Using students’ spontaneous reasoning to guide the design of effective instructional strategies

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Outline

• Physics Education Research (PER) in the USA
• The UW Physics Education Group: An empirically oriented research program
• Two illustrative examples
Physics Education Research in the USA

• Primary focus: teaching and learning at the university level

• Researchers: embedded in the physics community
  – many obtained a PhD in a traditional area of research
  – typically located in physics departments
  – graduate students often earn a PhD in physics

• Research programs: influenced by the culture of physics
  – projects often reflect shared instructional goals and values
  – efforts to establish causal relationships are favored over efforts to describe phenomena
  – hypotheses are rarely stated explicitly
  – projects often have both basic and applied aspects
Physics Education Research in the USA

Major research universities with tenured physics faculty who do PER and where students can earn a PhD in Physics for PER

- University of Washington
- University of Maryland
- University of Illinois at Urbana-Champaign
- University of Colorado
- University of Maine
- The Ohio State University
- Kansas State University
- North Carolina State University
- Oregon State University
Physics Education Research in the USA

• Meetings and conferences
  – American Physical Society meetings
  – American Association of Physics Teachers meetings
  – Physics Education Research Conference
  – Foundations and Frontiers in PER (biannual)

• Journals
  – *American Journal of Physics*
  – *Proceedings of the Physics Education Research Conference*
  – *Physical Review Special Topics - Physics Education Research*

In addition to fostering interaction among researchers, a major goal is to influence the physics community.
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Physics Education Group at UW
2011-2012

Faculty
Paula Heron
Lillian McDermott
Peter Shaffer

Lecturers & post-docs
Donna Messina
David Smith

Program Coordinator
Nina Tosti

IT Specialist
Isaac Leinweber

Physics PhD students
Carolyn Auchter
Paul Emigh
Ryan Hazelton
Alexis Olsho
Heather Russell
Brian Stephanik
Stella Stylianidou
Physics Education Group at UW

**Primary goal:**

- improve student learning from kindergarten through graduate school

**Primary activities:**

- conduct basic research on student understanding
- develop **instructional materials** for university-level courses
- provide **professional development** for
  - school teachers
  - university faculty
  - current and future physics education researchers
Preparing pre-university teachers to teach physics and physical science*

*Physics by Inquiry*
*John Wiley & Sons, Inc., 1996*

Improving student learning in introductory physics**

*Tutorials in Introductory Physics*
*Prentice Hall, 2002*

* available in Greek and Polish
** available in Spanish and German
Physics Education Group at UW

Instructional goals

To help students develop:

• a functional understanding of important concepts and principles

• the reasoning ability to apply these concepts and principles in novel situations

• the ability to reflect on their own thinking

Reflect what we think is important
Physics Education Group at UW
Conceptual framework

“small-c constructivist”

• Existing knowledge (whether or not it is “correct”) is the foundation on which new knowledge is built

• Constructing stable and coherent knowledge structures requires effort

• Social interaction plays an important role in learning

Reflects our beliefs about learning
To improve student learning of a given topic we need to:

- Find out what students already know
- Understand how their thinking interacts with instruction
- Identify instructional strategies on a topic-by-topic basis
- Generalize findings (cautiously)

*Reflects what we have found to be useful*
“The point of view taken here is that of a physics instructor whose primary motivation for research is to understand better what students find difficult about physics and to use this information to help make instruction more effective.”

Lillian C. McDermott, in *Toward a scientific practice of science education*, Gardner, Greeno, Reif, Schoenfeld, diSessa, & Stage, eds. (Erlbaum, 1990)
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How can students’ spontaneous reasoning teach us about learning?

An example in the context of the equilibrium of rigid bodies

Ortiz, Heron and Shaffer (Am. J. Phys. 2005)
• Introductory calculus-based physics
  – physics, chemistry, & engineering students

• Engineering mechanics courses (statics & dynamics)
  – engineering students (2\textsuperscript{nd} year)

• Special courses for prospective and practicing elementary and secondary teachers
  – varied backgrounds
The “baseball bat” question

A student balances a baseball bat on a finger.

• Is the center of mass to the right, to the left, or at point $P$?
• Is the mass to the left greater then, less than, or equal to the mass to the right?

Explain your reasoning.
“If you were to consider each of the pieces to have a center of mass of their own, the $x_{cm}$ on A would be at a farther distance from the break. $m_A$ would be smaller than $m_B$ whose $x_{cm}$ is not as far away from the break.”
Sample *incorrect* responses

“To be able to balance the bat, the forces on the right of P and the forces on the left of P cancel each other out... the masses [to left and right of P] are equal.”

“\(m_A = m_B\). The term ‘center of mass,’ when translated into everyday English means the ‘center of mass,’ i.e., if separated at the center, half will be on one side and half on the other.”
Maybe students responded incorrectly because:

- they are not very smart
- they had not been taught the relevant material
- they *had* been taught the material, but poorly
- they misunderstood the question or made unintended assumptions
- they were misled by the term “center of mass”
- they weren’t taking the question seriously
- they ignored their correct intuition because it was a physics test
- they haven’t had enough real-world experience (“kids today …”)
- ...

*Most of these explanations, while reasonable, are not supported by evidence*
Results on baseball bat question

9 sections of introductory physics; $N_{\text{total}} > 1000$
Results on baseball bat question

9 sections; $N_{\text{total}} > 1000$
◊ Students tend to give the same responses whether or not grades are awarded for the correct answer.

Results on baseball bat question

- "teaching to the test"
When ideas are counter-intuitive, “teaching to the test” is more difficult than commonly assumed.
The effect of additional instruction: Example from introductory physics

- A demonstration based on the bat question was performed by a professor familiar with our research

- 40% answered the bat question correctly several days later ($N = 84$)

- Common *incorrect* response:
  
  “$m_A = m_B$ like Professor X showed us in class. Also, if they weren’t equal, the bat would tip over.”
There is a strong tendency to “see” what one expects.


“Confronting” incorrect ideas may be insufficient; most students need help resolving the underlying conceptual difficulties.
The effect of additional instruction: Example from second-year engineering statics at UW

- Students had a three-hour session on centroids and center of mass
  - Worked in small groups
  - Made predictions about the location of the center of mass of assorted shapes
  - Checked their predictions with real apparatus

- 15% later answered the bat question correctly ($N > 70$)
◊ Certain conceptual and reasoning difficulties are not addressed by traditional instruction.

◊ Even “pedagogically sound” instruction may not address serious and persistent difficulties.

Modifying the **form** of instruction may be necessary, but is not sufficient. Attention to student ideas about the topic is essential.

Instruction should be evidence-based not ideology-based
Interpretation of results of baseball bat problem (and related questions):

Student errors result from an underlying difficulty:

*The failure to differentiate torque (moment) from the more familiar concept of force*

A problem at the intersection of prior knowledge and new concepts.
Comment

“failure to differentiate” two concepts: tendency to use one concept when the other is appropriate in some but not all circumstances

not a “misconception” in the sense of a robust alternative theory
How can student difficulties be addressed while respecting existing instructional constraints?

Need for flexible, research-based instructional materials.
Tutorials in Introductory Physics

A set of instructional materials to supplement instruction in large introductory courses

General goals:
• Constructing concepts
• Developing reasoning ability
• Relating physics formalism to the real world

General instructional strategies:
• Teaching is by questioning (not by telling)
• Discussions among students are emphasized

Specific goals and strategies are determined by research
Introductory calculus-based physics at UW

• ~1000 students at any one time

• Standard textbook

• Weekly schedule:
  – lectures (3 x 1hr)
  – laboratory session (1 x 2hr)
  – “tutorial” session (1 x 1hr)
  – homework problems from textbook

• Instruction by faculty and graduate teaching assistants
Basic features of tutorial system at UW

- small groups (3-4) work through worksheets
- tutorial instructors (TAs) teach *by questioning*
- all course examinations include questions on tutorial material
Matching the strategy to the difficulty

• Difficulty:
  – Assumption that if there is equal mass (weight/force) on both sides of the fulcrum then the object will balance

• Strategy
  – Help students recognize that equal mass on both sides of the fulcrum is neither necessary nor sufficient to ensure balancing
Example of tutorial activity

Hang board from hole to right of center of mass.

Use clay to balance the board.

Predict how the total mass to the right of the pivot compares to the total mass to the left.

a. Move the clay toward the pivot.

   Does the board remain balanced?
   Does the total mass to either side of the pivot change?

b. Balance board again, with larger piece of clay.

   Does the total mass to either side of the pivot change?
How do we know if a tutorial helped?

*The challenge of causal attribution*

*In real classrooms there are many variables, we need to understand the effect of those we cannot control*
“Non-randomized control trial”

Same question(s) given to different students at different stages

Class A

lecture → question → tutorial

Class B

lecture → tutorial → question
“Non-randomized control trial”

Experience indicates that performance is not typically influenced by:

- experience or popularity of the instructor
- textbook
- precise content of lectures
- testing conditions (e.g. graded vs non-graded)
- “time on task” alone
- many other variables …

Differences in performance can be attributed to a tutorial
Results on baseball bat question

13 classes; $N_{\text{TOTAL}} > 1200$
How can students’ spontaneous reasoning teach us about teaching?

An example in the context of momentum conservation

Close and Heron (Am. J. Phys. 2010)
The three collisions problem

Before collision | After collision
---|---
Case 1
A $v_o$ | $A$ $rac{1}{3}v_o$
$v = 0$ | $v = ?$

Case 2
B $v_o$ | $B$ $v = 0$
$v = 0$ | $v = ?$

Case 3
C $v_o$ | $C$ $rac{1}{6}v_o$
$v = 0$ | $v = ?$

$m_A = m_B = m_C$
and
$m_X = m_Y = m_Z$

Rank the final speeds of the target pucks.

Correct answer ($v_X > v_Y > v_Z$) given by 35% after standard instruction ($N > 500$)
The three collisions problem

Common incorrect response

The target struck by the incident puck that stops has the greatest final speed

“Y gets all of the $p$ from B…”

*Momentum as a conserved scalar quantity*
Some responses to written problems suggested a **scalar** momentum conservation principle.

A tutorial designed to help students distinguish momentum from kinetic energy had limited success.

*Need for interviews to probe thinking in greater detail.*
Interviews: First round

Real collisions (like the written problem)
- equal mass targets
- different interactions (differing degrees of elasticity)

Students typically:
- made the “scalar” momentum prediction
- expressed surprise at the outcome, *but not dismay*
- concluded (cheerfully) that momentum is not always conserved in collisions

*Students did not resolve the conflict appropriately*
Interviews: Second round

Real collisions
- different mass targets
- same interactions (all approximately elastic)

Students were:
- shown a collision
- asked to predict how the final speed would differ in a collision with a target of greater mass (most were correct)
- shown the outcome
- asked to compare the momenta of the two targets (most struggled)
Interview excerpt

(Student is considering the final momentum question)

S: Well, if you had enough mass on that cart [the target] when A collides with it, it would come in and bounce back with the same speed.

I: According to your coordinate system, after the collision, the total momentum is positive, negative, or zero, for A and X?

S: positive.

I: B and Y?

S: positive.

I: What about this other situation that you just described…?

S: Um… Now I’m not quite sure. A would still have momentum that would have changed direction but it would be the same value. The direction shouldn’t matter.
I: You’re remembering that…?

S: No, it’s just kind of popping into my head.

I: Do you remember from your course somebody saying direction was not important or that it was important?

S: No, honestly I do not recall. But that’s what it seems to me, direction shouldn’t matter.
(With guidance, student concludes correctly that $p_{Xf} < p_{Yf}$.)

I: How is it possible that the final momentum of Y could be greater than X when it’s slower?

S: The speed $\vec{v}$ could be less and the mass $\vec{m}$ could be more so that the momentum $\vec{mv}$ is more.

I: Is it possible that the momentum could actually get larger as you go down the line [as the target mass gets bigger and bigger]?

S: I don’t see how that would be possible … It seems false to me. Because if the momentum just keeps getting larger, then that falsifies a cart coming in and rebounding at the same speed.
The massive target’s momentum is **large** even though its velocity is almost zero (correct)

Conflicting ideas

The massive target’s momentum is **almost zero** (compatible with scalar conservation principle)
Significant results

Two (!) students

• introduced the giant-target limit spontaneously and treated it as authoritative
• knew the observable outcome but did not interpret it correctly
• assumed that the momentum of a massive, slowly-moving object is essentially zero
• seemed (implicitly) committed to conservation

New tutorial on momentum conservation
New tutorial on momentum conservation

Guiding assumptions:

• a belief in conservation (of something) will be widespread

• a limiting-case argument will be compelling (even to students who would not use one spontaneously)

• the series of elastic collisions culminating in the “giant-target” limit will:
  – elicit tendency to treat momentum as a conserved scalar
  – elicit tendency to assume momentum is dominated by velocity
  – provoke a conflict that will not be dismissed easily
After standard instruction

After an earlier tutorial

After current tutorial

N > 500
5 sections

N = 234
2 sections

N = 374
3 sections

Correct response given by:

35%
60%
80%

Same time on task
Knowledge of student ideas in specific topic areas is essential for improving instruction.

Intuition, experience, and theories may help, but at least at present, this knowledge must be assembled empirically.
Educational constructivism: Four essential points

- The importance of the student’s active involvement if anything like understanding is to be reached
- The importance of respect for the student and the student’s own ideas
- That science consists of ideas created by human beings
- That the design of teaching should give high priority to making sense to students, of capitalising and using what they know and addressing difficulties that may arise from how they imagine things to be

Thank you for your attention.