

# Remodeling University Physics with Physics Education Research

synopsis of a speech by David Hestenes at the AAPT conference in 2000 for physics department chairs.

## Abstract:

We review the design, results and implications of the Force Concept Inventory (FCI) as an instrument for evaluating the effectiveness of physics instruction at both the high school and college level. This is one of several instruments used to evaluate ongoing reforms at ASU.

For several years, we have been developing a University Physics course organized around models and modeling to make the subject matter and procedural knowledge more explicit, systematic and coherent. This has required extensive “remodeling” of the standard course. The instructional method employed is a variant of the *modeling method* that has proved so successful in high school physics. Students work in collaborative groups in a technology-rich studio classroom. With well-documented success in a small classroom environment, we are currently adapting the approach to a large classroom and developing workshops for wide dissemination.

**Speaker:** David Hestenes 480/965-6277  
Dept. of Physics and Astronomy hestenes@asu.edu  
Arizona State University  
Tempe, Arizona 85287-1504  
Modeling website: <<http://modeling.asu.edu/>>

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## I. Evaluation of Instruction

One basic task for **Physics Education Research (PER)** is to develop instruments for evaluating outcomes of instruction. To enable fair comparison of different instructional methods, instruments must be carefully constructed, validated and calibrated.

For evaluating mechanics instruction, the most widely used instrument, by far, is the **Force Concept Inventory (FCI)**. We have FCI data on more than 20,000 physics students at every level from 8<sup>th</sup> grade to first year graduate and every kind of school from urban and rural high schools to Harvard University. This extensive data base has proved to be exceptionally reproducible, reliable and informative.

Design, data and implications of the FCI have been thoroughly discussed in published articles, which should be consulted by anyone interested in using the FCI. Here is a short list of **primary references**:

- D. Hestenes, Guest comment: Who needs physics education research!?, *Am. J. Phys.* **66**: 465-467 (1998).

- D. Hestenes, M. Wells, and G. Swackhamer, Force Concept Inventory, *The Physics Teacher* **30**: 141-158 (1992).
- An up-to-date account of Richard Hake's analysis of extensive FCI/MBT data and its implications is available on his website: <http://www.physics.indiana.edu/~hake>. Check out his two invited talks:
  1. R.R. Hake, "What Can We Learn from the Physics Education Reform Effort?", ASME Mechanical Engineering Education Conference: "Drivers and Strategies of Major Program Change," Fort Lauderdale, Florida, March 26-29, 2000.
  2. R.R. Hake, "Towards Paradigm Peace in Physics-Education Research," presented at the annual meeting of the American Educational Research Association, New Orleans, April 24-28, 2000.

### **Some Conclusions from FCI data**

- Students who understand Newtonian physics always get high FCI scores (>90%).
- Students who have not studied physics get low FCI scores (< 30%).
- Under **traditional instruction** FCI gains are **small and bounded** (< 30%); this result is independent of the instructor's qualifications and mode of instruction.
- Under **PER-based instruction** FCI gains average 48% and some exceed 70%. (Following Hake, gains are expressed as % of the maximum possible gain.)
- FCI scores **correlate strongly with problem solving** performance and other measures of student understanding.
- Students with FCI scores below 60% do not have sufficient mastery of Newtonian concepts to use them reliably in problem solving or scientific reasoning. Consequently, they systematically misunderstand most of what they hear and read about physics; they have no alternative to rote methods in studying for examinations, and they suffer frustration and humiliation from not understanding what they are doing wrong. At the university level, this applies to about half the students completing physics under traditional instruction.

The upshot is that that the FCI has generated powerful evidence in support of physics teaching reform. A case in point is the modeling approach to physics teaching described below.

## **II. Reform of Introductory University Physics**

Physics Education Research (PER) is stimulating and guiding reforms in many physics departments. Here we consider one of the most radical reform movements and its rationale as it is evolving at Arizona State University

### **A. A wake-up call**

Quite apart from any PER-based reforms of physics courses, the traditional lecture-based physics course is sure to be replaced by **courses delivered over the Internet**.

Internet courses will be cheaper, more convenient and certainly no less effective. They can be designed and delivered by outstanding professors and enhanced by multimedia affordances comparable to resources of the entertainment industry. Internet education is projected to be a billion-dollar industry within the next decade. With a potential world-wide audience, costs for design and production of a single course may approach a million dollars.

To compete with this trend, universities must supply what the Internet cannot deliver. They must develop courses for which **physical presence of the student is essential**. The courses must be designed to take full advantage of

- Hands-on access to materials and equipment (labs),
- Heads-on personal interactions with faculty and other students.

On returning from the meeting of physics chairs, I learned that the same message had recently been delivered to chairs of mechanical engineering by MIT Professor Woodie Flowers, only in more **apocalyptic terms** with many specifics. His argument is forcefully illustrated by the fact that his entire talk is available online at:

<<http://hitchcock.dlt.asu.edu/media2/cresmet/flowers>>

In case you are not up to speed on the Internet, to view his talk in lively telepresence you need to download *Real Player 7 Basic*, free from <<http://www.real.com/player>>. Then just follow the wizards.

Flowers' talk sent a shockwave through the audience. He predicts that the Internet monster will be heartily gobbling up courses within 5 years. Will your department be ready to fight?

## **B. Studio Physics**

The term was coined by RPI physicist Jack Wilson for a computer-based alternative to traditional physics instruction. Studio physics is popular within the PER community as an optimal environment for enhancing student learning. It is characterized by the following

- Takes place in a dedicated room (the 'studio') in which students sit at tables, rather than desks. Each table has one computer for every two or three students and space to do experiments.
- Has little or no formal lecture.
- Emphasizes active learning through a wide variety of short experiments (often computer-based), pencil-and paper exercises and discussion questions.
- Emphasizes small group learning.
- Uses materials and methods derived from PER.

Before the name was coined, studio physics was pioneered by Malcolm Wells for (small) high school classrooms and by Priscilla Laws for (small) college classrooms. Jack Wilson introduced the first scale-up to large classrooms at RPI. Further development and use is increasing, for example, at NCSU, Cal Poly (San Luis Obispo) and ASU.

### **Objectives of Studio Physics:**

- Integrate lab and theory

- Optimize student engagement:
  - Collaborative learning,
  - Immediate feedback,
  - Adaptation to student knowledge state,
  - Shift locus of control from teacher to students
- Optimize integration of technology into the physics curriculum.  
The **Technological Imperative!**

The studio classroom is an ideal arena for experiments on improving instruction. Consequently, there is great variety in the way that studio courses are conducted, and many new developments are likely.

### **Class size:**

Extensive experience in the Modeling Program at ASU suggests that the optimal size for a studio physics class is 24 or less, though up to 32 can be accommodated. Scale-up to larger classes requires a room design that permits partitioning into smaller collaborative groups. This is being tried out at NCSU and ASU as well as RPI. It is by no means clear that such scale-up is advantageous. It may be that, after the current obsession with large classes is destroyed by competition with the Internet, small classes will be recognized as essential for effective physics instruction. But scale-ups must be tried and objectively evaluated to see if they have real advantages.

The SCALE-UP of studio physics at NCSU is well described on their PER website: <<http://www.ncsu.edu/PER/>>.

### **C. Modeling R&D at ASU**

For the last five years, the Modeling Research Group at ASU has been experimenting with reform of University Physics in a studio physics classroom. The most unique feature of this reform is its grounding in a *Modeling Theory of Physics Instruction* developed at ASU over the last two decades. With the overall objective of increasing the coherence of student understanding, the reform has developed along three main lines:

1. Course content organized around **models** rather than topics.
2. Systematic use of **modeling tools** to elucidate the models.
3. Student activities and discourse **structured around models and modeling.**

These points are elaborated below.

## **Modeling Theory**

Central thesis (applies to science generally):

- Scientists explore the physical world for **reproducible patterns** which they represent by **models** and organize into **theories** according to **laws**.
- The **content core** of science is composed of *models, laws and theories*

- The **procedural core** of science concerns *making and using models* = **modeling**

**Research themes:**

- Explicate, analyze and classify **models inherent in all branches of physics**
- Analyze **theories as systems of laws** (guidelines) **for constructing models**
- Study the use of representational tools in physics to ascertain **optimal designs for modeling tools**
- Explicate and analyze **cognitive aspects of modeling** in science

**References:** Ref. [1] discusses scientific and cognitive foundations for Modeling Theory. Refs. [2] and [3] describe designs and devices for implementing the theory that have been extensively applied to high school physics with well-documented success. We have applied the same ideas to University Physics, but with some modifications and improvements.

[1] D. Hestenes, Modeling Games in the Newtonian World, *Am. J. Phys.* **60**: 732-748 (1992).

[2] D. Hestenes (1997), Modeling Methodology for Physics Teachers. In E. Redish & J. Rigden (Eds.) *The changing role of the physics department in modern universities*, American Institute of Physics Part II. p. 935-957.

[3] M. Wells, D. Hestenes, and G. Swackhamer, A Modeling Method for High School Physics Instruction, *Am. J. Phys.* **63**: 606-619 (1995).

## **Modeling Instruction**

### **1. Structure and coherence of the curriculum**

- **Local structure** is determined by delineating models.

**Models** are primary units of coherently structured knowledge.

**Coherence** derives primarily from the coordinated application of physical laws to the construction and analysis of models.

Conventional instruction induces students to organize their learning around problems and their solutions as units of knowledge.

Modeling instruction is organized around a small number of basic models. Problem solving is subsidiary to modeling. One model solves many problems.

- **Large scale structure** is determined by thematic use of physical laws threaded through the curriculum. Two major themes:
  - (a) Energy thread (or strand).** Newtonian mechanics modified to generalize and separate energy conservation from momentum conservation: Thorough preparation for
    - Concept of electric potential
    - Energy level diagrams & spectroscopy
  - (b) Structure of matter:** particle models and electromagnetic interactions

## 2. Modeling tools (examples)

- Coordinated use of *complex numbers and vectors* for trigonometry, rotations and harmonic motion
- *Coordinate-free use of vectors* in modeling 2-d motion saves time and combats “vector avoidance”

## 3. Management of student activities and discourse (See Ref. [1])

- **Collaborative learning** (no lectures)

Students work in teams

**Guided inquiry:** Many activities organized into a *modeling cycle*

("learning cycle" with modeling structure)

- Developing skills in **scientific discourse**

Discourse structured around models to make scientific claims, explanations and arguments clear and precise.

≈ **1/3 of class time** devoted to student presentations and discussion

**Interview techniques** for educational research are built into discourse management.

Engage students in

– *Eliciting* and evaluating their own beliefs about physics

– *Negotiating meanings* of terms and representations

**Evaluation.** Course development began with an Honors section of university physics, because that guaranteed the class size needed for studio physics. Progress was monitored by % FCI gains, which for successive years were: 40%, 56%, 64%, 68%, 56%. During the last two years the method was applied to a community college class with gains of 82% and 64%. The former is the first recorded FCI gain over 72%. Evaluation with several other instruments gave equally impressive results. This convinced NSF reviewers that the course is ready for export to other schools, and we were awarded a grant to do just that.