on research-based worksheets)
- Observed outcomes:
  - Improved performance on concept-focused exam
  - Equal or better performance on traditional quantitative/calculational problems

Redesign of homework assignments:
Emphasize qualitative elements

- sketching diagrams
- plotting graphs
- describing mathematical solutions in words
- explaining reasoning

Upper-level instruction: University of Colorado model

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  - Instruction guided by previous research on student learning of course topics
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  - Redesign of homework to emphasize qualitative elements
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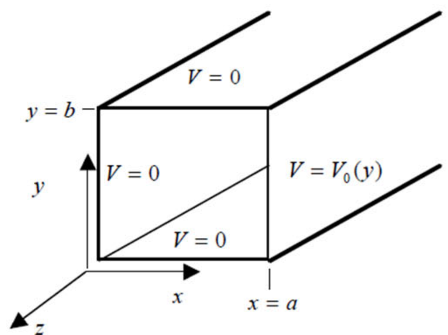
★TUTORIAL 5b: BREAKING DOWN THE STEPS ★
SEPARATION OF VARIABLES

Part 1: Laplace's Equation and Separation of Variables

Within a very long, rectangular, hollow pipe, there are no electric charges. The walls of this pipe are kept at a known voltage (they are known because in a lab, you can control them).
Three of the walls are grounded: $V(x=0,y,z)=0$; $V(x,y=0,z)=0$; $V(x,y=b,z)=0$
The fourth wall maintains a potential that varies with y: $V(x=a,y,z)=V_o(y)$ which will be specified later.



In order to find out the voltage inside the pipe, you will need to solve Laplace's equation:

$$\nabla^2 V = \frac{\partial^2 V}{\partial x^2} + \frac{\partial^2 V}{\partial y^2} + \frac{\partial^2 V}{\partial z^2} = 0$$

i. What does it mean to "separate variables" of $V(x,y,z)$. What advantage is there to using that approach here?

In-Class TUTORIAL 5b – SEPARATION OF VARIABLES

ii. Plug the separated form of V into Laplace's equation. After doing this, you should have several terms.
   - Simplify as much as possible.
   - Are any of the terms zero in this case?
   - What must be true about the remaining terms in order to satisfy Laplace's equation?
   - Write down the ordinary differential equations you need to solve to find V.

iii. The boundary conditions on the pipe are listed below. Which boundary condition(s) allow you to determine the direction (x or y) that must have sinusoidal behavior?

1. $V(x,y=0,z)=0$
2. $V(x,y=b,z)=0$
3. $V(x=0,y,z)=0$
4. $V(x=a,y,z)=V_o$

Write down and modify your general expression for the voltage everywhere inside the pipe so that it satisfies the first three boundary conditions. **Do *not* apply the 4th boundary condition yet**.

Upper-level instruction: University of Colorado model

Transformation of intermediate course on Electricity and Magnetism

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  - Interactive elements introduced during lectures
  - Redesign of homework to emphasize qualitative elements
  - Optional weekly tutorial sessions (group work on research-based worksheets)
- Observed outcomes:
  - **Improved performance on concept-focused exam**
  - Equal or better performance on traditional quantitative/calculational problems

Improved performance on concept-focused exam

Scores on concept-focused posttest:

- Students in standard courses: 44% ±1.6%
- Students in transformed courses: 57% ±1.3%

Upper-level instruction: University of Colorado model

Transformation of intermediate course on Electricity and Magnetism

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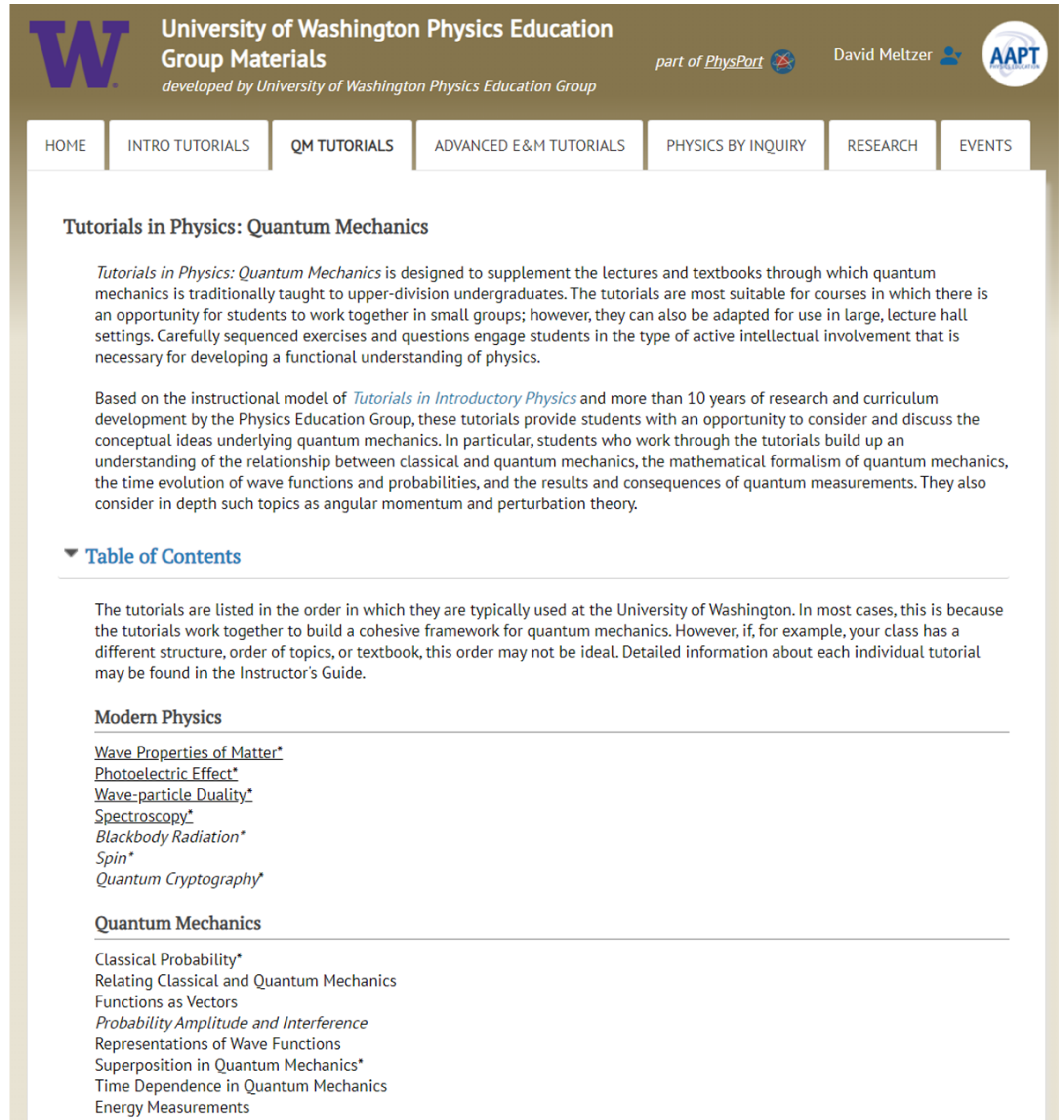
  - Redesign of homework to emphasize qualitative elements
  - Optional weekly tutorial sessions (group work on research-based worksheets)
- Observed outcomes:
  - Improved performance on concept-focused exam
  - **Equal or better performance on traditional quantitative/calculational problems**

Upper-level instruction: University of Colorado model: Other observations

- Both high-performing “A” students and low-performing “C” and “D” students had higher assessment scores in the transformed course
- Students rated tutorials and clicker questions as both enjoyable *and* useful for learning
- Instructors found both tutorials and clicker questions useful in gaining insight into student difficulties, and enjoyable to use

Other models for active learning in upper-level instruction

[Extension of University of Washington Tutorials to upper-level instruction in quantum mechanics and electricity and magnetism]


University of Washington Physics Education Group Materials

developed by University of Washington Physics Education Group

part of PhysPort

David Meltzer

HOME | INTRO TUTORIALS | QM TUTORIALS | ADVANCED E&M TUTORIALS | PHYSICS BY INQUIRY | RESEARCH | EVENTS

Tutorials in Physics: Quantum Mechanics

Tutorials in Physics: Quantum Mechanics is designed to supplement the lectures and textbooks through which quantum mechanics is traditionally taught to upper-division undergraduates. The tutorials are most suitable for courses in which there is an opportunity for students to work together in small groups; however, they can also be adapted for use in large, lecture hall settings. Carefully sequenced exercises and questions engage students in the type of active intellectual involvement that is necessary for developing a functional understanding of physics.

Based on the instructional model of *Tutorials in Introductory Physics* and more than 10 years of research and curriculum development by the Physics Education Group, these tutorials provide students with an opportunity to consider and discuss the conceptual ideas underlying quantum mechanics. In particular, students who work through the tutorials build up an understanding of the relationship between classical and quantum mechanics, the mathematical formalism of quantum mechanics, the time evolution of wave functions and probabilities, and the results and consequences of quantum measurements. They also consider in depth such topics as angular momentum and perturbation theory.

Table of Contents

The tutorials are listed in the order in which they are typically used at the University of Washington. In most cases, this is because the tutorials work together to build a cohesive framework for quantum mechanics. However, if, for example, your class has a different structure, order of topics, or textbook, this order may not be ideal. Detailed information about each individual tutorial may be found in the Instructor's Guide.

Modern Physics

Wave Properties of Matter*
Photoelectric Effect*
Wave-particle Duality*
Spectroscopy*
*Blackbody Radiation**
*Spin**
*Quantum Cryptography**

Quantum Mechanics

Classical Probability*
Relating Classical and Quantum Mechanics
Functions as Vectors
Probability Amplitude and Interference
Representations of Wave Functions
Superposition in Quantum Mechanics*
Time Dependence in Quantum Mechanics
Energy Measurements

Other models for active learning in upper-level instruction

“Paradigms in Physics”
(Oregon State University)
https://paradigms.oregonstate.edu/

PHYSICAL REVIEW PHYSICS EDUCATION RESEARCH **16,** 020156 (2020)

Research-based quantum instruction: Paradigms and Tutorials

Paul J. Emigh,[1,*] Elizabeth Gire,[1] Corinne A. Manogue,[1]
Gina Passante,[2] and Peter S. Shaffer[3]
[1]*Department of Physics, Oregon State University, Corvallis, Oregon 97331-6507, USA*
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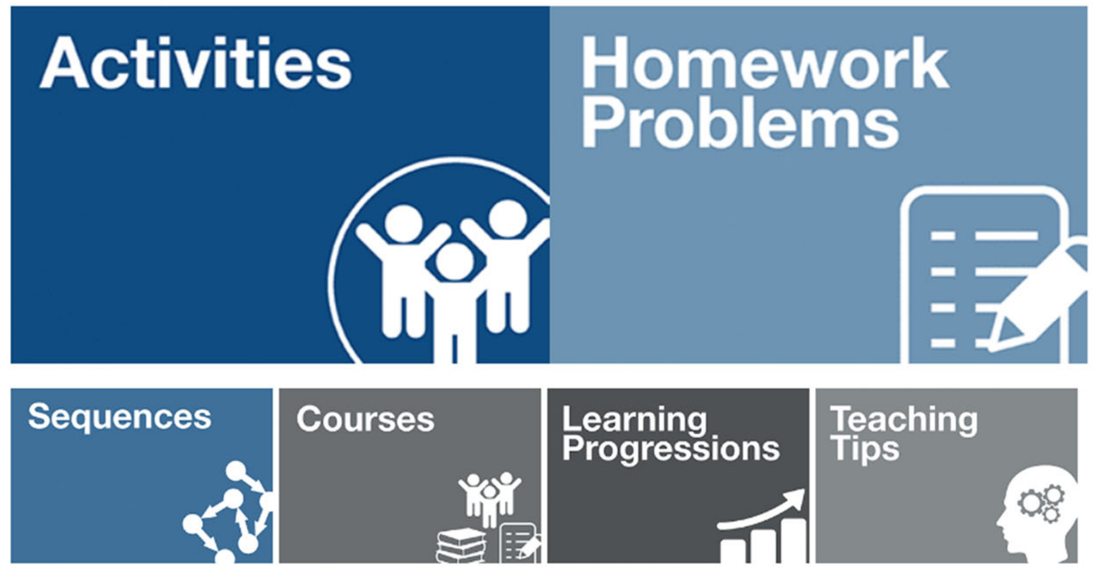
(Received 9 July 2019; accepted 13 December 2019; published 4 December 2020)

A growing body of research-based instructional materials for quantum mechanics has been developed in recent years. Despite a common grounding in the research literature on student ideas about quantum

Welcome to the Paradigms in Physics curricular materials website!

This site is under construction, and currently the easiest way to find activities and problems is with the search bar on the upper right.



Visit our OSU PER group website for more information about related research.

Featured Searches:

quantum | angular momentum | spin | arms | kinesthetic | "Raising Physics to the Surface"

Other models for active learning in upper-level instruction

|P⟩⟨P| Paradigms @ OSU   Activities   Whitepapers   About   Account

“Paradigms in Physics”
(Oregon State University)
https://paradigms.oregonstate.edu/

Upper-Division Pedagogies

How to use Small Whiteboard Questions

Our favorite examples:

- Dot Product Review

How to use Small Group Activities

Our favorite examples:

- Plane Waves Activity

How to use Compare and Contrast Activities

Our favorite examples:

- Plane Waves Activity (Great for Professional Development Workshops)
- Systems of Equations (High School Algebra)

How to use Kinesthetic Activities

Our favorite examples:

- Complex Numbers with Arms
- Quantum Measurement Play

How to Use Small Group Activities with Surfaces (Raising Physics to the Surface Project)

Our favorite examples:

- Changes in Internal Energy handout guide
- Covariation in Thermal Systems handout guide

Graduate-level instruction:

Graduate-level instruction: Ohio State University model

Graduate-level instruction: Ohio State University model

PHYSICAL REVIEW PHYSICS EDUCATION RESEARCH **16,** 020127 (2020)

Effectiveness of guided group work in graduate level quantum mechanics

C. D. Porter and A. F. Heckler

Department of Physics, The Ohio State University, 191 West Woodruff Avenue, Columbus, Ohio 43210, USA

(Received 22 May 2020; accepted 3 September 2020; published 23 October 2020)

We investigate the effects of guided group work sessions on graduate student performance on a quantum mechanics assessment. Data from a single large Midwestern university were taken over a five-year period, during which guided group work sessions were offered to accompany the graduate-level quantum mechanics course. Students were pre- and post-tested using a set of mostly conceptual items that we call the graduate quantum mechanics assessment. The reliability and validity of this assessment are addressed. A mixed linear model is used to analyze the dependence of post-test scores on factors such as group work attendance, pretest scores, GRE Physics scores, and others. We find a statistically significant effect of group work attendance on post-pre gains, specifically that attendance of one 60-min group work session improves performance on a related post-test item by 6.4%, administered 2–10 weeks after the session. We discuss the lack of a randomized control group and address possible confounding effects such as student self-selection, and attitudinal and motivational factors. Overall, the results of this study indicate that guided group work sessions at the graduate level can be feasible and effective. We note preliminary observations of differences in group interactions and classroom logistics compared to group work at the undergraduate level.

DOI: 10.1103/PhysRevPhysEducRes.16.020127

I. INTRODUCTION

According to a 2008 report by the Council of Graduate Schools [1] the 10-year completion rate for students enrolling in a U.S. physics Ph.D. program is 55%. The rate is lower still (37%) for African American students. The

the tone for the students' experiences in the department and in the field of physics. At OSU, core course GPAs are used in lieu of a qualifying exam, and thus have great significance for students' progression toward a Ph.D. At OSU, physics graduate students with GPAs below 3.3 after their first attempt at core courses (they may be repeated) are https://www.physport.org/

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Curricula »Guided group work for graduate core courses

Guided group work for graduate core courses

developed by Christopher D. Porter, Taylor Murphy, Humberto Gilmer, and Andrew Heckler

The PER team at The Ohio State University (OSU) developed guided group material for common graduate-level core courses: Classical Mechanics, Statistical Mechanics, Quantum Mechanics, and Electricity and Magnetism. The development process began with classroom observations, both at OSU and at collaborating institutions. We then used a combination of open-ended interviews, and think-aloud interviews with draft material to identify key areas of student difficulty. These materials were implemented in group work sessions for OSU physics graduate students and materials were iterated for 3-6 years (depending on the OSU course). Questions, short keys for students, and full worked solutions for instructors are available.

In some cases, materials take the form of scaffolded, single-topic lessons that might rightly be called a tutorial. This is particularly true of most of the materials in statistical mechanics. In other cases, we have needed to work to accommodate multiple topics presented by a lecturer in a given week, such that "tutorial" is not quite appropriate. We have general implementation notes, but not individual item notes.

The quantum mechanics materials and their effectiveness at increasing students' performance on a conceptual assessment of quantum mechanics were the subject of a peer-reviewed paper here.

- General Implementation Notes
- Classical Mechanics
- Electricity and Magnetism
- Quantum Mechanics
- Statistical Mechanics

These materials arose as part of OSU's APS Bridge Program with support from the departmental teaching funds. Early work was partially supported by OSU's Center for Emergent Materials, an NSF MRSEC (award number **DMR-2011876**). The bulk of this development was supported by the NSF Innovations in Graduate Education NRT award (award number **1735027**).

Feedback

Graduate-level instruction: Ohio State University model

Transformation of graduate courses for Ph.D. students

- Primary aspects of the transformation of the quantum mechanics course:
  - About 30% of enrolled students attended optional weekly “Guided Group Work” (GGW) sessions
  - Group work consisted of questions ranging from conceptual to calculational
  - Some sessions strongly guided with printed tutorials; other present problems to solve
  - Group work problems, questions, and tutorials are based in part on research on student learning

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  - Student performance on assessments was positively correlated with number of sessions attended
  - Both low-performing and high-performing students benefitted from the group work sessions

7501 Tutorial 8 **Mon. 11-8-21**

Spin, expectation values, uncertainty, and time-evolution (as always, just pick the stuff that looks interesting)

Concepts:

1.) Three friends are working on a spin problem in which an initial state is given as

$$|\psi_i\rangle = \frac{4}{5}|+\rangle_x + \frac{3}{5}|-\rangle_x = \frac{4}{5\sqrt{2}}\begin{pmatrix}1\\1\end{pmatrix} + \frac{3}{5\sqrt{2}}\begin{pmatrix}1\\-1\end{pmatrix} = \begin{pmatrix}7/5\sqrt{2}\\1/5\sqrt{2}\end{pmatrix}.$$

Friend A says, "This state is written in the x-basis." Friend B says, "No, it is written in the z-basis." Help them reconcile their differences.

2.) Two friends are preparing spin states. Friend A is in one room and prepares a beam of particles in the state $|+\rangle_x = \frac{1}{\sqrt{2}}\begin{pmatrix}1\\1\end{pmatrix}$. Friend B is in a different room and prepares a different beam in a 50-50 mixture of the two states $|+\rangle_z = \begin{pmatrix}1\\0\end{pmatrix}$ and $|-\rangle_z = \begin{pmatrix}0\\1\end{pmatrix}$. Friends A and B disagree about whether these two beams are the same thing. One says that those cases are different, both experimentally and mathematically, and the other says they are the same, both experimentally and mathematically. What do you think? Can you offer the incorrect friend a really convincing argument?

3.) Consider the operator

$\hat{S}_{\hat{n}} = \hat{\vec{S}}\cdot\hat{n} = \hat{\vec{S}}\cdot(\sin(\theta)\cos(\phi), \sin(\theta)\sin(\phi), \cos(\theta))$.

(a) Give a physical interpretation of this operator.

(b) What are this operator's eigenvalues, for the case of spin-1/2 particles? It is good to check this, explicitly, but it is also great if you can answer this using intuition.

4.) Consider the state $\frac{1}{\sqrt{13}}\begin{pmatrix}2\\3i\end{pmatrix}$.

(a) What is the physical interpretation of this state? Discuss possible measurements and probabilities if it is helpful

(b) Can you actually create this experimentally, in the lab? If so, explain how (at least qualitatively). If not, explain why we use such objects in physics courses. You can use that the eigenstates of

$\hat{S}_{\hat{n}} = \hat{\vec{S}}\cdot\hat{n} = \hat{\vec{S}}\cdot(\sin(\theta)\cos(\phi), \sin(\theta)\sin(\phi), \cos(\theta))$

are

$|+n\rangle = \cos(\theta/2)|\uparrow\rangle + \sin(\theta/2)e^{i\phi}|\downarrow\rangle$

$|-n\rangle = \sin(\theta/2)|\uparrow\rangle - \cos(\theta/2)e^{i\phi}|\downarrow\rangle$

Spin calcs:

5.) Explain how you can experimentally produce a state $|\psi\rangle = \frac{1}{3\sqrt{3}}\begin{pmatrix}1+i\\5\end{pmatrix}$.

6.) Immediately after producing the state above, what is the probability that a measurement of the spin projection on the z axis will yield $+\hbar/2$?

TABLE I. Some topics emphasized in guided group work sessions and an example question for each topic. This is not an exhaustive list of topics or questions related to these topics.

Topic	Example group work item
Wave functions	In the square well below <finite potential well shown>, qualitatively sketch: (a) The ground state ($n = 1$), (b) the 2nd excited state ($n = 3$), and (c) the 5th excited state ($n = 6$), assuming all these states exist. Compare with your neighbor and resolve any differences.
Math or linear algebra	You are working on a quantum mechanics problem with a friend, and the problem involves an operator $\hat{\Omega}$. You are very pleased with your choice of basis, in which the matrix corresponding to $\hat{\Omega}$ is diagonal: $$\hat{\Omega} = c\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 2 & 0 \\ 0 & 0 & 0 & 4 \end{pmatrix}.$$ (a) Find a way of representing your basis states $\|1a\rangle, \|1b\rangle, \|2\rangle, \|4\rangle$. (b) Your friend insists he has used a different basis than you, but he also has a diagonal matrix. How is this possible? Convince your skeptical friend.
Expectation values	Without doing a direct calculation, explain to your partner which values of n yield nonzero results in the following expressions in the context of a quantum harmonic oscillator: (a) $\langle n\|\hat{x}^2\|0\rangle$, (b) $\langle 3\|\hat{x}^3\|n\rangle$, (c) $\langle n\|\hat{p}\|0\rangle$.
Operators vs eigenvalues	When can we make the replacement $e^{-i\hat{H}t/\hbar} \rightarrow e^{-iEt/\hbar}$? Explain this to your neighbor.
Spin	Explain how you can experimentally produce a spin state $\|\Psi\rangle = \frac{1}{3\sqrt{3}}\binom{1+i}{5}$.

Graduate-level instruction: Ohio State University model

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PHYSICAL REVIEW PHYSICS EDUCATION RESEARCH **15,** 010139 (2019)

Graduate student misunderstandings of wave functions in an asymmetric well

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(Received 20 August 2018; published 11 June 2019)

Quantum mechanics is a notoriously counterintuitive subject within physics and has been the subject of a number of studies at the undergraduate level, and a few pioneering studies at the graduate level. The sketching of wave functions in a confining well is in one sense one of the most basic activities in quantum mechanics. But in another sense, it may be viewed as a rather advanced skill, as it requires the coherent inclusion of a number of details of the wave function, such as wavelength, probability amplitude, and boundary conditions, among others. Although sketching a wave function is not a common activity at the

2016 PERC Proceedings, edited by Jones, Ding, and Traxler; Peer-reviewed, doi:10.1119/perc.2016.pr.056

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Student understanding of potential, wavefunctions and the Jacobian in hydrogen in graduate-level quantum mechanics

C. D. Porter, A. Bogdan and A. F. Heckler
Dept. of Physics, The Ohio State University, 191 West Woodruff Ave, Columbus, OH 43210

Abstract: This study examined student difficulties related to the potential in the hydrogen atom, and the corresponding ground state, with special attention paid to the role of the Jacobian. The study focused on a population of graduate students at The Ohio State University, and their ability to (1) sketch the approximate

2022 PERC Proceedings edited by Frank, Jones, and Ryan; Peer-reviewed, doi.org/10.1119/perc.2022.pr.Heckler

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Graduate student understanding of quantum mechanical spin

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A framework of cyclic observation and triangulation was applied over a period of 4 years to graduate student difficulties related to quantum spin, in which numerous in-class observations and interviews were used to identify common, persistent difficulties. Written items were iteratively developed over two years to add a quantitative component. Items were administered to graduate students at two collaborating institutions, over three years. We find that students generally obtained scores or correct proportions ranging from 30%-70% on the written items, and answering patterns were similar across all institutions. All items were identified by the course instructors as being relevant to instructional goals of the course. We report on a number of graduate student difficulties with spin, including orthogonality of spin-1/2 states, projections of spin states, spin addition, and exchange symmetry. We briefly discuss possible theoretical frameworks through which to interpret these results.

Graduate-level instruction: Ohio State University model

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Summary

- Research-based active-learning in physics incorporates an *extremely wide range* of diverse instructional methods, curricular materials, and classroom contexts.
- Common characteristics include a basis in research on student learning, student activities and speaking during class time, and rapid feedback.
- Multiple measures demonstrate the effectiveness of this form of instruction in improving student learning.
- Each instructor must determine how best to adapt this form of instruction to their own students, classroom context, and personal instructional style.