Research as a guide for improving student learning

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Evolution of UW Physics Education Group

Early 1970's:	K-12 teacher preparation
Mid 1970's:	Physics Education Research *(PER)* and Ph.D. program in Department of Physics
1980's:	Research-based development of curriculum for K-12 teachers
1990's onward:	Research-based development of curriculum for • K-12 teachers • Undergraduates Research-based professional development of TAs as instructors in undergraduate physics

Discipline-based research on learning and teaching

- differs from traditional education research
  (in which emphasis is on educational theory and methodology)
- focuses on student understanding of science content
- is an important field for scholarly inquiry by science faculty in science departments

can be an effective approach for improving student learning (K–20+)

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 beyond a particular course, instructor, or institution
- reproducible

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

Goal: ongoing cumulative improvement in

- research base on student understanding of physics
- undergraduate instruction *(introductory and beyond)*
- K-12 teacher preparation *(preservice and inservice)*
- professional development *(grad. students, post-docs, faculty)*

within culture and constraints
of research-oriented physics department

Perspective:

- Research in physics education is a science.

Physics Education Group

Procedures:

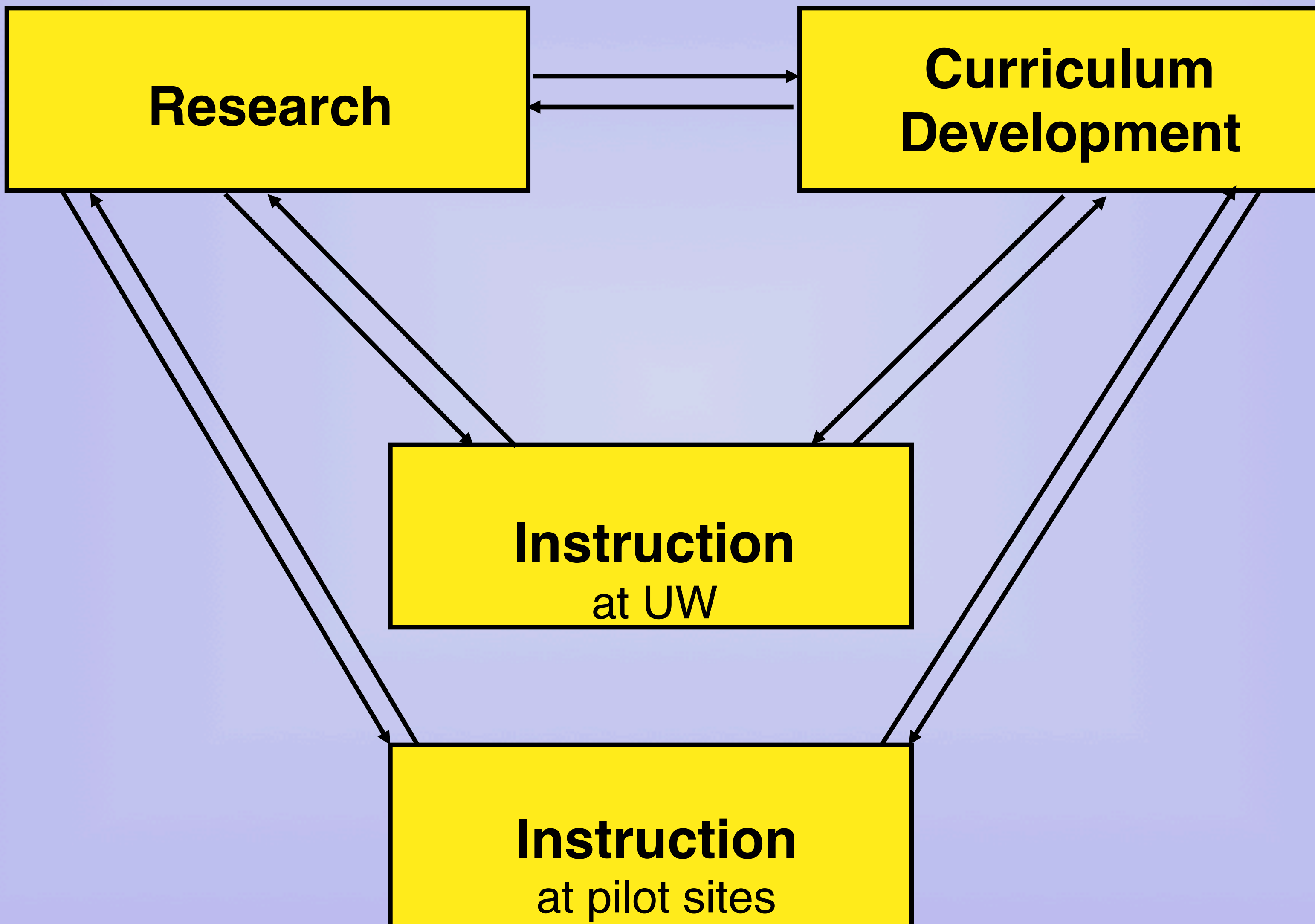
- conduct systematic investigations
- apply results (*e.g.,* develop instructional strategies)
- assess effectiveness (*e.g.,* through pre- and post-testing)
- document methods and results so that they can be replicated
- report results at meetings and in papers

The procedures are characteristic of an empirical applied science.

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

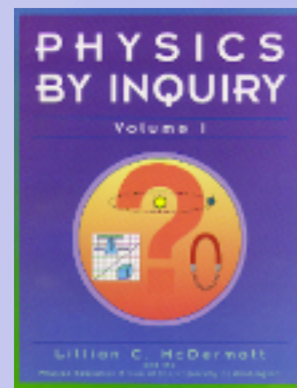
- **individual demonstration interviews**
  - for probing student understanding in depth
- **written questions with explanations**
  (pretests and post-tests)
  - for ascertaining prevalence of specific difficulties
  - for assessing effectiveness of instruction
- **descriptive studies during instruction**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

Application of research to development of curriculum



Research-based curriculum development

Preparing precollege teachers to teach physics and physical science

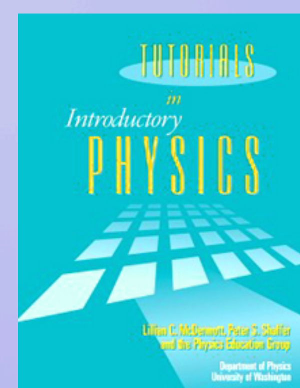


– Physics by Inquiry –

(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

– Electric circuits

– Mechanics

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)

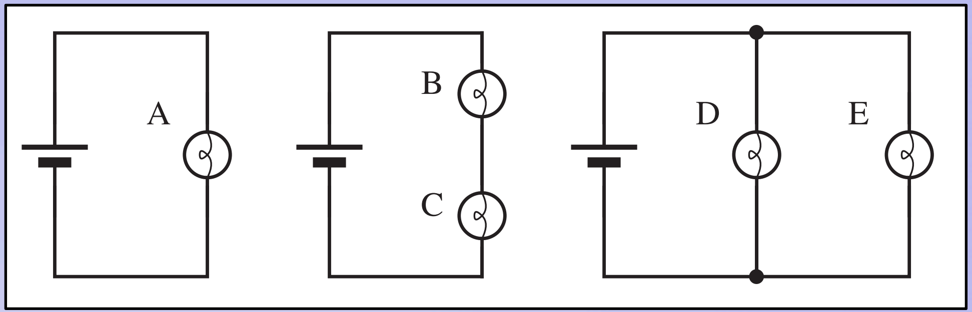
What students *could* do

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.***

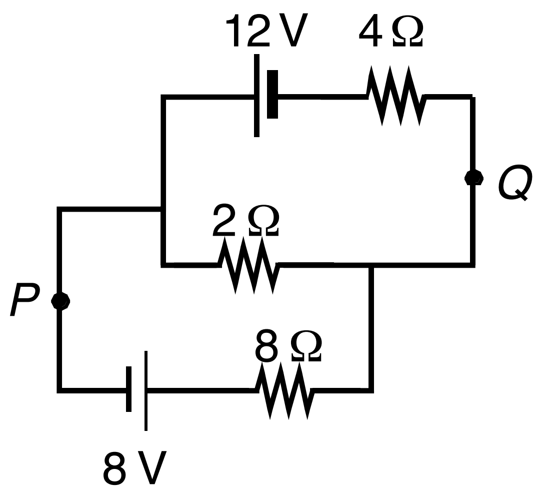
Questions that require qualitative reasoning and verbal explanations are essential for assessing student learning.

Such questions are an effective strategy for helping students learn.

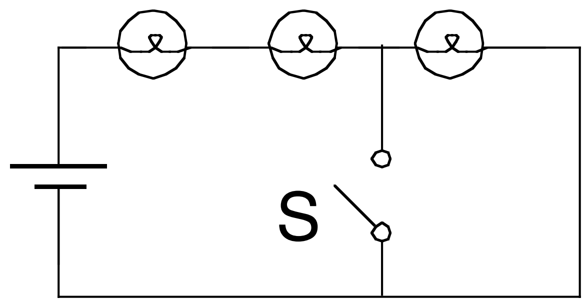
* Ability to apply concepts and reasoning to situations not explicitly memorized

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 ‘*misconception*’ may trivialize the problem

Concepts in physics are interrelated.

They cannot be ‘fixed’ in isolation.

- **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*

↓

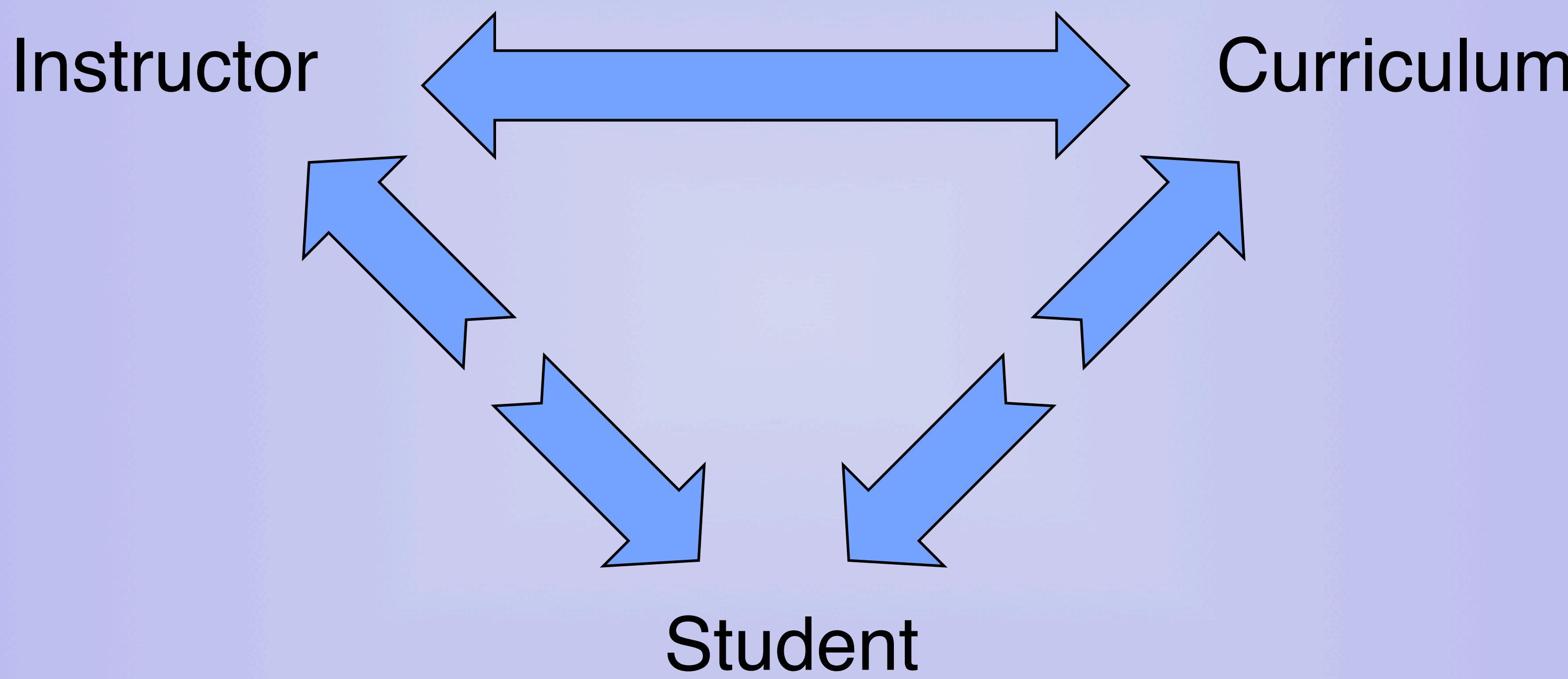
Hearing lectures, reading textbooks, seeing demonstrations, doing homework, and performing laboratory experiments often have little effect on student learning.

- ◊ **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.

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 the *Electric Circuits* module in *Physics by Inquiry*

- 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)*

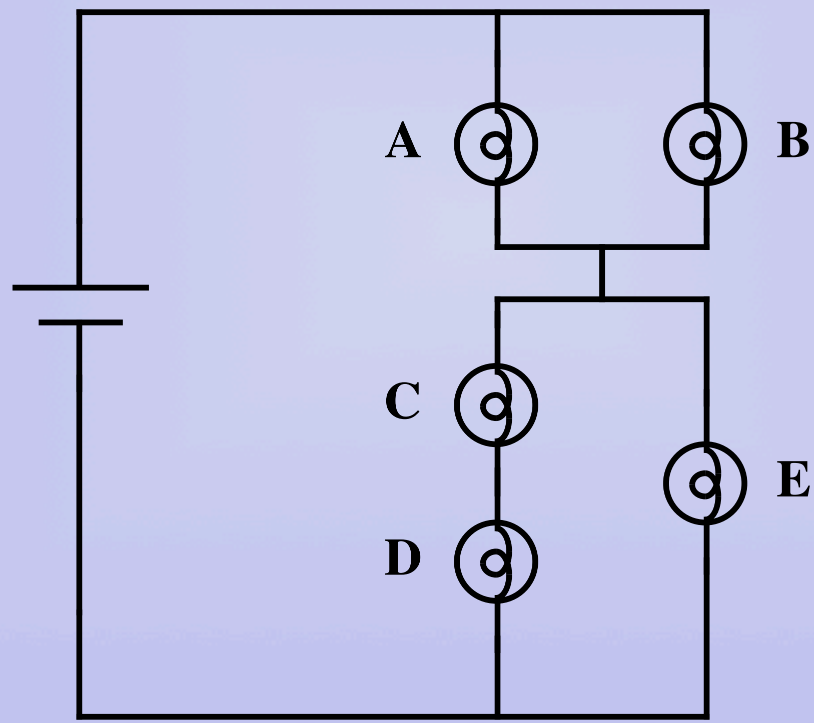
- Questions that require qualitative reasoning and verbal explanations guide development of a functional understanding.

- Curriculum explicitly addresses conceptual and reasoning difficulties identified through research

  Example of instructional strategy: elicit, confront, resolve
  apply, reflect, generalize

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

Application of research and teaching experience to large introductory course

Challenge

to improve student learning in standard physics courses
(constraints of large class size, breadth of coverage, and fast pace)

Need

to secure mental engagement of students
(at a sufficiently deep level)

Requirement

to develop a practical, flexible, sustainable approach
(acceptable to physics faculty)

Response

improve instruction in introductory physics through cumulative, incremental change

(evolution not revolution)

- by recognizing the constraints imposed by lecture-based courses
- by developing research-based tutorials that supplement standard instruction with a modified version of the intellectual experience provided by *Physics by Inquiry*
- by implementing weekly, small-group tutorials that foster development of reasoning ability

Tutorials in Introductory Physics

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

Context (at UW) for tutorials

Each week:

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

Use at other institutions can vary, depending on constraints.

(e.g., 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*

Many iterations of curriculum are required to:

- to clarify the nature, persistence, and inter-relationship of specific student difficulties
- to produce consistent, long-term gains in student learning

Research-based ≠ Research-validated

NFW Example:
a tutorial from mechanics

Pretest

Motivation for Tutorial

Part I of *Tutorial*

Part II of *Tutorial*

Assessment of student learning

NFW Example:
a tutorial from mechanics

Pretest

NFW Example:
a tutorial from mechanics

Pretest

→ Motivation for Tutorial

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

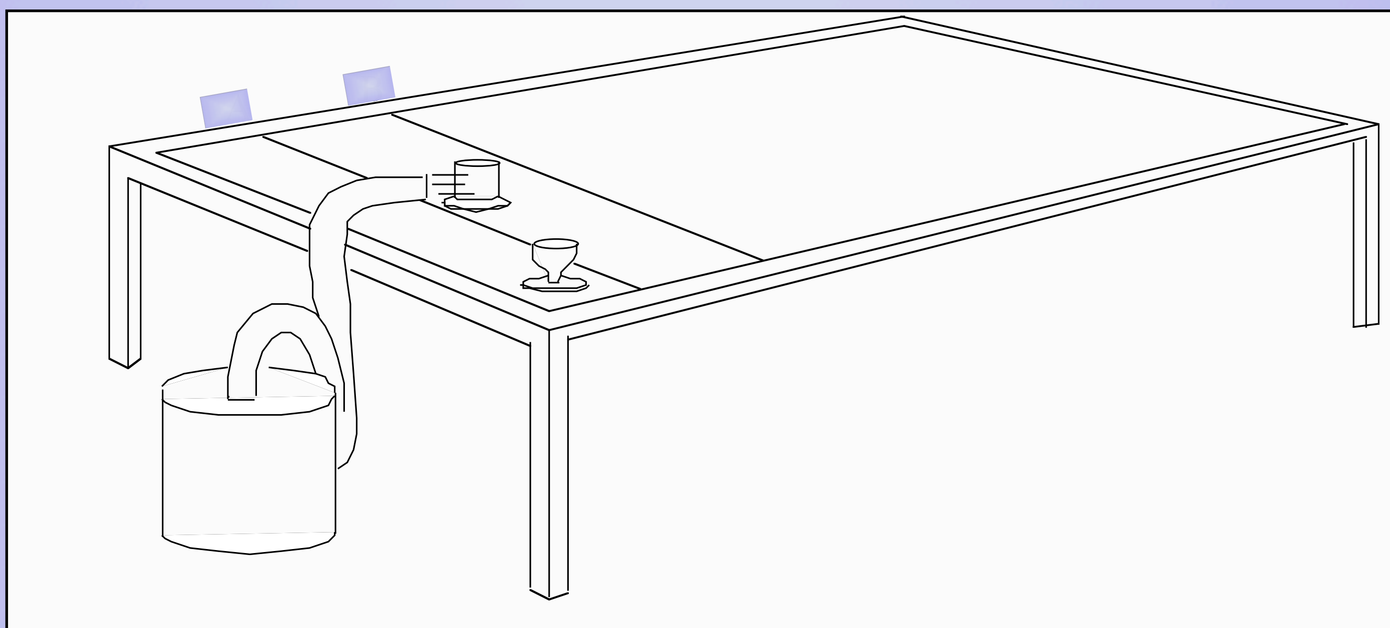
  R.A. Lawson and L.C. McDermott, “Student understanding of the work-energy and impulse-momentum theorems,” Am. J. Phys., ***55****, 811–817, 1987.*

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

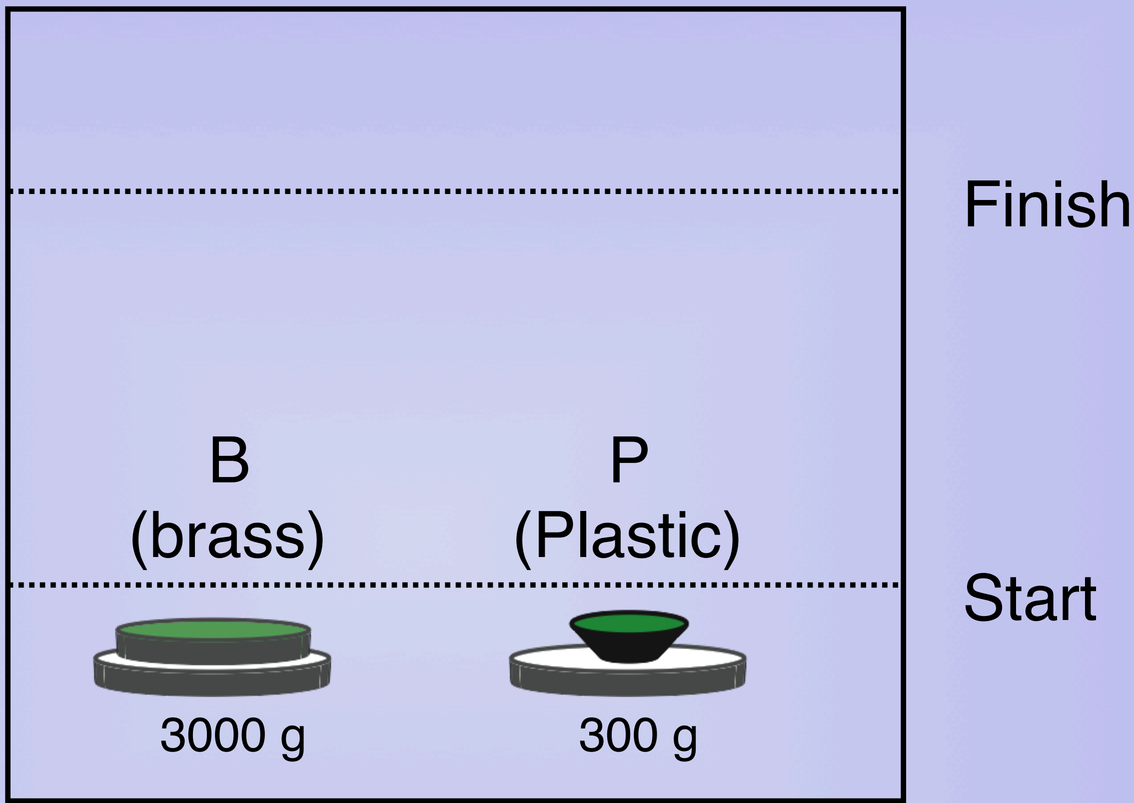
  T. O’Brien Pride, S. Vokos, and L.C. McDermott, “The challenge of matching learning assessments to teaching goals: An example from the work-energy and impulse-momentum theorems,” Am. J. Phys., ***66****,147-157, 1998.*

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 interview tasks 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.

Incorrect Comparison
Incorrect Reasoning

$m_P < m_B$

same Δx

$p_P = p_B$ *(instead of* $p_P < p_B$*)*

Common incorrect explanations:

- *compensation:* (small m) • (large v) = (large m) • (small v)
- *'momentum is conserved' (memorized rule)*
- *same* F *so* same momentum (and same kinetic energy)

$K_P > K_B$ *(instead of* $K_P = K_B$*)*

Common incorrect explanation:

- *compensation:* (small m) • (large v^2) > (large m) • (small v^2)

Correct Comparison
Incorrect Reasoning

$m_P < m_B$

same Δx

$K_P = K_B$

Common incorrect explanations

- compensation: (small m) • (large v^2) = (large m) • (small v^2)
- *'energy is conserved'* (memorized rule)
- *same* F *so same kinetic energies*

Right answers for wrong reasons

Compensation arguments often used by students

Theorems treated as mathematical identities

Cause-effect relationships not understood

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

◊ **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.

Questions that probe student understanding may often be transformed into effective instructional strategies.

⬇

Improvement during some interviews suggested a basic design for the tutorial.

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 (Part 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.

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

Students would have completed various 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*

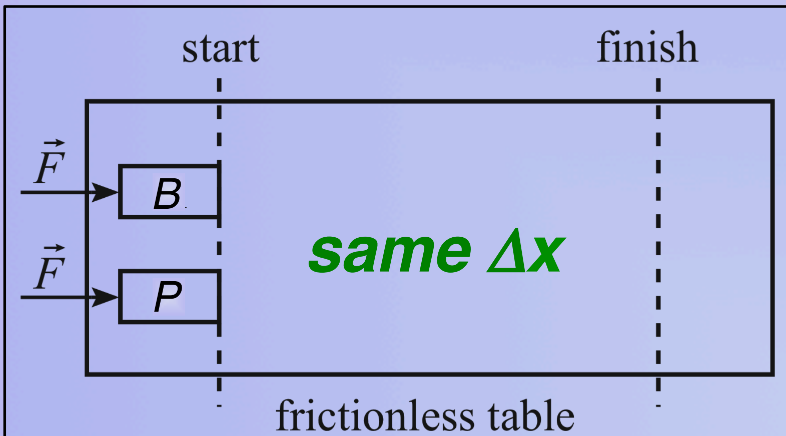
(Guides students in applying theorems in more complicated situation in order to strengthen their conceptual understanding – as well as their ability to reason with vectors.)

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

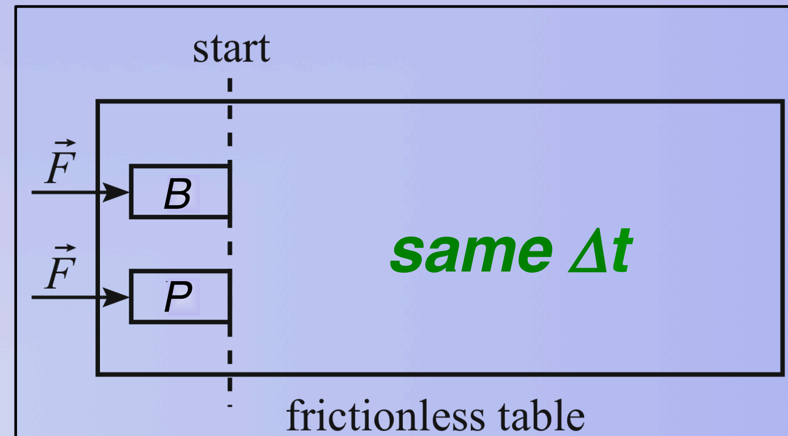


$m_B > m_P$

$v_0 = 0$

Same F

Post-test



Compare final K and p.

	Pretest	Post-test
K:	Same $F\Delta x \rightarrow K_B = K_P$	(Same Δt so brass does not go as far. Thus) * $F\Delta x_B < F\Delta x_P \rightarrow K_B < K_P$
p:	(Same Δx so brass takes longer. Thus) * $F\Delta t_B > F\Delta t_P \rightarrow p_B > p_P$	Same $F\Delta t \rightarrow p_B = p_P$

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 TA's at UW and faculty in national workshops

	TA's Before tutorial N = 74	**Faculty** Before tutorial N = 382	**TA's** After tutorial N = 20
Correct with correct explanation	**Pretest** Same Δx	**Pretest** same Δx	**Post-test** $\Delta t_P \neq \Delta t_B$ $\Delta x_P \neq \Delta x_B$
K comparison	65%	65%	95%*
p comparison	70%	60%	95%*

- *All 20 gave correct comparisons but one gave no explanation.*

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*

Nationally reported MBT results and UW pretest results

	MBT results *after standard instruction** *N = 1100*	**UW Pretest** *after standard instruction (but before tutorial)* *N = 985*
K comparison	*10% - 70%*	*15%*
p comparison	*30% - 70%*	*5%*

** In some instances, instruction before the MBT included the tasks.*

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*

Nationally reported MBT results and UW post-test results

	MBT results after instruction same Δx N = 1100	UW Post-test after lecture and tutorial same Δt N = 435	
Explanations?	**N/A**	**considered**	**ignored**
K comparison	10% - 70%	35%	65%
p comparison	30% - 70%	50%	80%

With explanations ignored, UW post-test results for motion in one dimension are at the top of the nationally reported MBT results.

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.

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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 an 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.