Research, Innovation and Reform in Physics Education

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Some fraction of students in introductory physics have always done “well”

- High-performing students seem to master concepts and problem-solving techniques, and do well in follow-up courses.

- The proportion of high-performing students varies greatly, depending on institution and student population.

- Many – if not most – students do not fall in the high-performing category.

- Even most high-performing students could benefit from improved instruction.
Goals of Improved Instruction

• Increase knowledge of physics concepts, and problem-solving ability, for majority of enrolled students (especially in introductory courses).

• Improve attitudes of students toward physics:
  – understanding of scientific process
  – enjoyment of physics instruction
Role of Physics Education Research

• Probe “alternative conceptions” of physical reality (misconceptions, preconceptions, etc.)

• Investigate particular conceptual stumbling blocks on road to understanding physics

• Explore differences between expert and novice problem solvers

** Apply research results to improve instruction! **
Probe “alternative conceptions” of physical reality (misconceptions, preconceptions, etc.)
“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 -- very 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
Investigate particular conceptual stumbling blocks on road to understanding physics
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
Learning Difficulties Explored by Research

- Difficulty in transforming among diverse representations (verbal, mathematical, diagrammatic, graphical, etc.) of physical concepts
- Weakness in “functional” understanding (i.e., making use of a concept to solve a problem)
- Difficulty in transforming among contexts (e.g., from “textbook” problems to “real” problems)
Difficulties in Translating Among Representations

Example: Elementary Physics Course at Southeastern Louisiana University, targeted at elementary education majors.

- Newton’s second law questions, given as posttest (from “Force and Motion Conceptual Evaluation”; nearly identical questions posed in graphical, and “natural language” form):
  - % correct on “force graph” questions: 56%
  - % correct on “natural language” questions: 28%
This slide shows the force graphs from the FMCE
This shows the force sled problems
Changing Contexts: Textbook Problems and “Real” Problems

- “Standard” Textbook Problem:
  - [textbook problem]

  - [example of context-rich talk]
Testing “Functional” Understanding

Applying the concepts in unfamiliar situations: Research at the University of Washington

- 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:** 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.

- [five bulbs problem]
**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.
[these are in Lincoln talk]

2 slides of interview transcript
[explain MBT #21]
Explore differences between expert and novice problem solvers
Results of Research: Problem Solving

Strong tendency for 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

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 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.”

• To encourage active learning, students are led to engage 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 them out for themselves.”)
“Interactive Engagement”

“Interactive Engagement” methods require an active learning classroom:

- Very high levels of interaction between students and instructor
- Collaborative group work among students during class time
- **Intensive** 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


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 Active-Learning Curricula for High-School Physics

• “Minds-On Physics” (U. Mass. Physics Education Group)

• Comprehensive Conceptual Curriculum for Physics [C^3P] (R. Olenick)

• PRISMS (Physics Resources and Instructional Strategies for Motivating Students) (R. Unruh)
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.
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)
This is photo from Eric’s book
This is title page of Workbook
This is page 1 of WB
This is page 19 of WB
• This is gravity page
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 $g = 0.48 \pm 0.14$

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

  (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])
[the next slide was not shown; here for reference]
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):

<table>
<thead>
<tr>
<th></th>
<th>Non-MBL</th>
<th>MBL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Graphical Questions</td>
<td>16</td>
<td>80</td>
</tr>
<tr>
<td>Natural Language</td>
<td>24</td>
<td>80</td>
</tr>
</tbody>
</table>

Effectiveness of New Methods: Conceptual Understanding (III)

University of Washington, Physics Education Group

RANK THE BULBS ACCORDING TO BRIGHTNESS.

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

[five bulbs in one circuit problem]

**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”*: 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, and energy 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.
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Characteristics of “Deep” Understanding

• Understand and use general principles (e.g., conservation laws, symmetry, Newton’s third law)

• Possess hierarchical, connected knowledge (e.g., interconnection among conservative forces, potential energy, work-energy theorem, etc.)

• Use qualitative understanding to structure and check problem solutions (e.g., estimate answer by ignoring small quantities)