Research in Physics Education as a Basis for Improved Instruction

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Physics Education: Art or Science?

- Thousands of physicist-years have been devoted to teaching physics in colleges and universities
- Implicitly or explicitly, most physicists have considered the teaching of physics as much more an art, than as a science
- Within the past 25 years, university-based physicists have begun to treat the teaching and learning of physics as a research problem
  - Systematic observation and data collection
  - Identification and control of variables
  - In-depth probing and analysis of students’ thinking
  - Reproducible experiments

Goals of Physics Education Research

- Improved learning by ***all*** students – “average” as well as “high performers”
- More favorable attitudes toward physics (and understanding of it) by ***nonphysicists***
- Better understanding of learning process in physics – to facilitate ***continuous improvement*** in physics teaching

® ***Not a search for the “Perfect Pedagogy”***

There is no Perfect Pedagogy!

Role of Physics Education Research

- Investigate learning difficulties
- Develop and assess more effective curricular materials
- Implement new instructional methods that make use of improved curricula

Tools of Physics Education Research

- Conceptual surveys or “diagnostics”: sets of written questions (short answer or multiple choice) emphasizing qualitative understanding *(often given “pre” and “post” instruction)*

  e.g. “Force Concept Inventory”; “Force and Motion Conceptual Evaluation”; “Conceptual Survey of Electricity”

- Students’ written explanations of their reasoning

- Interviews with students

  e.g. “individual demonstration interviews” (U. Wash.): students are shown apparatus, asked to make predictions, and then asked to explain and interpret results in their own words

Caution: Careful probing needed!

- It is ***very easy*** to overestimate students' level of understanding.
- Students ***frequently*** give correct responses based on incorrect reasoning.
- Students' written explanations of their reasoning are powerful diagnostic tools.
- Interviews with students tend to be profoundly revealing … and extremely surprising (and disappointing!) to instructors.

Excerpt from interview: nontechnical physics student

DEM: Suppose she is speeding up at a steady rate with constant acceleration. In order for that to happen, do you need to apply a force? And if you need to apply a force, what kind of force: would it be a constant force, increasing force, decreasing force?

STUDENT: Yes you need to have a force.
It can be a constant force, or it could be an increasing force.

DEM: . . .She is speeding up a steady rate with constant acceleration.

STUDENT: Constantly accelerating? Then the force has to be increasing . . . Wait a minute . . .The force could be constant, and she could still be accelerating.

DEM: Are you saying it could be both?

STUDENT: It ***could*** *be both, because if the force was increasing she would still be constantly accelerating.*

DEM: What do we mean by constant acceleration?

STUDENT: Constantly increasing speed; a constant change in velocity.

Some Specific Issues

Many (if not most) students:

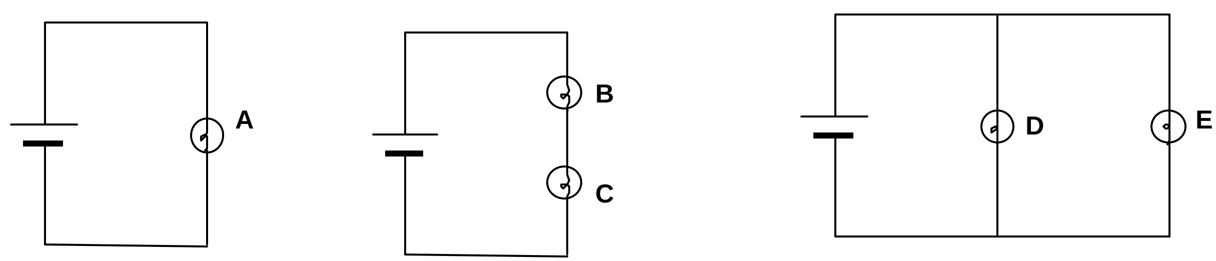
- develop weak ***qualitative*** understanding of concepts *(If lacking a quantitative problem solution, they are unable to determine relative magnitudes, directions, and rates of change)*
- have a strong tendency to view concepts as unrelated and context-dependent (not as interlinked aspects of broad universal principles)
- Lack a **"*functional*"** understanding of concepts (which would allow problem solving in unfamiliar contexts)

Testing "Functional" Understanding

Applying the concepts in unfamiliar situations: Research at the University of Washington [McDermott, 1991]

- Even students with good grades may perform poorly on qualitative questions in unexpected contexts
- Performance both before ***and after*** standard instruction is essentially the same

Example: *All batteries and bulbs in these three circuits are identical; rank the brightness of the bulbs.* *[**Answer:** A = D = E > B = C]*



This question has been presented to over 1000 students in algebra- and calculus-based lecture courses. Whether before ***or*** after instruction, ***fewer than 15%*** give correct responses.

Investigations of Expert vs. Novice Problem-Solving Methods [Maloney, 1994]

- Novices fail to make use of ***qualitative analysis*** to construct appropriate representations.
  [McMillan & Swadener, 1991]

- Novices attempt to analyze problems based on ***surface features*** ("spring" problem, "inclined-plane" problem, etc.) instead of broad physical principles.
  [Chi et al., 1982]

- Novices lack ***hierarchical, interlinked knowledge structures*** which provide a foundation for expert-like problem-solving technique. [Reif, et al., 1982-84]

Key Obstacles to Improved Learning

- Students hold many firm ideas about the physical world that may conflict strongly with physicists' views
- Most introductory students lack study and learning skills that would permit more efficient mastery of physics concepts

“Misconceptions”/Alternative Conceptions

Student ideas about the physical world that conflict with physicists’ views

- Widely prevalent; there are some particular ideas that are almost ***universally*** held by beginning students

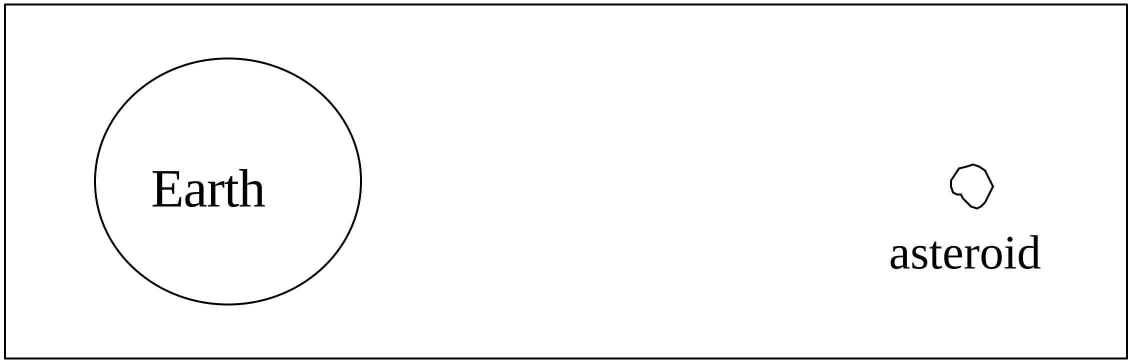
- Often very well-defined – not merely a “lack of understanding,” but a very specific idea about what *should* be the case (but in fact is not)

- Often -- *usually* -- ***<u>very</u>*** tenacious, and hard to dislodge; ***Many*** repeated encounters with conflicting evidence required

Examples:

- **An object in motion *must* be experiencing a force**
- **A given battery always produces the *same* current in *any* circuit**
- **Electric current gets “used up” as it flows around a circuit**

Example: Students' Understanding of Gravitational Forces [Jack Dostal and D.E.M., 1999]



Is the magnitude of the force exerted **by the asteroid on the Earth** *larger than, smaller than, or the same as the magnitude of the force exerted* **by the Earth on the asteroid*?*** *Explain the reasoning for your choice.*

This question was presented in the first week of class to all students taking calculus-based introductory physics at ISU during Fall 1999.

First-semester Introductory Physics *(N = 546)*: ***15% correct responses***

Second-semester Introductory Physics *(N = 414)*: ***38% correct responses***

Majority of students <u>persist</u> in claiming that Earth exerts greater force because it is larger or more massive

Another Example: Students' Beliefs About Gravitation [Jack Dostal and D.E.M., 1999]

Imagine that an astronaut is standing on the surface of the moon holding a pen in one hand. If that astronaut lets go of the pen, what happens to the pen? Why?

This question was presented in the first week of class to all students taking calculus-based introductory physics at ISU during Fall 1999.

First-semester Introductory Physics *(N = 534)*:

32% state that it will "float" or "float away"

Second-semester Introductory Physics *(N = 408)*:

23% state that it will "float" or "float away"

Significant fraction of students persist in claiming that there is "no gravity" or "insignificant gravity" on the moon

But … *some* students learn efficiently . . .

- Highly successful physics students (e.g., future physics instructors!) are ***"active learners."***
  – they continuously probe their own understanding of a concept (pose their own questions; examine varied contexts; etc.)
  – they are sensitive to areas of confusion, and have the confidence to confront them directly

- Great majority of introductory students are unable to do efficient "active learning" on their own: they don't know "which questions they need to ask"
  – they require considerable prodding by instructors, aided by appropriate curricular materials
  – they need frequent confidence boosts, and hints for finding their way

Keystones of Innovative Pedagogy

- Instruction recognizes – and deliberately elicits – students' preexisting "alternative conceptions" and other common learning difficulties.

- To encourage active learning, students are led to engage ***during class time*** in deeply thought-provoking activities requiring intense mental effort. ***("Interactive Engagement.")***

- The "process of science" is used as a means for ***learning*** science (***"Inquiry-based learning" –*** *physics as exploration and discovery*): students are not "told" things are true; instead, they are guided to "**figure it out for themselves."**

Elicit Students' Pre-existing Knowledge Structure

- Have students make predictions of the outcome of experiments***. (Selected to address common conceptual stumbling blocks)***

- Require students to give written explanations of their reasoning. ***(Aids them to precisely articulate ideas.)***

- Pose specific problems that consistently trigger certain types of learning difficulties. ***(Based on research)***

- Structure subsequent activities to confront difficulties that were elicited. ***(Tested through research)***

“Interactive Engagement”

“Interactive Engagement” methods require an <u>active learning</u> classroom:

- Very high levels of interaction between students and instructor
- Collaborative group work among students during class time
- ***<u>Intensive</u>*** active participation by students in focused learning activities during class time

Inquiry-based Learning/ “Discovery” Learning

Pedagogical methods in which students are guided through investigations to “discover” concepts

- Targeted concepts are generally ***not*** told to the students in lectures before they have an opportunity to investigate (or at least ***think*** about) the idea
- Can be implemented in the instructional laboratory (“active-learning” laboratory) where students are guided to form conclusions based on evidence they acquire
- Can be implemented in “lecture” or recitation, by guiding students through chains of reasoning utilizing printed worksheets

New Approaches to Instruction on Problem Solving

- **A. Van Heuvelen**: Require students to construct multiple representations of problem (draw pictures, diagrams, graphs, etc.)
- **P. and K. Heller:** Use “context rich” problems posed in natural language containing extraneous and irrelevant information; teach problem-solving strategy
- **F. Reif et al.:** Require students to construct problem-solving strategies, and to critically analyze strategies
- **P. D’Allesandris:** Use “goal-free” problems with no explicitly stated unknown
- **J. Mestre, W. Gerace, W. Leonard, R. Dufresne:** Emphasize student generation of qualitative problem-solving strategies

New Instructional Methods: Active-Learning Laboratories

- **“Microcomputer-based Labs”** *(P. Laws, R. Thornton, D. Sokoloff)*: Students make predictions and carry out detailed investigations using real-time computer-aided data acquisition, graphing, and analysis. *“Workshop Physics” (P. Laws)* is ***entirely*** lab-based instruction.

- **“Socratic-Dialogue-Inducing” Labs** *(R. Hake)*: Students carry out and analyze activities in detail, aided by “Socratic Dialoguist” instructor who asks leading questions, rather than providing ready-made answers.

New Instructional Methods: Active Learning Text/Workbooks

- ***Electric and Magnetic Interactions***, R. Chabay and B. Sherwood, Wiley, 1995.
- ***Understanding Basic Mechanics***, F. Reif, Wiley, 1995.
- ***Physics: A Contemporary Perspective***, R. Knight, Addison-Wesley, 1997-8.
- ***Six Ideas That Shaped Physics***, T. Moore, McGraw-Hill, 1998.

New Instructional Methods: University of Washington Model

"Elicit, Confront, Resolve"

Most thoroughly tested and research-based physics curricular materials; based on 20 years of ongoing work

- ***"Physics by Inquiry":*** 3-volume lab-based curriculum, primarily for elementary courses, which leads students through extended intensive group investigations. Instructors provide "leading questions" only.

- ***"Tutorials for Introductory Physics":*** Extensive set of worksheets, designed for use by general physics students working in groups of 3 or 4. Instructors provide guidance and probe understanding with "leading questions." Aimed at eliciting deep conceptual understanding of frequently misunderstood topics.

Research-based Software/Multimedia

- ***Simulation Software:*** *ActivPhysics (*Van Heuvelen and d'Allesandris); *Visual Quantum Mechanics* (Zollman, Rebello, Escalada)

- ***"Intelligent Tutors":*** *"Freebody," (*Oberem); *"Photoelectric Effect," (*Oberem and Steinberg)

- ***"Reciprocal Teacher":*** *"Personal Assistant for Learning," (*Reif and Scott)

New Instructional Methods: Active Learning in Large Classes

- ***"Active Learning Problem Sheets"*** (A. Van Heuvelen): Worksheets for in-class use, emphasizing multiple representations (verbal, pictorial, graphical, etc.)
- ***"Interactive Lecture Demonstrations"*** (R. Thornton and D. Sokoloff): students make written predictions of outcomes of demonstrations.
- ***"Peer Instruction"*** (E. Mazur): Lecture segments interspersed with challenging conceptual questions; students discuss with each other and communicate responses to instructor.
- ***"Workbook for Introductory Physics"*** (D. Meltzer and K. Manivannan): combination of multiple-choice questions for instantaneous feedback, and sequences of free-response exercises for in-class use.

Active Learning in Large Classes

- Use of “Flash-card” communication system to obtain instantaneous feedback from entire class;
- Cooperative group work using carefully structured free-response worksheets -- ***“Workbook for Introductory Physics”***
- Drastic de-emphasis of lecturing

Goal: *Transform large-class learning environment into “office” learning environment (i.e., instructor + one or two students)*

Effectiveness of New Methods:(I)

Results on “Force Concept Inventory” (diagnostic exam for mechanics concepts) in terms of “g”: overall learning gain (posttest - pretest) as a percentage of ***maximum possible gain***

- Survey of 4500 students in 48 “interactive engagement” courses showed g = 0.48 ± 0.14

--> highly significant improvement compared to non-Interactive-Engagement classes (g = 0.23 ± 0.04)

(R. Hake, *Am. J. Phys.* **66**, 64 [1998])

- Survey of 281 students in 4 courses using “MBL” labs showed g = 0.34 (range: 0.30 - 0.40)

(non-Interactive-Engagement: g = 0.18)

(E. Redish, J. Saul, and R. Steinberg, *Am. J. Phys.* **66**, 64 [1998])

Effectiveness of New Methods: (II)

Results on "Force and Motion Conceptual Evaluation" (diagnostic exam for mechanics concepts, involving both graphs and "natural language")

Subjects: 630 students in three noncalculus general physics courses using "MBL" labs at the University of Oregon

Results (posttest; % correct):

	Non-MBL	**MBL**
Graphical Questions	16	80
Natural Language	24	80

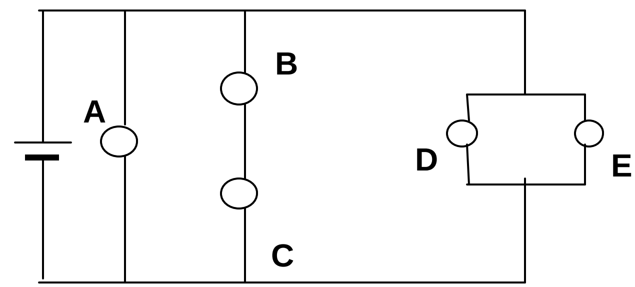
(R. Thornton and D. Sokoloff, *Am. J. Phys.* 66, 338 [1998])

Effectiveness of New Methods: (III)

University of Washington, Physics Education Group

RANK THE BULBS ACCORDING TO BRIGHTNESS.

ANSWER: *A=D=E > B=C*



Results: Problem given to students in calculus-based course 10 weeks after completion of instruction. Proportion of correct responses is shown for:

Students in lecture class: 15%

Students in "lecture + tutorial" class: 45%

(P. Shaffer and L. McDermott, *Am. J. Phys.* **60**, 1003 [1992])

[At Southeastern Louisiana University, problem given on final exam in algebra-based course using ***"Workbook for Introductory Physics"***

Results: more than 50% correct responses.]

Challenges Ahead . . .

- Many (most?) students are comfortable and familiar with more passive methods of learning science. ***Active learning methods are always challenging, and frequently frustrating for students. Some (many?) react with anger.***

- Active learning methods and curricula are not "instructor proof." Training, experience, energy and commitment are needed to use them effectively.

Summary

- Much has been learned about how students learn physics, and about specific difficulties that are commonly encountered.

- Based on this research, many innovative instructional methods have been implemented that show evidence of significant learning gains.

- The process of improving physics instruction is likely to be endless: we will never achieve “perfection,” and there will always be more to learn about the teaching process.