Research in physics education: A resource for improving student learning

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Physics Education Group at the University of Washington

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Goals of UW Physics Education Group

- Conduct research on learning and teaching of physics (and astronomy) concepts and reasoning (differs from traditional education research)

- Develop instructional procedures that:
  - are effective at helping students learn (concepts and reasoning)
  - yield similar results when used by faculty at other institutions

- Document impact and procedures in journals that are read by physics faculty (written in language accessible to physicists)

To help faculty interested in improving the effectiveness of instruction who may or may not be engaged in physics education research.

Joint AAPT and APS resolution (1999) in support of research in physics education conducted within traditional research-oriented physics departments

Evolution of UW Physics Education Group

Early 1970's: K-12 teacher preparation (begun by A. Arons) and underprepared students

Mid 1970's: Physics Education Research *(PER)* and Ph.D. program in Department of Physics

⇩ *Small classes of students lacking physics background led to insights into conceptual difficulties and design of strategies that fostered conceptual development and reasoning ability.*

1980's: Research-based development of curriculum for K-12 teachers and underprepared students

1990's onward: Extended research-based curriculum development for undergraduates (introductory and advanced)

Research-based preparation of TAs for their current and future roles as instructors

Perspective on teaching as a science (as well as an art)

Results from documented research

indicate:

- many students encounter same conceptual and reasoning difficulties
- same instructional strategies are effective for many students

are:

- **generalizable and reproducible** (beyond a particular course, instructor, or institution)

become:

- publicly shared knowledge that provides a basis for acquisition of new knowledge and for cumulative improvement of instruction

∴ **constitute:**

- a rich **resource** for improving instruction

Criteria for effectiveness of instruction

Teaching as an art

- Motivational effect of personal qualities and style of instructor
- Instructor's subjective assessment of student learning
- Student enthusiasm and self-assessment of learning
- Student evaluations of the course or instructor

Criteria are not tightly linked to student learning.

Teaching as a science

- *Assessment of student learning by specified intellectual outcomes*

Criterion is student learning.

Physics Education Group

Procedures:

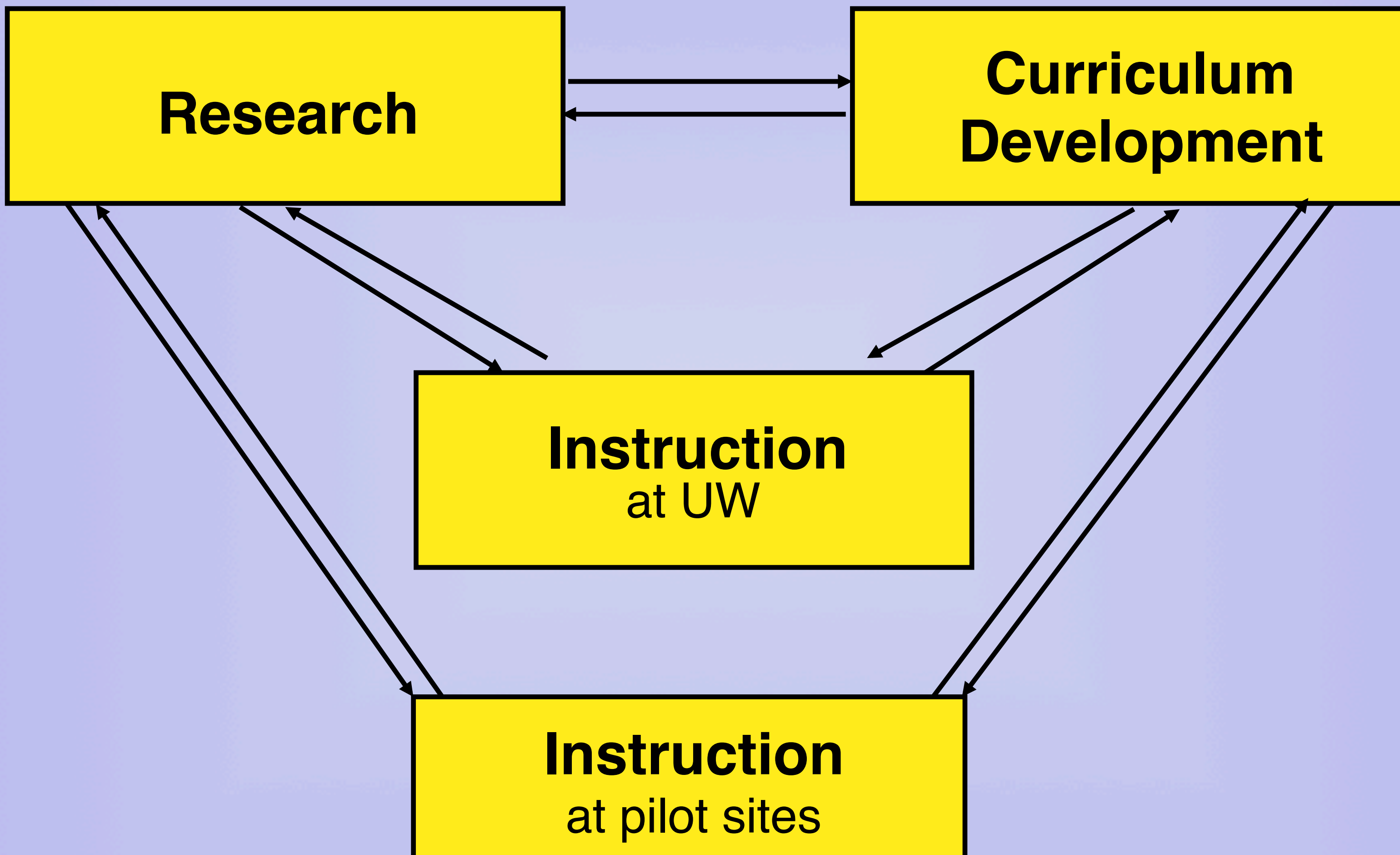
- conduct systematic investigations
- apply results (*e.g.,* develop instructional strategies)
- assess effectiveness (*e.g.,* through pre- and post-testing)
- document methods and results so that they can be replicated
- report results at meetings and in papers

The procedures are characteristic of an empirical applied science.

Systematic investigations of student learning (at the beginning, during, and after instruction)

- **individual demonstration interviews**
  - for probing student understanding in depth
- **written questions with explanations**
  (pretests and post-tests)
  - for ascertaining prevalence of specific difficulties
  - for assessing effectiveness of instruction
- **descriptive studies during instruction**
  - for providing insights to guide curriculum development

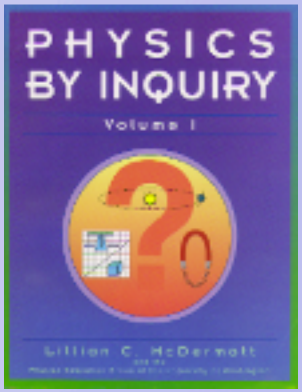
Application of research to development of curriculum



Research-based ≠ Research-validated

Research-based curriculum development

Preparing precollege teachers to teach physics and physical science



– Physics by Inquiry –

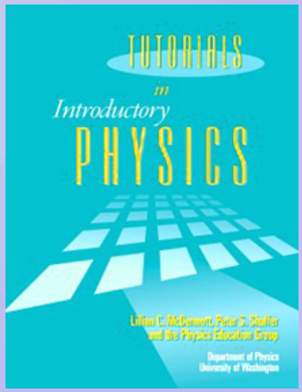
(John Wiley & Sons, Inc., 1996)

Self-contained, laboratory-based, no lectures

Improving student learning in introductory physics

– Tutorials in Introductory Physics –

(Prentice Hall, 2002)



Supplementary to lecture-based course

Examples in two different contexts

– Resistive electric circuits

– Mechanics: Work-energy & impulse-momentum theorems

Investigation of student understanding: an example from electric circuits

- *"Research as a guide for curriculum development: An example from introductory electricity. Part I: Investigation of student understanding,"* L.C. McDermott and P.S. Shaffer, *Am. J. Phys.* **60** (1992)
- *"Research as a guide for curriculum development: an example from introductory electricity, Part II: Design of instructional strategies,"* P.S. Shaffer and L.C. McDermott, *Am. J. Phys.* **60** (1992)
- *"Preparing teachers to teach physics and physical science by inquiry,"* L.C. McDermott, P.S. Shaffer, and C.P. Constantinou, *Phys. Educ.* **35** (2000)
- *"New insights into student understanding of complete circuits and the conservation of current,"* M.R. Stetzer, P. van Kampen, P.S. Shaffer, and L.C. McDermott, *Am. J. Phys.* **81** (2013)

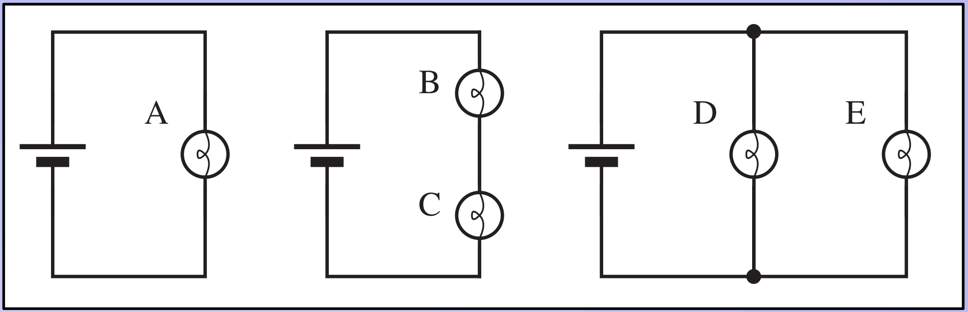
What students *could* do

Solve many end-of-chapter circuit problems by applying Kirchhoff's rules

What students could *not* do

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

Rank the bulbs from brightest to dimmest. Explain.



Answer: 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

Generalizations
on *learning* and *teaching*

inferred and validated

by research and development of

Physics by Inquiry and

Tutorials in Introductory Physics

serve as a practical guide in ongoing iterative process
of curriculum development

- ◊ **Facility in solving standard quantitative problems is not an adequate criterion for functional understanding.***

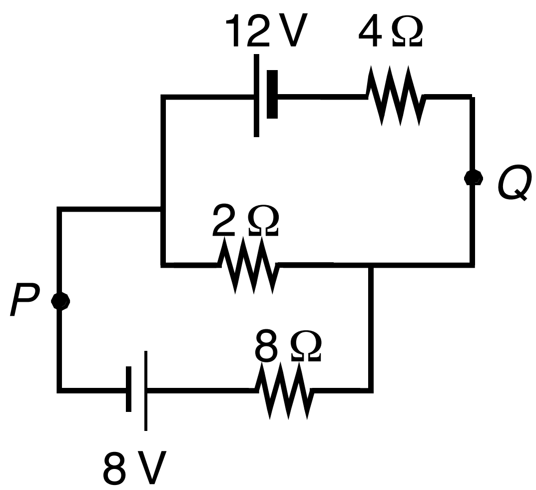
  Questions that require qualitative reasoning and verbal explanations are essential for assessing student learning.

  Such questions are an effective strategy for helping students learn.

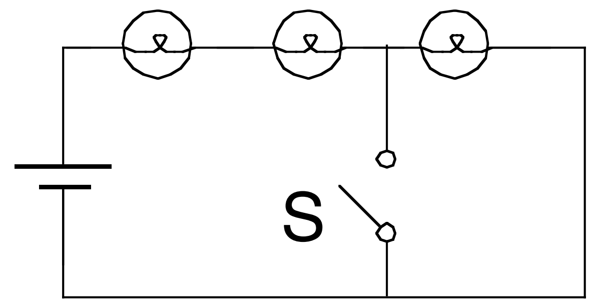
* Ability to apply concepts and reasoning to situations not explicitly memorized

Similar situation at other universities
(e.g., Harvard University; Eric Mazur)

Paired examination questions



Calculate current in 2-Ω resistor and potential difference between *P* and *Q.*



When the switch is closed, do the following *increase, decrease, or stay the same?*

- intensities
- i_{bat}
- voltage drops

Student performance substantially worse on conceptual problem.

- **Certain conceptual difficulties are not overcome by traditional instruction. (Advanced study may not increase student understanding of basic concepts.)**

Persistent conceptual difficulties must be explicitly addressed.

Examples of persistent conceptual difficulties with electric circuits

- *belief that the battery is a constant current source*
- *belief that current is “used up” in a circuit*

Basic underlying difficulty

- *lack of a* ***conceptual model*** *for an electric circuit*

Important note:

Use of term ‘*misconceptions*’ may trivialize the problem

They cannot be ‘fixed’ in isolation.

Concepts in physics are interrelated.

◊ **A coherent conceptual framework is not typically an outcome of traditional instruction.**

Students need to go through the reasoning involved in the process of constructing scientific models and applying them to predict and to explain real world phenomena.

On certain types of qualitative questions, student performance is essentially the same over a wide range of student ability:

- *before and after standard instruction*
- *in calculus-based and algebra-based courses*
- *with and without standard demonstrations*
- *with and without standard laboratory*
- *in large and small classes*
- *regardless of popularity of the instructor*

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Hearing lectures, reading textbooks, seeing demonstrations, doing homework, and performing laboratory experiments often have little effect on student learning.

◊ **Teaching by telling is an ineffective mode of instruction for most students.**

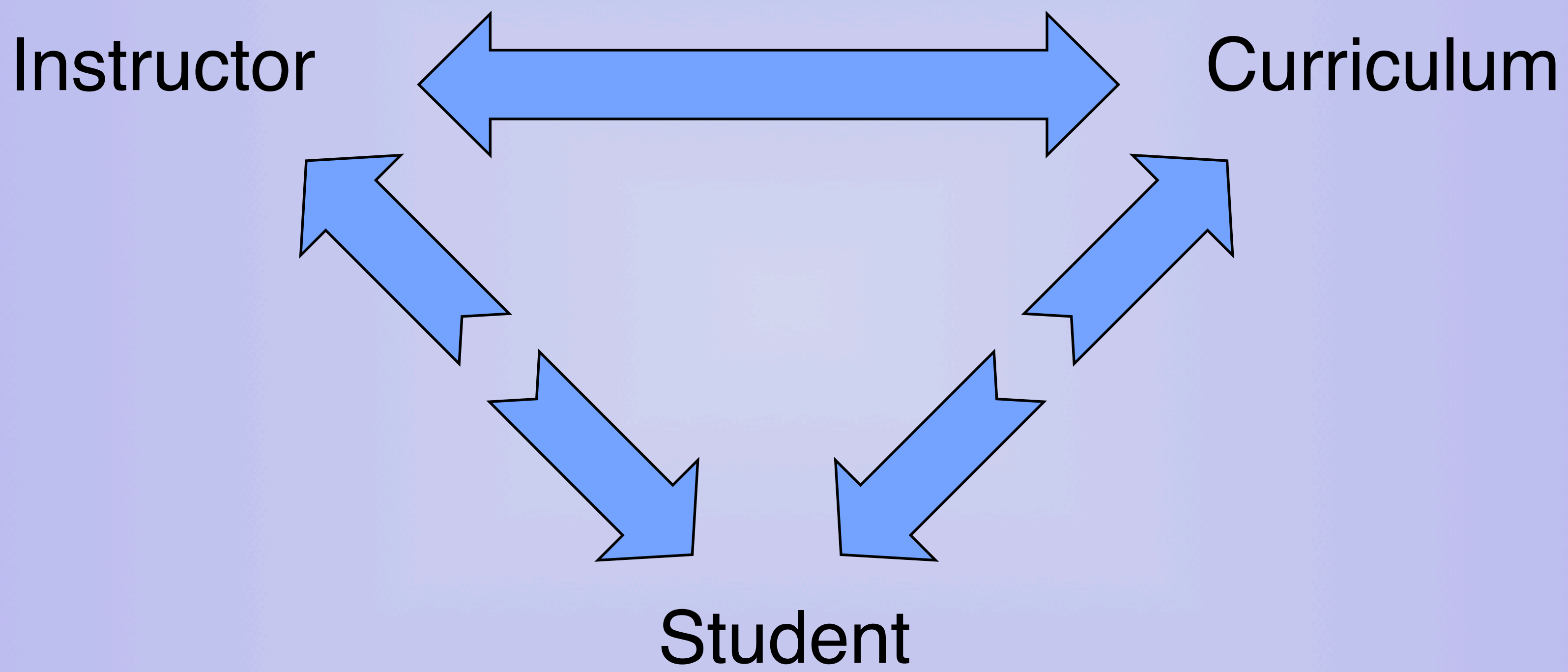
Teaching by questioning can be more effective.

Students must be intellectually active to develop a functional understanding.

Caution: "active learning" does not always lead to "intellectual engagement"

Documented research is necessary.

Evidence from research indicates a gap



Gap greater than most instructors realize

Traditional instruction in physics:

is based on perspective of university instructors

- present understanding of physics
- belief they can “transmit” knowledge to students and teachers
- personal perception of students and teachers

ignores differences between physicists and students

- small for future physicists and some K-12 teachers
- large for most students and most K-12 teachers

As a result, students often:

– ***tend to view physics as a collection of facts and formulas***
– ***make less progress on concepts and reasoning than they could***

Need for a different instructional approach

↓

guided inquiry

↓

Physics by Inquiry

and

Tutorials in Introductory Physics

Instruction by guided inquiry:

an example from *Electric Circuits*

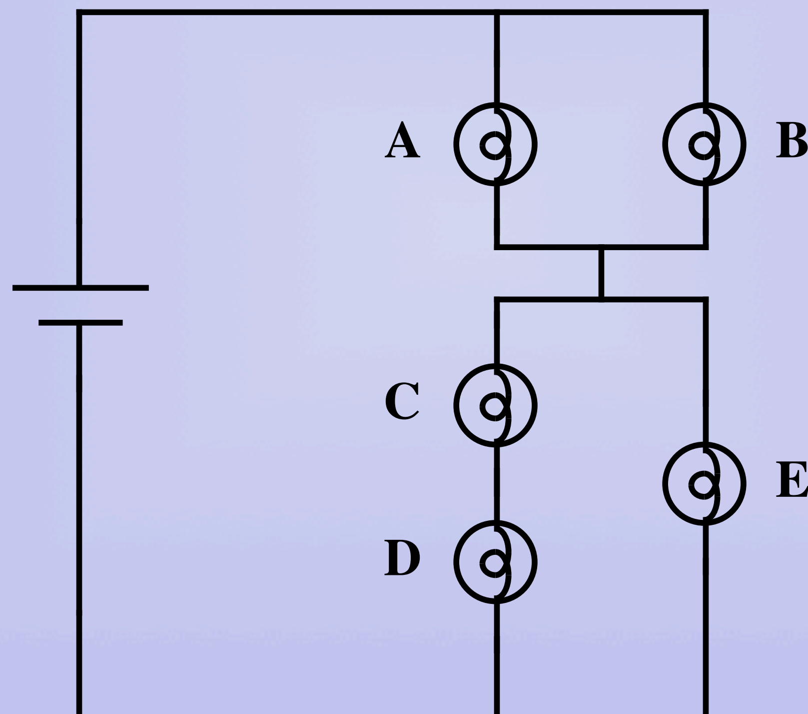
- Students construct a conceptual model for an electric circuit based on their observations through "hands on" experience with batteries and bulbs. *(i.e., develop a mental picture and a set of rules to predict and explain the behavior of simple circuits)*

- Questions that require qualitative reasoning and verbal explanations guide development of a functional understanding.

- Curriculum explicitly addresses conceptual and reasoning difficulties using instructional strategies, *e.g., elicit, confront, resolve.*

Assessment of student learning

Virtually all teachers (K-12) develop a model that they can apply to relatively complicated dc circuits.



E > A = B > C = D

Tutorials respond to the research question:

Is 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?

Emphasis in tutorials is

on

- constructing concepts
- developing reasoning ability
- relating physics formalism to real world

not on

- solving standard quantitative problems

Primary context (at UW) for tutorials

Each week:

- 3 lectures (50 minutes)
- 1 laboratory (2-3 hours)
- 1 tutorial (50 minutes)

Use at UW and elsewhere can vary (in lectures, labs, etc.), depending on constraints. (class size, room availability, number of lecturers, number of TAs or peer-instructors, etc.)

Tutorial Components

- **weekly pretests**
  - *given usually after lecture on relevant material but before tutorial*
- **tutorial sessions or interactive tutorial lectures**
  - *small groups (3-4) work through carefully structured **worksheets***
  - *tutorial instructors question students in semi-socratic manner*
- **tutorial homework**
- **examination questions**
  - *all examinations include questions as **post-tests** on tutorial topics*
- ***required weekly seminar for tutorial instructors***
  - *TA's, peer instructors, etc.*
  - *preparation in content and instructional method*

NFW Example:
a tutorial from mechanics

Pretest

Motivation for Tutorial

Discussion: Part I of *Tutorial*

Workshop: Part II of *Tutorial*

Assessment of student learning

Motivation for tutorial

Investigation of student understanding of the impulse-momentum and work-energy theorems

- ***Individual Demonstration Interviews** (1981 - 1984)*
  - 12 students in honors calculus-based physics
  - 16 students in algebra-based physics

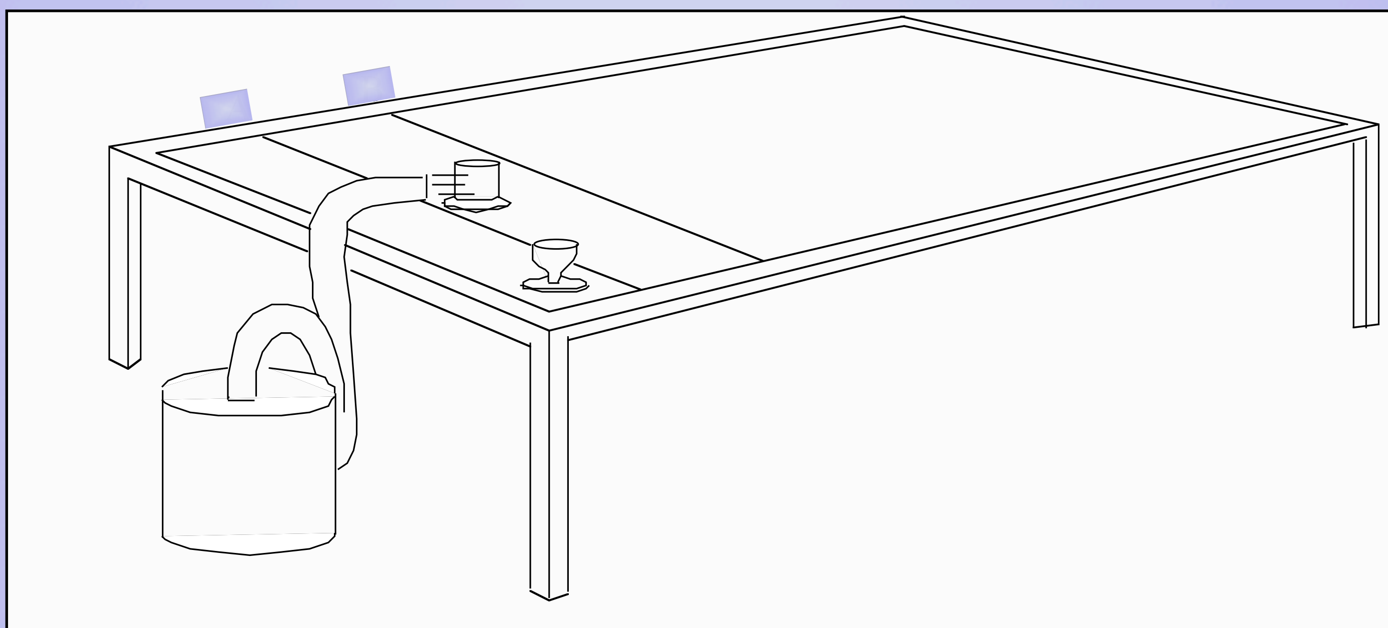
  *R.A. Lawson and L.C. McDermott, “Student understanding of the work-energy and impulse-momentum theorems,” Am. J. Phys., **55**, 811–817, 1987.*

- ***Descriptive Study & Curriculum Development** (1991-present)*
  - 1400 students in calculus-based physics

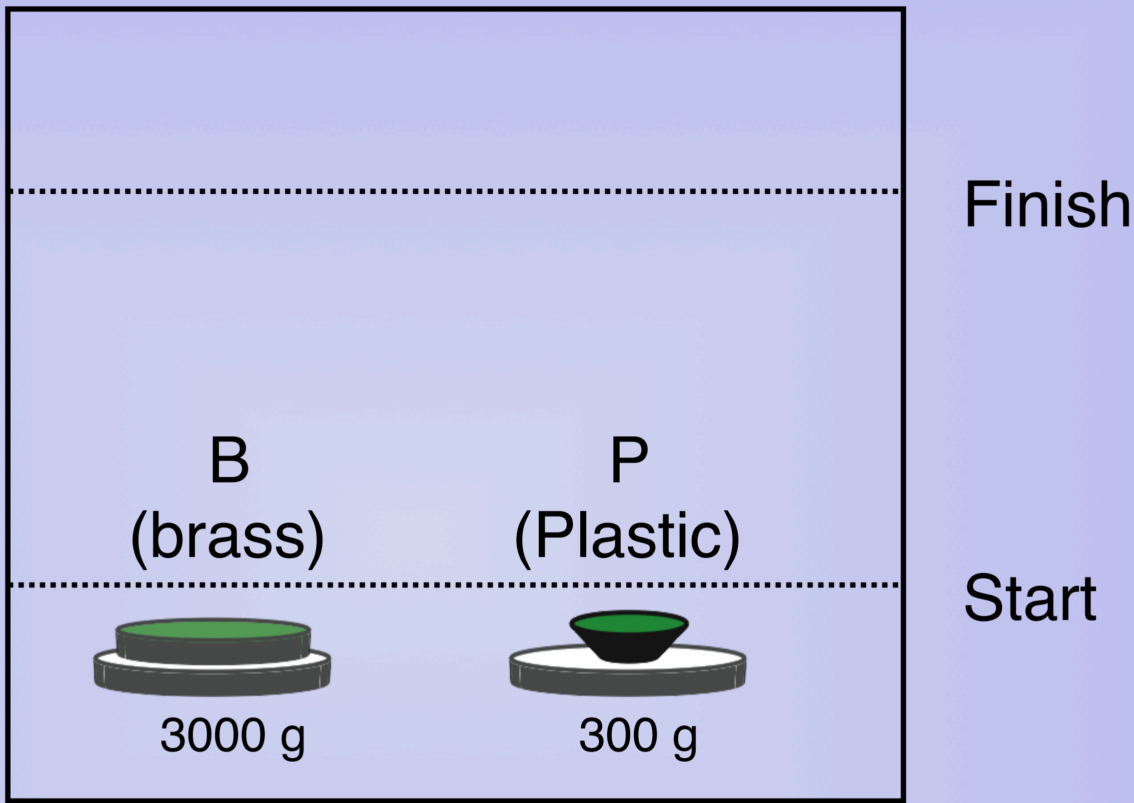
  *T. O’Brien Pride, S. Vokos, and L.C. McDermott, “The challenge of matching learning assessments to teaching goals: An example from the work-energy and impulse-momentum theorems,” Am. J. Phys., **66**,147-157, 1998.*

Apparatus used in Individual Demonstration Interviews

Pucks are pushed with constant force between starting and finishing lines by steady stream of air.



Comparison tasks



Tasks **After crossing the finish line, do the brass (B) and plastic (P) pucks have the same or different:**

- **kinetic energy?**
- **momentum?**

Criterion for understanding

Ability to apply work-energy and impulse-momentum theorems to a simple real motion

Correct Response:

$K_B = K_P$ *because* $\Delta K = F\Delta x$

$p_B > p_P$ *because* $\Delta p = F\Delta t$

Results from individual demonstration interviews and written questions

Correct explanation required
for responses to be counted as correct.

	Interviews		Written questions
Correct on:	**Honors physics (N = 12)**	**Algebra-based physics (N = 16)**	**Calculus-based physics (N = 965)**
kinetic energy comparison	**50%**	**0%**	**15%**
momentum comparison	**25%**	**0%**	**5%**

- ◊ **Connections among concepts, formal representations** (algebraic, diagrammatic, graphical, etc.) **and the real world are often lacking after traditional instruction.**

Students need repeated practice in interpreting physics formalism and relating it to the real world.

Example of intervention during interview

I: ...What ideas do you have about the term work?

S: Well, the definition that they give you is that it is the amount of force applied times the distance.

I: Okay. Is that related at all to what we've seen here? How would you apply that to what we've seen here?

S: Well, you do a certain amount of work on it for the distance between the two green lines: you are applying a force for that distance, and after that point it's going at a constant velocity with no forces acting on it.

I: Okay, so do we do the same amount of work on the two pucks or different?

S: We do the same amount.

I: Does that help us decide about the kinetic energy or the momentum?

S: Well, work equals the change in kinetic energy, so you are going from zero kinetic energy to a certain amount afterwards ... so work is done on each one …

... but the velocities and masses are different so they (the kinetic energies) are not necessarily the same.

Incomplete causal reasoning

◊ **Short responses (even if correct) do not necessarily indicate understanding.**

There is a need for probing.

Common incorrect explanations on written questions

- *'Momentum is conserved'*
- *'Energy is conserved'*

} *Memorized rules*

- *Compensation*
  - ***p****:* (small *m*) • (large v) = (large *m*) • (small v)
  - ***E:*** (small *m*) • (large v^2) > (large *m*) • (small v^2)

Theorems treated as mathematical identities

Cause-effect relationships not understood

Need for tutorial on work-energy and impulse-momentum theorems

Tutorials are <u>one way</u>:

- to get students intellectually engaged in thinking about physics

and

- to arrive at a functional understanding of important concepts and principles.

Workshop

Example of a research-based tutorial from *Tutorials in Introductory Physics*

Changes in energy and momentum

Tutorial: *Changes in energy and momentum*

- Start on Section II, page 3. (Section I has been discussed.)
- Work in groups of 4.
- Discuss your answers *and your reasoning* with your partners.
- Use large sheets of paper to record drawings and answers.
  Please draw diagrams LARGE.

We will circulate among groups
illustrating interactions with students.

Tutorial intended for use after students have studied
all relevant concepts (work, kinetic energy, momentum, etc.)

Students would have completed tutorials on
kinematics, forces, work, energy, and momentum

Commentary on tutorial:

Changes in energy and momentum

Part I: *Application of theorems in one dimension*

(Guides students through the reasoning to answer pretest)

Part II: *Application in more than one dimension*

(Guides students in applying theorems in a more complicated situation in order to strengthen their conceptual understanding – as well as their ability to reason with vectors.)

Reason for choice of this tutorial for New Faculty Workshop:

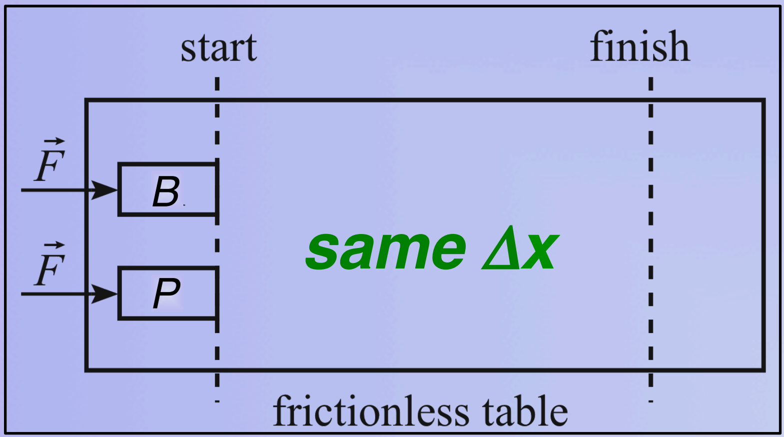
Many faculty (like ourselves) do not immediately know the answers. Thus, they must go through a similar reasoning process as students do for most tutorials.

Assessment of effect of tutorial on student understanding of changes in energy and momentum (in one dimension)

Comparison of pretest and post-test results from UW calculus-based course

Examples of questions used for assessment

Pretest

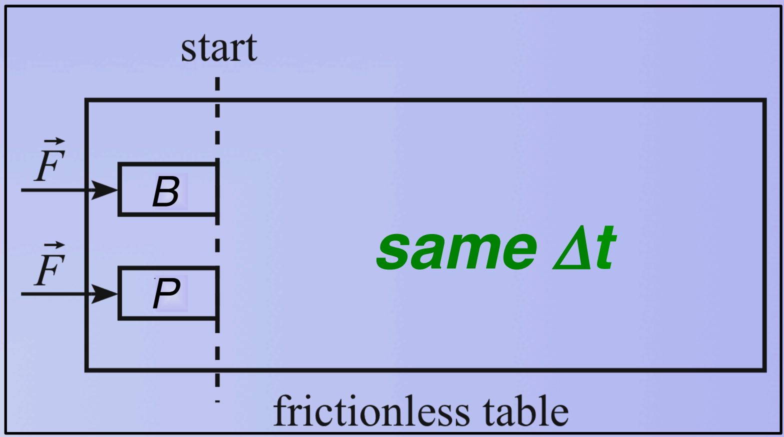


$m_B > m_P$

$v_0 = 0$

Same F

Post-test



Compare final K and p.

Similar reasoning required.

Results from pretest and post-tests

UW Introductory Calculus-based Course

Correct with correct explanation	**Pretest** (same Δx) After lecture before tutorial N = 985	**Post-test** (same Δt) After lecture and tutorial N = 435
K comparison	15%	35%
p comparison	5%	50%

Results on other post-tests consistent

Results from pretest and post-tests

Physics TAs

	TAs Before tutorial N = 74
Correct with correct explanation	**Pretest** Same Δx
K comparison	65%
p comparison	70%

Comparison of in-depth and broad assessment of student understanding

Mechanics Baseline Test (MBT) published in *The Physics Teacher**

- Two of the multiple-choice test questions were based on the UW comparison (pretest) tasks.
- Results from 8 groups of students at other universities and high schools reported in *TPT*.
- UW results near bottom of range reported in *TPT*.

** D. Hestenes and M. Wells, The Physics Teacher, March 1992*

Why were UW results near the bottom of the range of MBT results?

- *MBT is multiple-choice*
- *UW pretest requires explanations*

⇓

Reassessed UW results ignoring explanations.

With explanations ignored,

- *pretest results at UW after traditional instruction are consistent with nationally reported MBT results.*
- *post-test results at UW after tutorial and lecture are at or above the top of the nationally reported MBT results. The tutorial:*
    - *helps students understand the theorems*
    - *is an opportunity to strengthen ability to reason*

Assessment of student learning

Effect of tutorials on student performance

On qualitative problems:

– *much better*

On quantitative problems:

– *typically somewhat better*

– *sometimes much better*

On retention:

– *sometimes much better*

despite less time devoted to solving standard problems

Answers without explanations are not a good measure of student understanding.

Explanations of reasoning must be required on homework and examinations in order to assess student understanding.

Advanced study often does not result in a functional understanding of basic concepts.

↓

Need for systematic preparation of tutorial instructors.

Practical criterion for effectiveness of a tutorial:

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

- **Growth in reasoning ability does not result from traditional instruction.**

Scientific reasoning skills must be expressly cultivated.

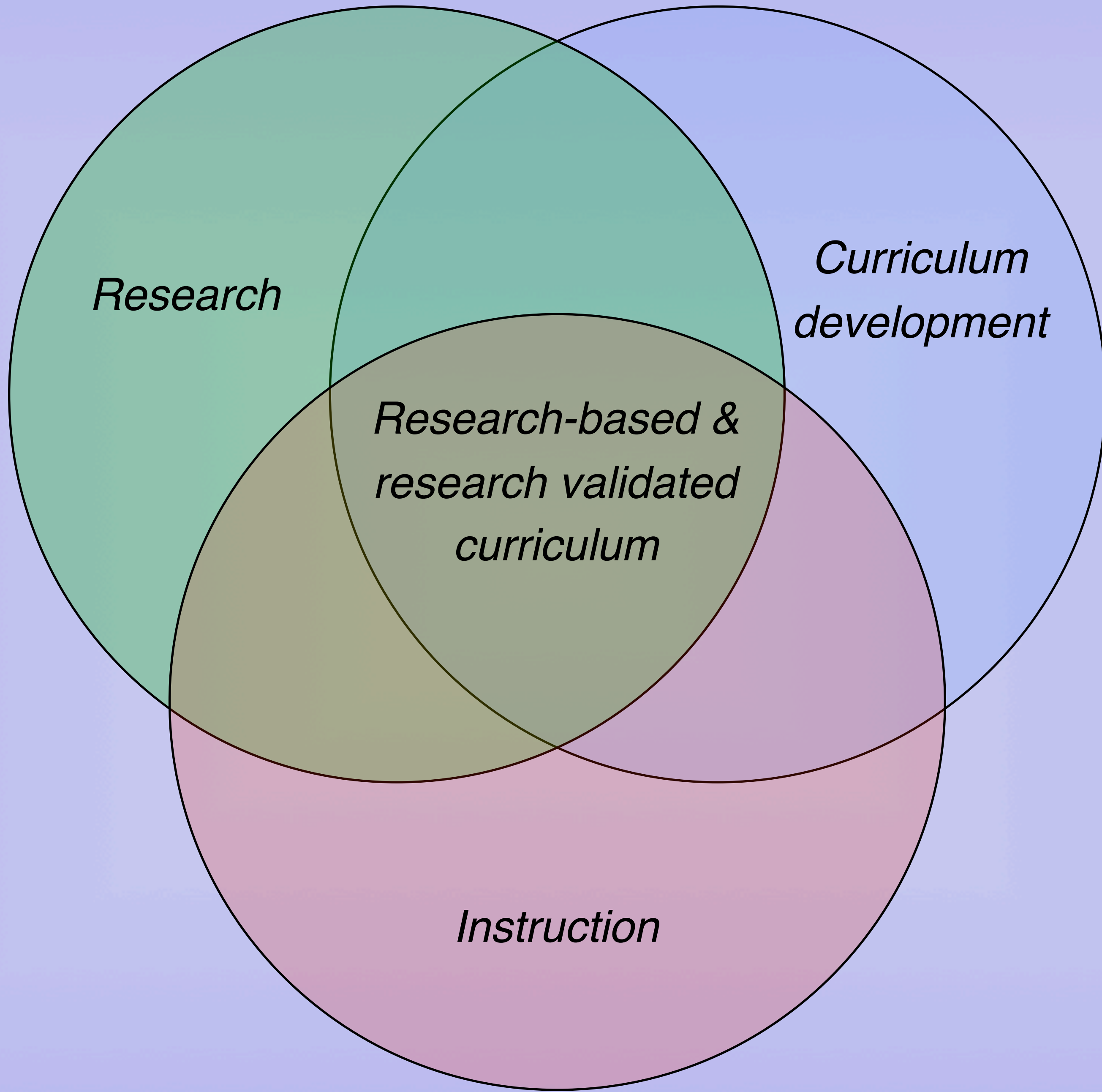
↓

Increasing the emphasis on reasoning can raise standards for student learning and does not "dumb down" a science course.

The tutorials are one example of how, with a small time allotment, a *research-based* and *research-validated* curriculum can help develop the type of qualitative understanding that can:

- make physics meaningful for students
- provide a foundation for quantitative problem solving
- develop scientific reasoning ability

For most students, the most important intellectual benefit from introductory physics is the development of scientific reasoning ability.


Research
Curriculum development
Research-based & research validated curriculum
Instruction