Effectiveness of Introductory Physics Instruction:

The Present Situation, and Pathways toward Improvement

[Keynote Address: Iowa Section Meeting, AAPT, November 7, 1998]

David E. Meltzer
Department of Physics and Astronomy
Iowa State University

Outline

- What do we mean by “effectiveness” of instruction?
- How do we determine effectiveness?
- What does research show regarding effectiveness of traditional instruction?
- What new methods have demonstrated significant improvements in effectiveness?

Physics instruction may have multiple goals:

- Improve student attitudes toward, and understanding of scientific process
- Improve ability in quantitative problem solving
- Improve students’ laboratory skills
- Improve students’ understanding of physics concepts, and reasoning skills

--> Effectiveness of instruction may be different for different goals

“Philosophical” Issues

- Individual instructors may value and emphasize different goals
- Individual instructors may target different groups within the student population

  e.g., aim instruction toward the “top 10%,” ***<u>or</u>*** *aim for significant improvement for majority of students enrolled*

Examples of Student Attitudes

- Do students view physics as a collection of loosely related facts, equations, and algorithms to be memorized, ***or*** as a process of exploration and inquiry, leading toward coherent knowledge?
- Do students believe a knowledge of physics has significance for their own lives?
- Are students strongly motivated to spend time and effort studying physics? *(Are they confident they can be successful?)*

Methods of Assessing Attitudes

- Interviews of students
- Student surveys (written questionnaires) given both before and after instruction

Examples (from “MPEX” survey):

¶ *“Physical laws have little relation to what I experience in the real world”*

¶ *“Knowledge in physics consists of many pieces of information each of which applies primarily to a specific situation”*

Answer on scale of 1 (strongly disagree) to 5 (strongly agree)

Results of Research: Student Attitudes

Results of the Maryland Physics Expectations Survey (MPEX) of 1500 students at six institutions, *Am. J. Phys.* ***66****, 212 (1998):*

- The initial state of student attitudes and expectations differs significantly from that of experts
- Student attitudes are very similar at different institutions
- **Student attitudes *deteriorated* as a result of instruction, in all six samples studied**

[Non-traditional instruction showed *slight improvement* on some items]

Methods of Assessing Problem-Solving

- **Analyze students' problem-solving *method*:** Is it based on general principles, or merely searching for "correct equation" that fits particular situation?
- **Vary context:** Can students utilize problem-solving methods in physical situations ***different*** from those they have practiced?
- *Are students simply memorizing procedures and algorithms for particular "standard" problems?*
- *Do they merely attempt to manipulate equations to yield desired quantities? ("Plug and Chug")*

Results of Research: Problem Solving

Traditional instruction leads students to adopt various suboptimal strategies:

- start immediately with equations (searching for the unknown) instead of conducting a qualitative analysis
- work backward from desired unknown, instead of beginning with general principles and working forward from given information
- fail to identify "implicit" procedural aspects omitted from textbook presentations (e.g., ***when*** to use a particular equation, instead of some other one)
- fail to use multiple representations (diagrams, graphs, etc.) to help analyze problem

Cf. David P. Maloney, *Research on Problem Solving: Physics (1994)*

Methods of Assessing Conceptual Understanding

- 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*

Results of Research: Conceptual Understanding (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 2100 students in 14 "traditional" courses at 9 institutions showed g = 0.23 ± 0.04

--> no correlation with instructor or pretest score

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

- Survey of 144 students in 5 "traditional" courses showed g = 0.18 (range: 0.01 - 0.29)

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

Results of Research: Conceptual Understanding (II)

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

Subjects: 240 students in two "traditional" noncalculus general physics courses at the University of Oregon

Results:

	Pretest	Posttest
	(percent correct responses)	
Graphical Questions	8	16
Natural Language	16	24

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

Results of Research: Conceptual Understanding (III)

The Physics Education Group at the University of Washington (Seattle) has carried out intensive investigations of student understanding over a 20-year period

- Even students with good grades in traditional courses perform poorly on concept-oriented qualitative questions
- Performance both before ***and after*** instruction is essentially the same.

Example: 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.

So is this really a problem, or what?

- Most students in traditional courses only develop very rudimentary problem-solving skills, and acquire naïve and mistaken ideas regarding the *nature* of science.
- Physics Education Research consistently shows that conceptual learning by average students in introductory courses is small to nonexistent [$\approx$ 0 - 25% of maximum possible gain].
- Students who go on to take more advanced physics or engineering courses may, in time, acquire basic conceptual knowledge. (*Or,* they may not . . .)
- Students who do ***not*** take other physics courses (life sciences majors, pre-professionals, etc.) would probably <u>***never***</u> learn fundamental physical principles.

“Traditional” Instruction

- Lectures, “end-of-chapter” quantitative problems, “follow-the-recipe” labs designed to verify known principles
- Instructor presents general principles and demonstrates applications in a few special cases

—> *Students not required to “think through” derivation of principles, nor to “discover” them from physical evidence*

Main Themes of New Instructional Methods

- Students do not come into the classroom as blank slates; rather, they often have strong preconceived ideas about physical principles.
- “Teaching by Telling” is ineffective in communicating physics concepts: ***instructors must help students “figure it out themselves.”***
- In order to synthesize their own understanding of new concepts, students must be aided to “actively engage” in deeply thought-provoking activities requiring intense mental effort. ***Traditional lectures, labs, and recitations are insufficient.***

“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

“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
- **W. Leonard, R. Dufresne, and J. Mestre:** 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.

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.

New Active-Learning Curricula for High-School Physics

- “Minds-On Physics” *(U. Mass. Physics Education Group)*
- Comprehensive Conceptual Curriculum for Physics [C^{3}P] *(R. Olenick)*
- PRISMS *(Physics Resources and Instructional Strategies for Motivating Students)* *(R. Unruh)*

Effectiveness of New Methods: Conceptual Understanding (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 (cf. 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) ***(Cf. g = 0.18)***

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

Effectiveness of New Methods: Conceptual Understanding (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):

	MBL	**"traditional"**
Graphical Questions	80	16
Natural Language	80	24

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

Effectiveness of New Methods: Conceptual Understanding (III)

This question, given as a posttest, is nearly identical to the "bulbs" problem studied by the University of Washington 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 "traditional" class: 15%

Students in "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"***: more than 50% correct responses.

Are Students' High Learning Gains Retained Over Time?

- Approximately 80% of high learning gains ($g > 0.40$) retained 1, 2, and 3 years after instruction using *Tutorials in Introductory Physics*. (G. Francis, J. Adams, and E. Noonan, *The Phys. Teacher*, November 1998)

- Significantly higher scores one year after instruction for students using active-learning textbook (*Electric and Magnetic Interactions)*, in comparison to traditional instruction. (B. Sherwood and R. Chabay, 1997)

Summary

- Traditional methods of introductory physics instruction produce few lasting gains in conceptual understanding for most students

- New methods of instruction employing active-learning strategies have demonstrated significant improvements in learning, and offer much hope for the future