

Modeling Instruction: An Effective Model for Science Education

The authors describe a Modeling Instruction program that places an emphasis on the construction and application of conceptual models of physical phenomena as a central aspect of learning and doing science.

Introduction

Modeling Instruction is an evolving, research-based program for high school science education reform that was supported by the National Science Foundation (NSF) from 1989 to 2005. The name *Modeling Instruction* expresses an emphasis on the construction and application of conceptual models of physical phenomena as a central aspect of learning and doing science (Hestenes, 1987; Wells et al, 1995; Hestenes, 1997). Both the *National Science Education Standards* (NRC, 1996) and National Council of Teachers of Mathematics Standards (NCTM), as well as *Benchmarks for Science Literacy* (AAAS, 1993) recommend “models and modeling” as a unifying theme for science and mathematics education. To our knowledge, no other program has implemented this theme so thoroughly.

From 1995 to 1999, 200 high school physics teachers participated in two four-week Leadership Modeling Workshops with NSF support. Since that time, 2500 additional teachers from 48 states and a few other nations have taken summer Modeling Workshops at universities in many states, supported largely by state funds. Participants include teachers from public and private schools in urban, suburban,

and rural areas. Modeling Workshops at Arizona State University (ASU) are the cornerstone of a graduate program for teachers of the physical sciences. Recently, Modeling has expanded to embrace the entire middle/high school physical science curriculum. The program has an extensive web site at <http://modeling.asu.edu>.

Product: Students Who Can Think

Modeling Instruction meets or exceeds NSES teaching standards, professional development standards, assessment standards, and content and inquiry standards.

Modeling Instruction produces students who engage intelligently in public discourse and debate about matters of scientific and technical concern. Betsy Barnard, a modeler in Madison, Wisconsin, noticed a significant change in this area after Modeling was implemented in her school: “I teach a course in biotechnology, mostly to seniors,

nearly all of whom had physics the previous year. When asked to formally present information to the class about controversial topics such as cloning or genetically modified organisms, it is delightfully clear how much more articulate and confident they are.”

Students in modeling classrooms experience first-hand the richness and excitement of learning about the natural world. One example comes from Phoenix modeler Robert McDowell. He wrote that, under traditional instruction, “when asked a question about some science application in a movie, I might get a few students who would cite 1-2 errors, but usually with uncertainty. Since I started Modeling, the students now bring up their own topics ... not just from movies, but their everyday experiences.” One of his students wrote, “Mr. McDowell, I was at a Diamondback baseball game recently, and all I could think of was all the physics problems involved.” A former student of another modeler, Gail Seemueller of Rhode Island, described it as follows: “She wanted us to truly LEARN and more importantly UNDERSTAND the material. I was engaged. We did many hands-on experiments of which I can still vividly remember, three years later.”

Kelli Gamez Warble of rural Arizona, who has taught physics and

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calculus for a decade using Modeling Instruction, has had numerous students whose career choices were influenced by Modeling Instruction. She wrote about discovering several former students when visiting an ASU Engineering Day, and all but one were females. She wrote, "As a former female engineering student myself, I was gratified but not surprised. Modeling encourages cooperation and discourse about complicated ideas in a non-threatening, supportive environment. Females who view science, engineering, and technology as fields encouraging cooperation and supportiveness will, I believe, become much more attracted to these non-traditional areas."

Excellence

Many modeling teachers have been recognized nationally. For example, three users of Modeling Instruction have received the National Science Teachers Association (NSTA) Shell Science Teaching Award. Numerous modelers have received the Presidential Award for Excellence in Math and Science Teaching (PAEMST). At Modeling Workshops and related graduate courses for science teachers at ASU, as well as at Modeling Workshops across the United States, teachers learn to impact students of various backgrounds and learning styles. Modeling Workshops and classrooms are thriving centers of interactive engagement.

The Essence of Modeling Instruction

The Modeling method of instruction corrects many weaknesses of the traditional lecture-demonstration method, including the fragmentation of knowledge, student passivity, and the persistence of naïve beliefs about

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the physical world. From its inception, the Modeling Instruction program has been concerned with reforming high school physics teaching to make it more coherent and student-centered, and to incorporate the computer as an essential scientific tool.

In a series of intensive workshops over two years, high school teachers learn to be leaders in science teaching reform and technology infusion in their schools. They are equipped with a robust teaching methodology for developing student abilities to make sense of physical experience, to understand scientific claims, to articulate coherent opinions of their own and defend them with cogent arguments, and to evaluate evidence in support of justified belief.

More specifically, teachers learn to ground their teaching in a *well-defined pedagogical framework* (modeling theory; Hestenes, 1987), rather than following rules of thumb; to organize course content around *scientific models* as coherent units of structured knowledge; to engage students collaboratively in *making and using models* to describe, explain, predict, design, and control physical phenomena; to involve students in *using computers as scientific tools* for collecting, organizing, analyzing, visualizing, and modeling real data; to

assess student understanding in more meaningful ways and experiment with more authentic means of assessment; to continuously improve and update instruction with new software, curriculum materials, and insights from educational research; and to work collaboratively in action research teams to mutually improve their teaching practice. Altogether, Modeling Workshops provide detailed implementation of the National Science Education Standards.

The modeling cycle, student conceptions, discourse

Instruction is organized into modeling cycles rather than traditional content units. This promotes an integrated understanding of modeling processes and the acquisition of coordinated modeling skills. The two main stages of this process are model development and model deployment.

The first stage—model development—typically begins with a demonstration and class discussion. This establishes a common understanding of a question to be asked of nature. Then, in small groups, students collaborate in planning and conducting experiments to answer or clarify the question. Students present and justify their conclusions in oral and written form, including the formulation of a model for the phenomena in question and an evaluation of the model by comparison with data. Technical terms and representational tools are introduced by the teacher as they are needed to sharpen models, facilitate modeling activities, and improve the quality of discourse. The teacher is prepared with a definite agenda for student progress and guides student inquiry and discussion in that direction with "Socratic" questioning

and remarks. The teacher is equipped with a taxonomy of typical student misconceptions to be addressed as students are induced to articulate, analyze, and justify their personal beliefs (Halloun and Hestenes, 1985b, Hestenes et al., 1992).

During the second stage—model deployment—students apply their newly-discovered model to new

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situations to refine and deepen their understanding. Students work on challenging worksheet problems in small groups, and then present and defend their results to the class. This stage also includes quizzes, tests, and lab practicums. An example of the entire modeling cycle is outlined in Table 1.

Table 1. Modeling Cycle Example: The *Constant Velocity* Model

<p>I. Model Development (Paradigm Lab)</p> <p>A. Pre-lab discussion Students observe battery-powered vehicles moving across the floor and describe their observations. The teacher guides them toward a laboratory investigation to determine whether the vehicle moves at constant speed, and to determine a mathematical model of the vehicle’s motion.</p> <p>B. Lab investigation Students collect position and time data for the vehicles and analyze the data to develop a mathematical model. (In this case, the graph of position vs. time is linear, so they do a linear regression to determine the model.) Students then display their results on small whiteboards and prepare presentations.</p> <p>C. Post-lab discussion Students present the results of their lab investigations to the rest of the class and interpret what their model means in terms of the motion of the vehicle. After all lab groups</p>	<p>have presented, the teacher leads a discussion of the models to develop a general mathematical model that describes constant-velocity motion.</p> <p>II. Model Deployment</p> <p>A. Worksheets Working in small groups, students complete worksheets that ask them to apply the constant-velocity model to various new situations. They are asked to prepare whiteboard presentations of their problem solutions and present them to the class. The teacher’s role at this stage is continual questioning of the students to encourage them to articulate what they know and how they know it, thereby correcting any lingering misconceptions.</p> <p>B. Quizzes In order to do mid-course progress checks for student understanding, the modeling materials include several short quizzes. Students are asked to complete these quizzes individually</p>	<p>to demonstrate their understanding of the model and its application. Students are asked not only to solve problems, but also to provide brief explanations of their problem-solving strategies.</p> <p>C. Lab Practicum To further check for understanding, students are asked to complete a lab practicum in which they need to use the constant-velocity model to solve a real-world problem. Working in groups, they come to agreement on a solution and then test their solution with the battery-powered vehicles.</p> <p>D. Unit Test As a final check for understanding, students take a unit test. (The constant-velocity unit is the first unit of the curriculum. In later unit tests, students are required to incorporate models developed earlier in the course into their problem solving; this is an example of the spiral nature of the modeling curriculum.)</p>
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That models and modeling should be central to an inquiry-based approach to the study of physics is no surprise. The NSES state, "Student inquiries should culminate in formulating an explanation or model... In the process of answering the questions, the students should engage in discussions and arguments that result in the revision of their explanations."

Traditional instruction often overlooks the crucial influence of students' personal beliefs on what they learn. Force Concept Inventory (FCI) data (Hestenes et al., 1992) show that students are not easily induced to discard their misconceptions in favor of Newtonian concepts. Some educational researchers have expended considerable effort in designing and testing teaching methods to deal with specific misconceptions. Although their outcomes have been decidedly

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better than the traditional ones, success has been limited. Many have concluded that student beliefs are so "deep-seated" that heavy instructional costs to unseat them are unavoidable. However, documented success with the Modeling method suggests that an indirect treatment of misconceptions is likely to be most efficient and effective. (Wells et al., 1995)

Cognitive scientists have identified metaphors as a fundamental tool of

human thought; we use metaphors so frequently and automatically that we seldom notice them unless they are called to our attention. Metaphors are used to structure our experience and thereby make it meaningful. A major objective of teaching should therefore be to help students "straighten out" their metaphors. In Modeling, instead of designing the course to address specific "naïve conceptions," the instructor focuses on helping students construct appropriate models to account for the phenomena they study. When students learn to correctly identify a physical system, represent it diagrammatically, and then apply the model to the situation they are studying, their misconceptions tend to fall away (Wells et al., 1995).

A key component of this approach is that it moves the teacher from the role of authority figure who provides the knowledge to that of a coach/facilitator who helps the students construct their own understanding. Since students systematically misunderstand most of what we tell them (due to the fact that what they hear is filtered through their existing mental structures), the emphasis is placed on student articulation of the concepts.

Laboratory experiences are centered on experiments that isolate one concept, with equipment that enables students to generate good data reliably. Students are given no pre-printed list of instructions for doing these experiments. Rather, the instructor introduces the class to the physical system to be investigated and engages students in describing the system until a consensus is achieved. The instructor elicits from students the appropriate dependent and independent variables to characterize the system. After obtaining reasoned defenses from the students for selection of these

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variables, the instructor asks the students to help design the experiment. A general procedure is negotiated so that students have a sense of why they are doing a particular procedure. Frequently, multiple procedures arise as students have access to equipment that allows them to explore the relationship in different ways. Lab teams are then allowed to begin collecting data.

Students have to make sense of the experiment themselves. The instructor must be prepared to allow them to fail. The apparatus should be available for several days, should they need it. Students use spreadsheet and graphing software to help them organize and analyze their data. After allowing time to prepare whiteboards to summarize their findings, the instructor selects certain groups to present an oral account of the group's experimental procedure and interpretation. Students use multiple representations to present their findings, including concise English sentences, graphs, diagrams, and algebraic expressions.

After some initial discomfort with making these oral presentations, students generally become more at ease and gradually develop the skills of making an effective presentation. They learn how to defend their views clearly and concisely. These

communication skills are valuable beyond their immediate application in the physics classroom.

Assessment

Clearly, one role of assessment is to ascertain student mastery of the skills and understanding of the concepts in the unit. An equally important role is the feedback it provides the instructor about his or her curriculum and teaching methods. The Modeling method stresses developing a sound conceptual understanding through graphical and diagrammatic representations before moving on to an algebraic treatment of problem solving. To be consistent with this end, the assessment instruments test students' ability to interpret graphs and draw conclusions, as well as to solve quantitative problems.

In addition to lab write-ups, in which students report their findings using a format outlined in the curriculum materials, the lab practicum is used as a means to check student understanding. In the practicum, an application problem is posed to the class as a whole. The class has a fixed period of time to figure out what model is appropriate to describe the situation, decide what measurements to make, collect and analyze the data, and then prepare a solution to the problem. This is used as the culminating activity in the unit and usually helps the students review key principles for the unit test.

Whiteboarding is another major component of assessment. In whiteboarding, small groups of students write up their results from a lab or solutions to a worksheet problem on a small whiteboard. One student from the group presents the whiteboard to the class, responding to questions from the class and the

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instructor. Other group members are allowed to help if needed. This is an important assessment tool that helps the instructor determine how well students have mastered the concepts. When one hears fuzzy or incoherent explanations, one has the opportunity to help students deal with their incomplete conceptions before moving on to the next topic. The two questions teachers ask most frequently are, "Why do you say that?" and "How do you know that?" Students have to account for everything they do in solving a problem, ultimately appealing to models developed on the basis of experiments done in class. Instructors trained in the Modeling method do not take correct statements for granted; they always press for explicit articulation of understanding. This probing by the teacher often reveals that the student presenter does not fully understand the concept (even when answers are correct). The teacher then has the opportunity to help the student correct his or her conceptions through Socratic questioning.

Whiteboarding has other valuable uses as well. First, it gives students a chance to reinforce their understanding of concepts; students often don't know exactly what they think until they've heard themselves express the idea. Second, students are highly motivated to understand the question they are assigned to present. No one enjoys

getting up before a group of peers with nothing to say. Additionally, during preparation, the instructor has the opportunity to help students if no one in the group knows how to do the problem.

Professional Development

Modeling Instruction places a strong emphasis on professional development, both during the workshops and afterward. The workshops are the beginning of a process of lifetime learning. Teachers are encouraged to network amongst themselves and to become leaders of reform in their schools and districts. The ASU web site and list-serve provide a forum for communication among Modelers across the nation and the world.

Since "teachers teach as they have been taught," the workshops include extensive practice in implementing the curriculum as intended for high school classes. Participants rotate through roles of student and instructor as they practice techniques of guided inquiry and cooperative learning. Plans and techniques for raising the level of discourse in classroom discussions and student presentations are emphasized. The workshops immerse teachers in the physics content of the entire semester, thereby providing in-depth remediation for under-prepared teachers.

The great success and popularity of the Modeling Workshops has generated an overwhelming demand for additional courses. In response to this demand, in 2001 ASU approved a new graduate program to support sustained professional development of high school physics teachers. Modeling Workshops are the foundation of the program, which can lead to a *Master of Natural Science* (MNS) degree. The National Science Education

Standards (NSES) emphasize that “coherent and integrated programs” supporting “lifelong professional development” of science teachers are essential for significant reform. They state that “The conventional view of professional development for teachers needs to shift from technical training for specific skills to opportunities for intellectual professional growth.” The MNS program at ASU is designed to meet that need.

Evidence of Effectiveness

Evaluation of Physics Instruction. The *Force Concept Inventory* (FCI) was developed to compare the effectiveness of alternative methods of physics instruction (Halloun et al., 1985a, Hestenes et al., 1992). It has become the most widely used and influential instrument for assessing the effectiveness of introductory physics instruction, and has been cited as producing the most convincing hard evidence of the need to reform traditional physics instruction (Hake, 1998).

The FCI assesses students’ conceptual understanding of the force concept, the key concept in mechanics. It consists of 30 multiple choice questions, but there is one crucial difference between the FCI questions and traditional multiple-choice items: distracters are designed to elicit misconceptions known from the research base. A student must have a clear understanding of one of six fundamental aspects of the Newtonian force concept in order to select the correct response. The FCI reveals misconceptions that students bring as prior knowledge to a class, and it measures the conceptual gains of a class as a whole. The FCI is research-grounded, normed with thousands

of students at diverse institutions. It is the product of many hours of interviews that validated distracters, and it has been subjected to intense peer review.

Including the survey by Hake (1998), we have FCI data on some 30,000 students of 1000 physics teachers in high schools, colleges and universities, throughout the world. This large data base presents a highly consistent picture, showing that the FCI provides statistically reliable measures of student concept understanding in mechanics. Results strongly support the following general conclusions:

- Before physics instruction, students hold naive beliefs about motion and force that are incompatible with Newtonian concepts.
- Such beliefs are a major determinant of student performance in introductory physics.
- *Traditional* (lecture-demonstration) physics instruction induces only a small change in student beliefs. This result is largely independent of the instructor’s knowledge, experience and teaching style.
- Much greater changes in student beliefs can be induced with instructional methods derived from educational research in, for example, cognition, alternative conceptions, classroom discourse, and cooperative learning.

These conclusions can be quantified. The FCI is best used as a pre/post diagnostic. One way to quantify pre/post gains is to calculate the normalized gain (Hake, 1998). This is the actual gain (in percentage) divided by the total possible gain (also in percentage). Thus, normalized gain = $(\%post - \%pre)/(100 - \%pre)$. Hence,

the normalized gain can range from zero (no gain) to 1 (greatest possible gain). This method of calculating the gains normalizes the index, so that gains of courses at different levels can be compared, even if their pretest scores differ widely.

A challenge in physics education research for more than a decade has been to identify essential conditions for learning Newtonian physics and thereby devise more effective teaching methods.

From pre/post course FCI scores of 14 traditional courses in high schools and colleges, Hake found a mean normalized gain of 23%. In contrast, for 48 courses using interactive engagement teaching methods (minds-on always, and hands-on usually), he found a mean normalized gain of 48%. The difference is much greater than a standard deviation—a highly significant result. This would indicate that traditional instruction fails badly, and moreover, that this failure cannot be attributed to inadequacies of the students because some alternative methods of instruction can do much better. A challenge in physics education research for more than a decade has been to identify essential conditions for learning Newtonian physics and thereby devise more effective teaching methods. Modeling Instruction resulted from pursuing this challenge. Results from using the FCI to assess Modeling Instruction are given below.

How effective is modeling instruction?

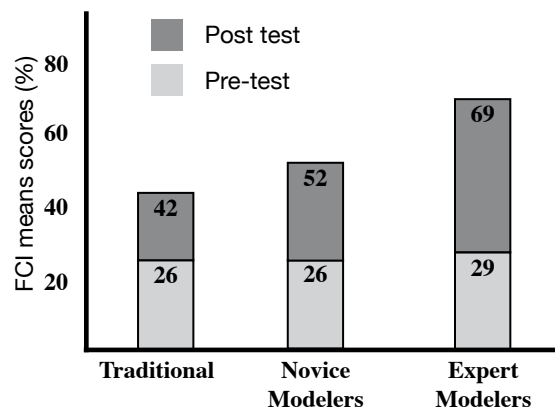
Figure 1 summarizes data from a nationwide sample of 7500 high school physics students who participated in Leadership Modeling Workshops from 1995 to 1998. Teachers gave the FCI to their classes as a baseline posttest when they were teaching traditionally (before their first Modeling Workshop), and as a pretest and posttest thereafter.

The average FCI pretest score was about 26%, slightly above the random guessing level of 20%. Figure 1 shows that traditional high school instruction (lecture, demonstration, and standard laboratory activities) has little impact on student beliefs, with an average FCI posttest score of 42%, well below the 60% score which, for empirical reasons, can be regarded as a *threshold* in understanding Newtonian mechanics. This corresponds to a normalized gain of 22%, in agreement with Hake's results.

After their first year of teaching with the Modeling method, posttest scores for 3394 students of 66 *novice modelers* were about 10 percentage points higher, as shown in Fig. 1. Students of *expert modelers* do much better. For 11 teachers identified as expert modelers after two years in the program, posttest scores for 647 students averaged 69%. This corresponds to a normalized gain of 56%, considerably more than double the gain under traditional instruction. After two years in the program, gains for under-prepared teachers were comparable to gains in one year for well-prepared teachers. Subsequent data have confirmed all these results for 20,000 students (Hestenes, 2000). Thus, student gains in understanding

under *expert* modeling instruction are more than doubled compared to traditional instruction.

Student FCI gains for 100 Arizona teachers who took Modeling Workshops were almost as high as those for leading teachers nationwide, even though three-fourths of the



participating Arizona teachers do *not* have a degree in physics. Teachers who implement the Modeling method most fully have the highest student posttest FCI mean scores and gains.

External evaluation of Modeling Instruction. The Modeling Instruction Program was assessed by Prof. Frances Lawrenz, an independent external evaluator for the National Science Foundation. We quote at length from the four page report on her July 22, 1998 site visit, because it describes the character of the workshops very well.

“This site visit was one of several over the past four years to sites in the modeling project ... I had the opportunity to observe the participants working in their concept groups and presenting to the full group. I also interviewed most of the participants, either as part of a small group or individually, and interviewed two coordinators of the workshop ... *The workshop appears*

to me to be a resounding success. My observations revealed a very conscientious, dedicated, and well-informed group of teachers actively involved in discussions about the most effective ways to present physics concepts to students. They were doing a marvelous job of combining what they knew about how children learn with what they knew about physics and the modeling approach. The discussions were very rich.”

“The interviews confirmed my observations about the nature of the group. All the participants were articulate about physics instruction and the modeling approach. The participants reported being pleased with everything that was happening at the workshop and spoke in glowing terms about the facilitators. The participants felt that the workshop was well run and that the facilitators were extremely knowledgeable about how best to teach physics. They also commented that the group itself was an excellent resource. They all could help each other.”

“I have almost never seen such overwhelming and consistent support for a teaching approach. It is especially surprising within the physics community, which is known for its critical analysis and slow acceptance of innovation. In short, the modeling approach presented by the project is sound and deserves to be spread nationally.”

Recognition by U.S. Department of Education. In September 2000, the U.S. Department of Education announced that the Modeling Instruction Program at Arizona State University is one of seven K-12 educational technology programs designated as exemplary or promising, out of 134 programs submitted to the

The Modeling method has a proven track record of improving student learning.

agency's Expert Panel. Selections were based on the following criteria: (1) Quality of Program, (2) Educational Significance, (3) Evidence of Effectiveness, and (4) Usefulness to Others. In January 2001, a U.S. Department of Education Expert Panel in Science recognized the Modeling Instruction Program as one of only two exemplary K-12 science programs out of 27 programs evaluated (U.S. Department of Education, 2001).

Long-term implementation. In a follow-up survey of Leadership Modeling Workshop graduates, between one and three years after they had completed the program, 75% of them responded immediately and enthusiastically. More than 90% reported that the Workshops had a highly significant influence on the way they teach. 45% reported that their use of Modeling Instruction has continued at the same level, while another 50% reported an increase. (Hestenes, 2000).

Final Thoughts

Instead of relying on lectures and textbooks, the Modeling Instruction program emphasizes active student construction of conceptual and mathematical models in an interactive learning community. Students are engaged with simple scenarios to learn to model the physical world. Modeling cultivates physics teachers as school experts on the use of technology in science teaching, and encourages teacher-to-teacher training in science teaching methods, thereby

providing schools and school districts with a valuable resource for broader reform.

Data on some 20,000 students show that those who have been through the Modeling program typically achieve twice the gains on a standard test of conceptual understanding as students who are taught conventionally. Further, the Modeling method is successful with students who have not traditionally done well in physics. Experienced modelers report increased enrollments in physics classes, parental satisfaction, and enhanced achievement in college courses across the curriculum.

Carmela Minaya of Honolulu, NSTA Shell Science Teaching Awardee, wrote: "The beauty of Modeling Instruction is that it creates an effective framework for teachers to incorporate many of the national standards into their teaching without having to consciously do so, because the method innately addresses many of the various standards. In a certain course, different students may learn the same material, except they never learn it in exactly the same way. This method appeals to all learning styles. Students cling to whatever works for them. Although the content is identical yearly, no two students ever are. The classroom becomes a dynamic center for student owned learning."

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