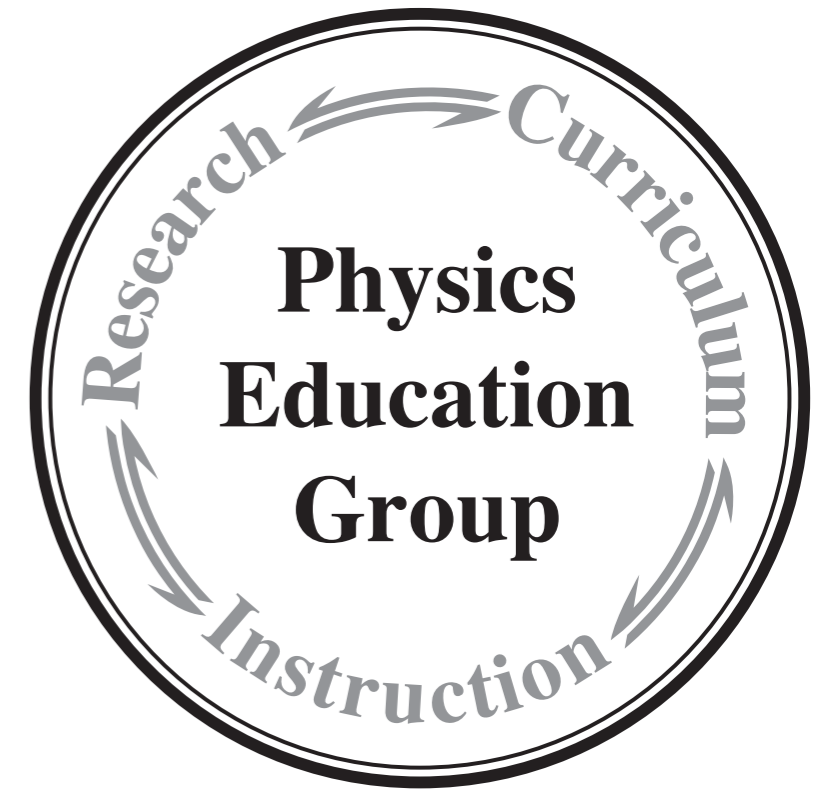


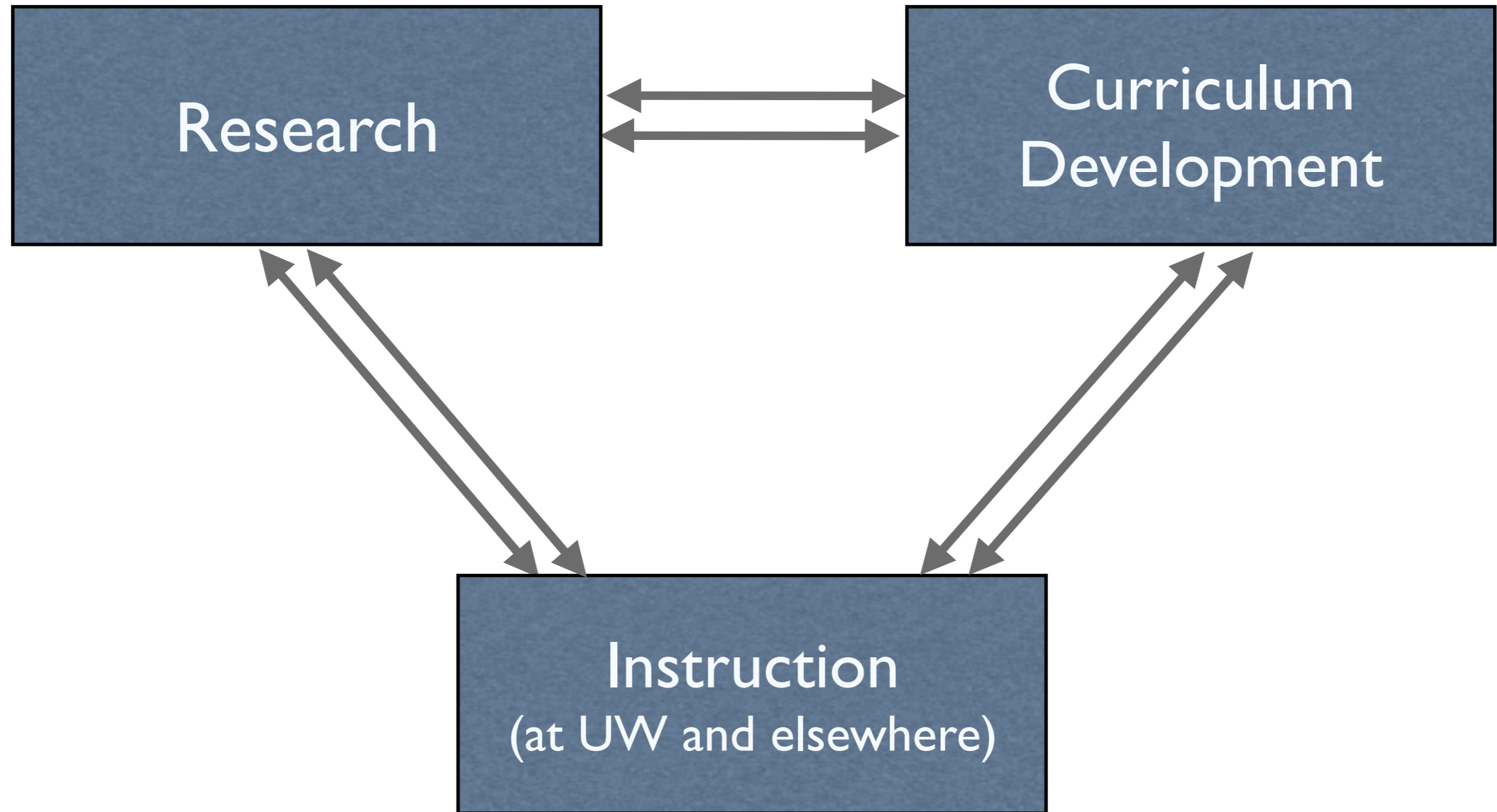
The development of research-based and research-validated curriculum:



**Peter S. Shaffer, Lillian C. McDermott
Paula R.L. Heron
and the Physics Education Group**

**Department of Physics
University of Washington
Seattle, WA**

Reflections on 30+ years of research, curriculum development, and instruction



Our coordinated program of research, curriculum development, and instruction is supported in part by grants from the National Science Foundation.

Timeline

Early 1970's	<i>Arnold Arons joins UW faculty (from Amherst College)</i>
	Preservice Course for Elementary Teachers (Arons, Lillian C. McDermott, Pat Autry [Heller])
	Summer Institute for Inservice Elementary Teachers (Arons/McDermott) Preservice Course for High School Teachers (McDermott)
1973	<i>Lillian C. McDermott appointed Assistant Prof. at UW</i>
mid-late 1970's	Course for underprepared students aspiring to science-related careers Summer Institute extended to be K-12
1979	David Trowbridge - First Ph.D. for research in physics education at UW (McDermott)
1991	Curriculum development extended to introductory physics courses
Early 2000's	Curriculum development extended to upper-division physics courses
2008	The group has grown to include three full professors each promoted on basis of research in physics education

Physics Education Group at the University of Washington

Faculty

- Lillian C. McDermott
- Paula Heron
- Peter Shaffer
- MacKenzie Stetzer

Lecturers and Post-docs

- Andrew Crouse
- Donna Messina

Visiting Scholar

- David Meltzer

Physics Ph.D. Candidates

- Isaac Leinweber
- Amy Robertson
- Brian Stephanik

Research/Teacher Education Coordinators

- Karen Wosilait
- Nina Tosti

Former Graduate Students

- Mila Kryjevskaja, 2008, North Dakota State
- Beth Lindsey, 2008, Georgetown
- Andrew Crouse, 2007, University of Washington
- Matthew Cochran, 2005, Kauai Community College
- Hunter Close, 2005, Seattle Public Schools
- Andrew Boudreaux, 2002, Western Washington University
- Luanna Ortiz, 2001, Buffalo State College
- Rachel Scherr, 2001, University of Maryland
- Christian Kautz, 1999, Hamburg University of Technology
- Stephen Kanim, 1999, New Mexico State University
- Michael Loverude, 1999, California State University, Fullerton
- Bradley Ambrose, 1999, Grand Valley State University
- Tara O'Brien Pride, 1997, Self-employed
- Pamela Kraus, 1997, FACET Innovations, Seattle
- Karen Wosilait, 1996, University of Washington
- Randall Harrington, 1995, The Blake School (Hopkins, MN)
- Peter Shaffer, 1993, University of Washington
- Diane Grayson, 1990, Self-employed
- Ronald Lawson, 1984, Shell Oil
- James Evans, 1983, University of Puget Sound
- Mark Rosenquist, 1982, Shell Oil
- David Trowbridge, 1979, Microsoft Corporation

Former PEG members and special colleagues

Post-docs

- Herb Lin
- Mark Somers
- Greg Francis
- Richard Steinberg
- Stamatis Vokos
- Mel Sabella
- John Thompson
- Elaine Fu
- Lesley Low
- Romana Crnkovic
- Homeyra Sadaghiani

Special UW colleagues

- Arnold Arons
- Pat Heller
- Mark McDermott
- Daryl Pedigo

M.S. Students

- Brian Popp
- Nelson Spickard
- Judy Wild
- Betty Ayres
- Davene Eyres
- Heidi Mauk-Gruner
- Ralph Minor
- Randol Meyer
- Kirk Haffner
- Lenore Hernandez
- Eleanor Close
- Matt Hahn
- Chris Border
- Sean Courtney
- Julie Crockett
- ...

Long-term faculty visitors and others (US)

- Patty Chastain
- Lezlie S. DeWater
- Dean Gaily
- Michael Gearen
- Gary Gladding
- Fred Goldberg
- Bill Moore
- Robert Morse
- Graham Oberem
- Joe Redish
- Chuck Robertson
- Ed Taylor
- Emily van Zee
- Betty Windham
- ...

Long-term foreign visitors

- Malcolm Bowling
- Costas Constantinou
- See Kit Foong
- Uri Ganiel
- Eunsook Kim
- Chor Yam Lau
- Paul Lee
- Brian McInnes
- Merlyn Mehl
- Sung-Jae Pak
- David Schuster
- Yehuda Shadmi
- Paul van Kampen
- Darren Wong
- ...

Others

- Gordon Aubrecht
- Constance Barsky
- Julio Benegas
- Phillipe Binder
- Chris Byrne
- David Campbell
- Audrey Champagne
- John Christopher
- Karen Cummings
- Bill Duxler
- Dewey Dykstra
- Judith Edgington
- David Elmore
- Robert Endorf
- Bat Sheva Eylon
- Noah Finkelstein
- Jim Freericks
- J.D. Garcia
- Uri Haber-Schaim
- Curt Hieggelke
- Ruth Howes
- Leon Hsu
- Len Jossem
- Ken Krane
- Priscilla Laws
- Sue Lee
- Amy Liu
- Ramon Lopez
- Jill Marshall
- Eric Mazur
- Rose McKenney
- Roberto Mercado
- Dawn Meridith
- Bruce Patton
- Steve Pollock
- Chew Leng Poon
- James Poth
- Ed Prather
- Fred Reif
- Rodrigo Rivera
- David Sokoloff
- Tim Steltzer
- Jim Stith
- Jack Taylor
- Beth Thacker
- Ron Thornton
- Joan Valles
- Alan van Heuvelen
- Ruth von Blum
- Ken Wilson
- Michael Wittmann
- Genaro Zavala
- Many others...

Many faculty in UW Physics Department

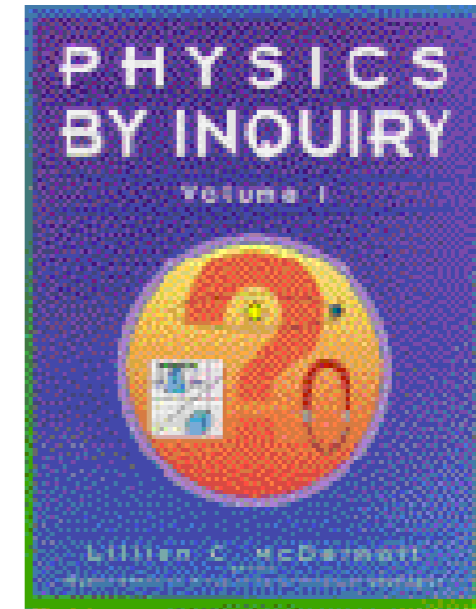
Application of research to the development of curriculum

- ***Physics by Inquiry*** -
(John Wiley & Sons, Inc., 1996)

K-12 teachers

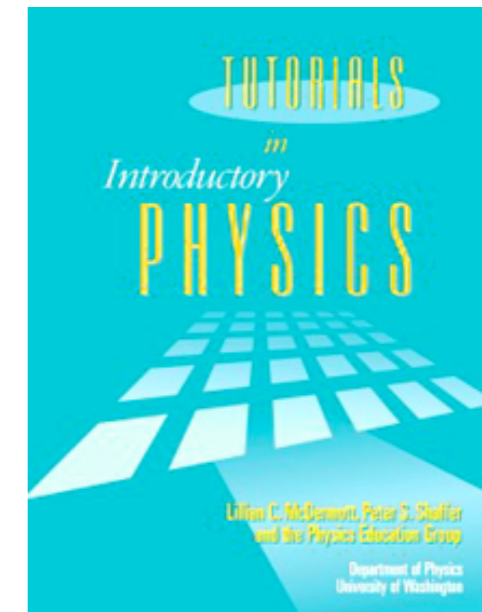
Underprepared students

Other liberal-arts majors



- ***Tutorials in Introductory Physics***
- (Prentice Hall, 2002)

Students in introductory physics courses



Outline

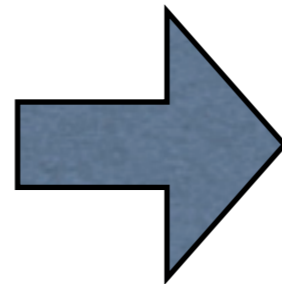
- Introduction
- *Physics by Inquiry*
 - Brief history
 - Examples from research base
 - Discussion of overall structure
- *Tutorials in Introductory Physics*
 - Brief history
 - Examples from research base
 - Discussion of overall structure
- Current and future work

Physics by Inquiry: Background

- **draws on *The Various Language by Arnold Arons***
(Based on teaching experience at Amherst College in liberal arts courses and at UW in courses for elementary teachers)
- **is based on many years of research and teaching experience by McDermott and PEG:**
 - courses for preservice and inservice K-12 teachers
 - courses for students underrepresented and underprepared in science and mathematics

Characteristics of Pbl course (guided by observations of students)

Observation that the person who learns the most from explanations is the instructor not the student



- Laboratory-based, no lectures
- Small groups of students work together (collaborative learning)
- Students required to go through reasoning involved in development and application of concepts

Course structure provided ideal environment for instructors to come to understand the difficulties that students encounter in learning a given body of material.

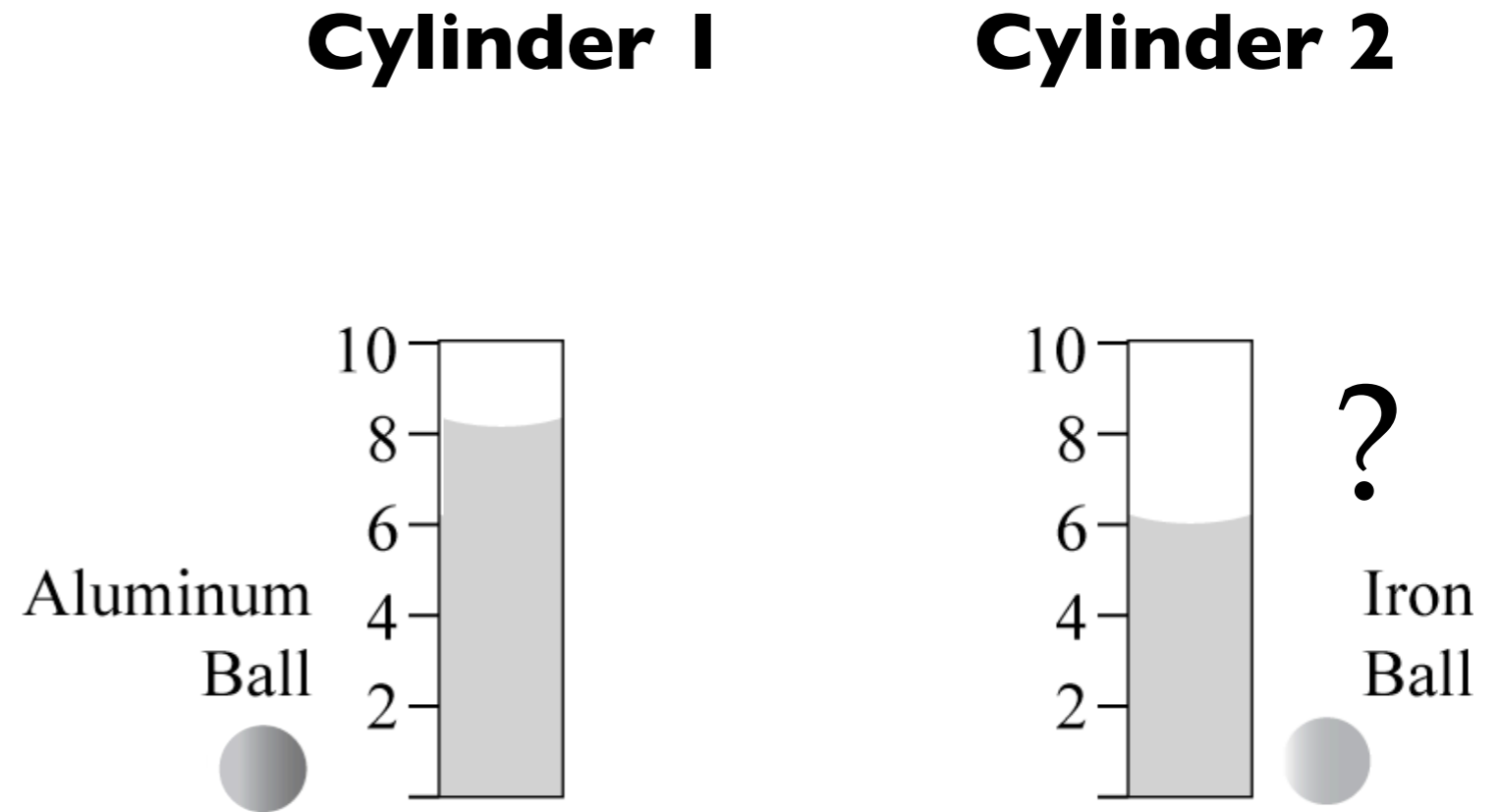
Example of how research has guided the design of Pbl

Research task*

Students are shown two balls of identical size and shape. Ball 1 is made of aluminum. Ball 2 is made of iron.

The students observe the water rise when the aluminum ball is placed in Cylinder 1.

The student is asked to predict the rise in cylinder 2.



Administered to:

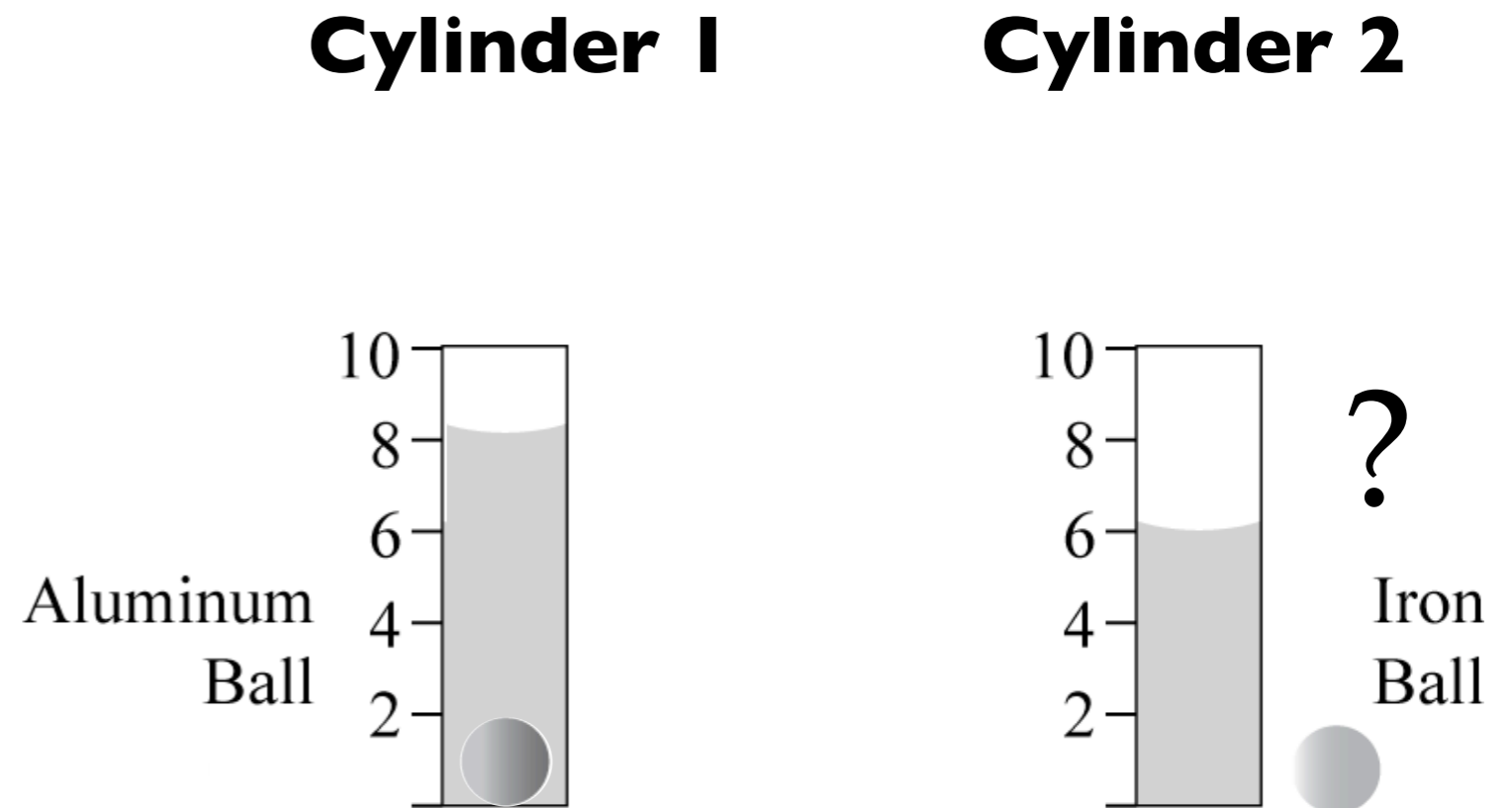
- (1) teachers in preservice and inservice courses and workshops
- (2) underprepared students
- (3) students in algebra-based physics course

Research task

Students are shown two balls of identical size and shape. Ball 1 is made of aluminum. Ball 2 is made of iron.

The students observe the water rise when the aluminum ball is placed in Cylinder 1.

The student is asked to predict the rise in cylinder 2.



~ 50% predicted a greater increase in water level for the iron ball.

Rosenquist: “... most of the students who predicted incorrectly were genuinely surprised at the outcome and at a loss to account for it.”

**Many other questions used to
probe student thinking of mass
and volume**

Results interpreted as confusion between related *mass and volume*

Similar finding in many other contexts:

density and concentration
position and velocity
velocity and acceleration
heat and temperature
etc.

*Failure of students to recognize which concepts
are applicable in a variety of situations.*

Most students could give descriptive definitions for mass and volume

- mass is the amount of matter in an object
- volume is the amount of space that an object occupies

Useless in science

**In *Physics by Inquiry*,
students formulate *operational definitions*
based on their observations.**

Mass: The mass of the unknown object is the number of standard mass units that balance the object on an equal arm balance.

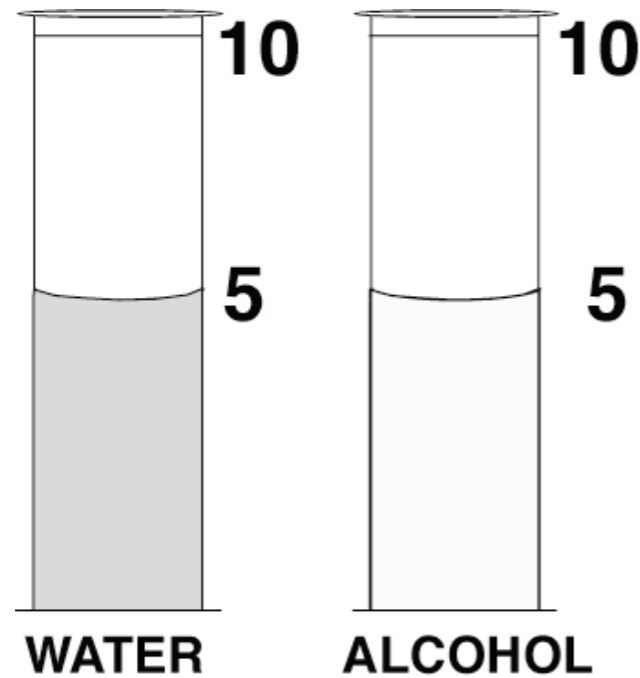
Volume: The volume of an object is the number of standard cubes that fit inside the object (or are displaced by the object when immersed in water)

*Students required to use operational definitions
in subsequent explanations of reasoning.*

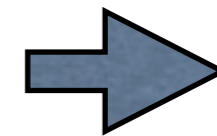
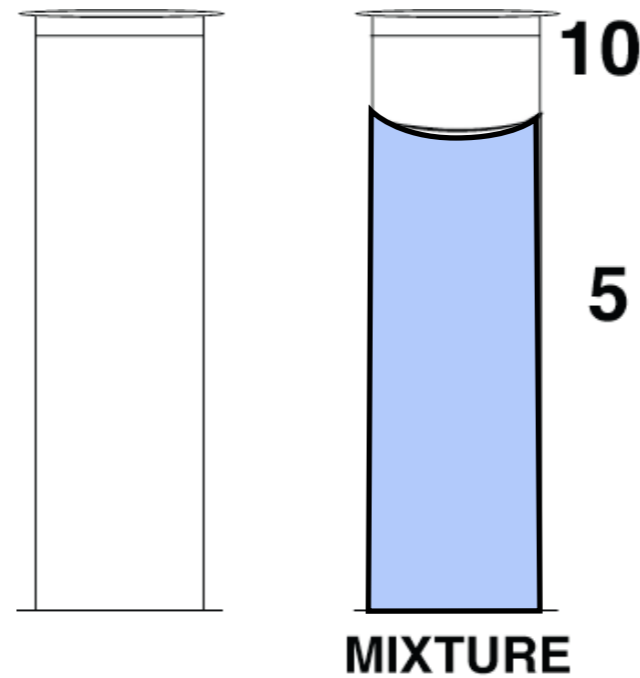
Experiments help students distinguish between concepts.

e.g., Mix water and alcohol

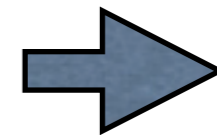
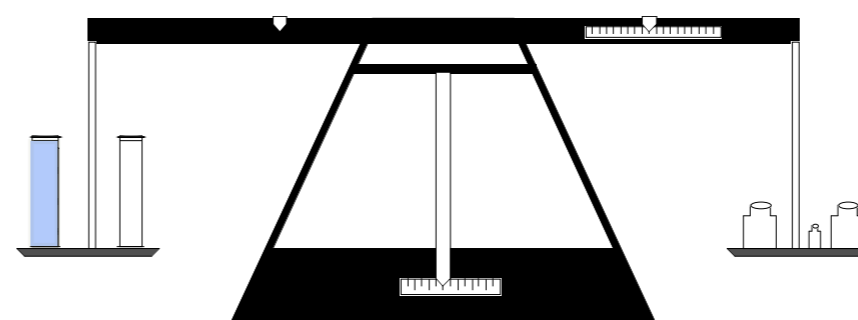
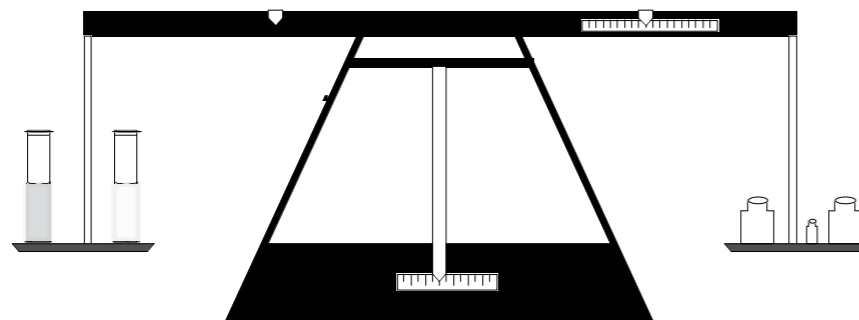
before



after



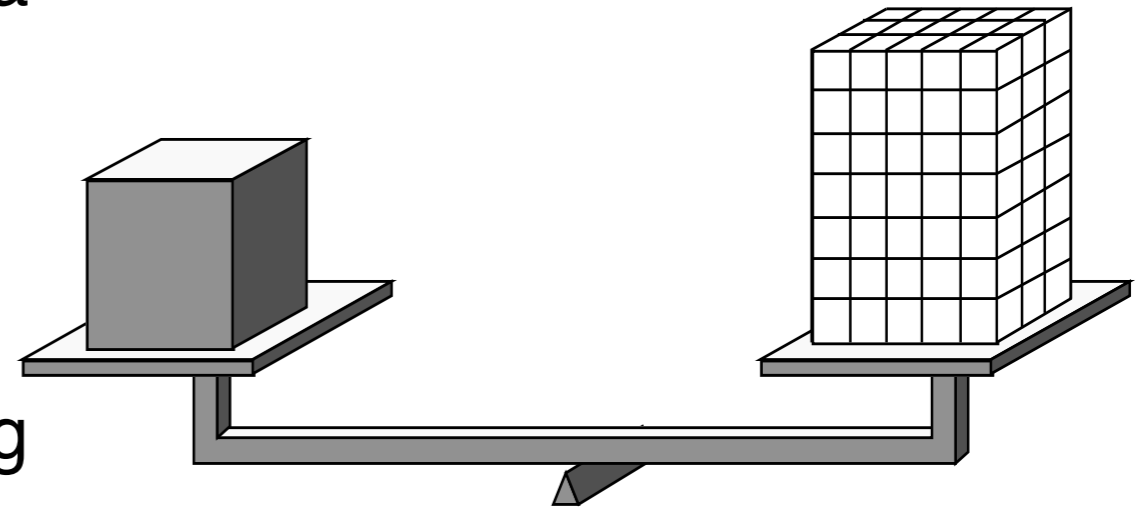
*Volume
is not
conserved.*



*Mass
is
conserved.*

Post-test question

On the left of the equal arm balance is a rectangular block of aluminum. On the right is a rectangular solid made of 105 one-centimeter plastic cubes.



(The arms were balanced before adding the objects.)

Which property of the aluminum block (mass, area, volume, *etc.*) does the number 105 describe? Explain your reasoning.

Correct response:

"The number 105 describes the mass because in order to balance, the two objects must have the same mass."

After *Pbl* instruction: ~100% correct

Identification of student difficulties

1. Confusion of concepts that apply to same situation

mass - volume

density - concentration

position - velocity

velocity - acceleration

2. Difficulty with scientific reasoning skills

proportional reasoning

control of variables

model-based reasoning

hypothetico deductive reasoning

3. Inability to reason by analogy and to transfer reasoning learned in one context to another

4. Lack of connection between the real world and scientific representations

words \leftrightarrow numbers \leftrightarrow graphs ...

Properties of Matter

- **Concepts**

- balancing
- mass
- volume, length, area
- density
- sinking and floating
- Archimedes' principle
- Concentration and solubility

- **Reasoning**

- operational definitions
- uncertainty
- proportional reasoning
- control of variables
- analogies
- graphing

*Critical role of reasoning in
development and application of concepts*

Observations during development of *Physics by Inquiry*

- Many students from diverse backgrounds encounter similar conceptual and reasoning difficulties
 - K-12 teachers
 - Students underprepared in science and math
 - Liberal Arts majors
 - Students in introductory physics courses (algebra and calculus)
 - Students at pilot sites for Pbl
 - Ohio State Systemic Initiative
(Constance Barsky, Ken Wilson, Sue Lea, Gordon Aubrecht, Robert Endorf)
 - UTeach
(Jill Marshall)

Observations during development of *Physics by Inquiry*

- Many students from diverse backgrounds encounter similar conceptual and reasoning difficulties
- Instructional strategies that prove effective at helping one population are often useful for others
- Knowledge of specific difficulties can guide the design of effective instruction (research-based)
- Systematic documentation is essential (research-validated)



*Research on the learning and teaching of physics
interpreted by our group as an **empirical applied science***

Tutorials in Introductory Physics: **Background**

Opportunity at UW in 1991:

- College-wide initiative to improve entry-level courses.
- Physics Department response: require laboratory of all student in calculus-based course and implement small group sections

Suggestion by Physics Education Group for sections that differ from typical recitations, problem-solving sections, etc.

- Motivation: observation that K-8 teachers often did better on certain questions than students in introductory physics
- Goal: to give students in introductory course some of the small group intellectual experience provided by Pbl

Course structure

Large lecture-based sequence

- ~ 1000 students / quarter
- 3 courses in sequence
(Mechanics, E&M, Waves & optics)
- Many faculty and TAs involved
 - 7–8 faculty teaching lectures
 - 3 faculty responsible for laboratories
 - ~ 30+ TAs

Challenge

to improve student learning (within constraints of large class size, breadth of coverage, and fast pace)

Need

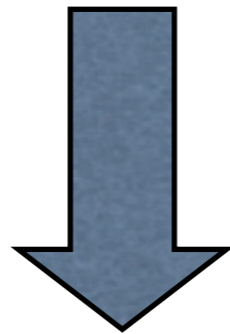
to secure mental engagement of students at deep level

Requirement

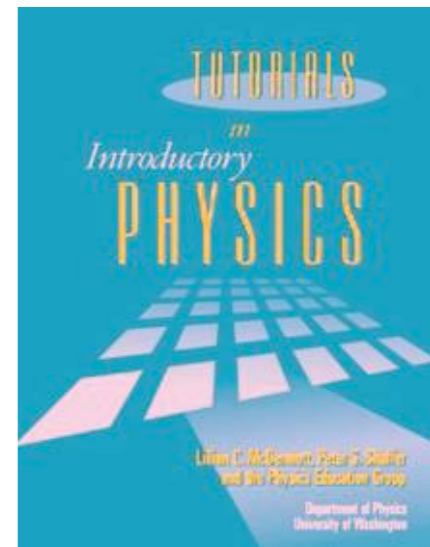
to develop a practical, flexible, sustainable approach

Goal

to improve instruction in introductory physics
through cumulative, incremental change
(evolution not revolution)



Tutorials in Introductory Physics
supplement to lecture-based course
(Prentice Hall, 2002)



Emphasis in tutorials is

on

- constructing concepts and models
- developing reasoning ability
- relating physics formalism to real world
- addressing known difficulties

not on

- solving standard quantitative problems

Tutorials in Introductory Physics

The tutorials respond to the research question:

Is the standard presentation of a basic topic in textbook or lecture adequate to develop a functional understanding?

(*i.e.*, the ability to do the reasoning necessary to apply relevant concepts and principles in situations not explicitly studied)

If not, what needs to be done?

Tutorial sequence consists of:

Pretest

(paper or web-based)

Worksheet

(collaborative small groups)

Homework

(individual)

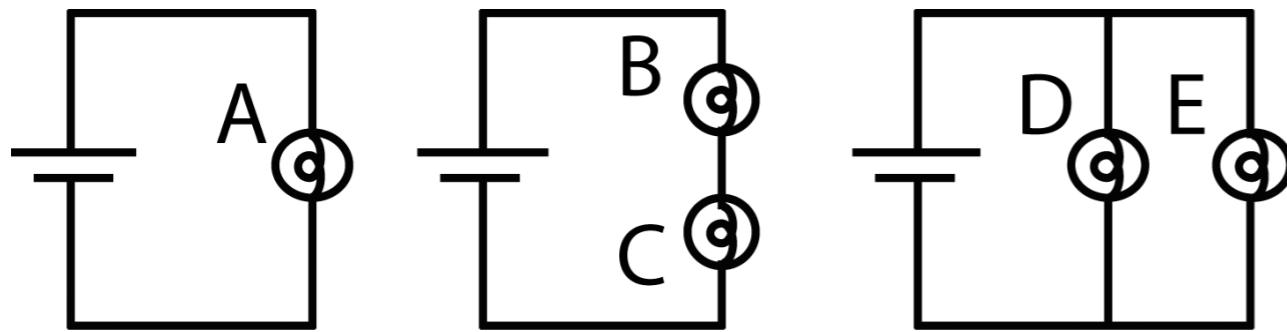
Post-test

(course examinations)

Example of pretest

The bulbs below are identical.
The batteries are identical and ideal.

Rank the five bulbs from brightest to dimmest. Explain.



$$A = D = E > B = C$$

Correct response:

given by ~ 15%

- students in calculus-based physics (N > 1000)
- high school physics teachers
- university faculty in other sciences and mathematics

given by ~ 70%

- graduate TA's and postdocs in physics (N ~ 100)

Results independent of whether administered before or after instruction in standard lecture courses

Students had many specific difficulties

- Battery is constant current source.
- Current is “used up” by elements in circuit.



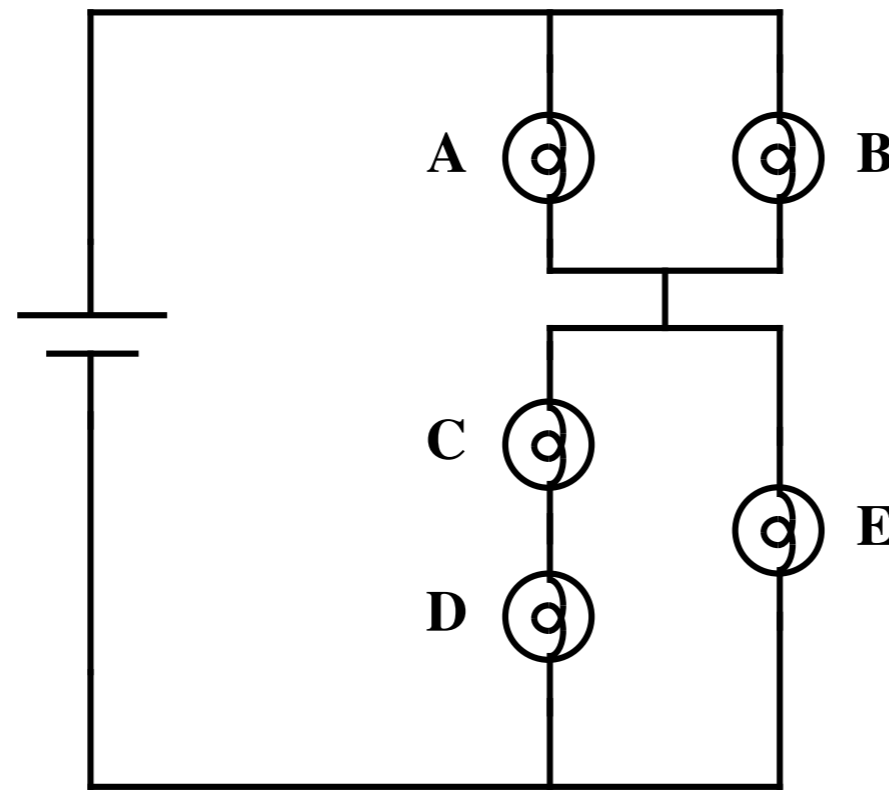
Basic underlying difficulty:

lack of a conceptual model for an electric circuit

Basic instruction by guided inquiry: an example from *Electric Circuits module*

- Students are guided to construct a conceptual model for an electric circuit through “hands on” experience with batteries and bulbs. Beginning with a few assumptions, they perform simple experiments, make observations, and use deductive and inductive reasoning.

Assessment of student learning



$$E > A = B > C = D$$

		Pretest	Post-test
K-12 teachers (N > 150)	<i>Physics by Inquiry</i>	15%	~100%
Undergraduates (N > 300)	<i>Tutorials</i>	15%	~60%
Graduate students (N > 100)		70%	--

Practical criterion for effectiveness of a tutorial

Post-test performance of introductory students
matches (or surpasses)
pretest performance of graduate students

**Standards for teachers
are much higher.**

Impact of Pbl and Tutorials on student learning

- improved understanding of university students and K-12 teachers as demonstrated through pretests and post-tests
- long-term retention improved
 - Francis, MSU; Constantinou, Cyprus; UW
- problem-solving skills same or better (despite less time spent on practice)
 - Mazur, Harvard; Gladding, U. of Illinois; UW
- improved preparation of graduate TAs
 - in their understanding of physics
 - for their role as current and future instructors

Lessons learned

- some conceptual and reasoning difficulties are very common and not effectively addressed through standard instruction (and may persist despite advanced instruction)
- student learning can be improved within a limited amount of time through a targeted approach
 - not as much as with Pbl (more thorough)
- the design of effective instructional materials is a difficult task requiring multiple iterations
- systematic documentation of results establishes a research base that can be used by others

Lessons learned

- some conceptual and reasoning difficulties are very common and not effectively addressed through standard instruction (and may persist despite advanced instruction)
- student learning can be improved within a limited amount of time through a targeted approach
 - not as much as with Pbl (more thorough)
- the design of effective instructional materials is a difficult task requiring multiple iterations
- systematic documentation of results establishes a research base that can be used by others
- students must be held accountable (exams)

Critical requirement for effective instruction:

Intensive preparation of Teaching Assistants

- in subject matter
 - need to address specific conceptual and reasoning difficulties
- in instructional method
 - need to overcome tendency to teach as one has been taught

TAs can benefit from working through the tutorials in the same way as their students.

Current and future work

- **Introductory physics**
 - Research on new topics; continued examination of others
 - Development and revisions of *Physics by Inquiry* and *Tutorials in Introductory Physics*
- **Advanced physics**
 - Relativity
 - Quantum mechanics
 - Electricity and magnetism
 - Upper division laboratories (e.g., on circuits)
- **Preparation of future faculty and K-12 teachers**

Research on the learning and teaching of physics as a field for

- **to improve instruction**
 - efficiently, systematically, cumulatively
- **to build a research base**
 - that documents the nature of specific difficulties and instructional strategies that do and do not work
 - that can be used as a basis for curriculum development
 - that provides sufficient evidence to convince colleagues of need for change
 - that extends beyond local classroom and institution
 - that is accessible to wider community through conferences and journals