Modeling Instruction for STEM Education Reform

[This document is an integrated version of extracts from unfunded NSF proposals written by David Hestenes from 2003 to 2008. Details about implementation and requirements for NSF solicitations are omitted. Feb. 2009]

Project Summary

This project will adapt and extend the successful *Modeling Instruction* Project in physics to create an engine for sustained professional development and educational reform across the K–12 STEM curriculum. The hallmark of modeling instruction is the integration of content and pedagogy around making and using scientific models, so it is applicable to the whole STEM domain. Approximately 3,000 teachers across the nation, including teachers of underserved and special-needs students, have taken intensive three-week modeling workshops; most say the experience has profoundly transformed the way they teach. Many schools and universities nationwide have sponsored local modeling workshops. Thus, a strong national base is already in place for extending modeling instruction to a national program for comprehensive STEM education reform. The key is to train and support teachers to do the job. This project will create an engine to get the train moving.

As a guide for systematic reform, this project will create and test a flexible *curriculum framework* to support coherent STEM instruction across subject and grade level. It will be incorporated in the design of courses connecting middle school science with a high school physics-chemistry course sequence. The course sequence will be thematically integrated by two conceptual threads: models and modeling, energy and structure of matter. The courses will be designed for coordination with mathematics courses through a common approach to mathematical modeling. To make science and mathematics more accessible and relevant to all students, the internationally recognized *PISA framework for science and mathematics literacy* will be thoroughly integrated into the curriculum design.

The project will develop, test and implement three kinds of professional development services. The foundation is a program of two intensive three-week summer workshops for each course, introducing teachers to the objectives of curriculum reform and training them to teach with the new curriculum materials and modeling inquiry techniques in full accord with the National Science Education Standards. To support collaboration in the community of modelers, the project will maintain a *modeling wiki* to engage modelers in continuous extensions and upgrades of curriculum materials, and a chat room to address issues in classroom teaching. Lastly, the project will offer a *Leadership Workshop* to prepare teachers to lead reform in a school or school district, including mentoring, induction and retention of teachers.

Intellectual Merit: The project develops, tests and implements a transformative professional development model that prepares teachers and students for 21st century advances in science. It is attuned to objectives of scientific literacy and makes physics and algebra accessible to all.

Broader Impacts: The project engages the national cyberinfrastructure for rapid updates and distribution of vetted research-based instructional materials. It promotes 21st century skills and mathematical and scientific literacy for students of all socioeconomic levels.

PROJECT DESCRIPTION

I. Introduction.

The traditional high school science sequence of biology, chemistry and physics in that order is a vestige of the nineteenth century when the sciences were regarded as independent disciplines. The great triumph of the twentieth century was unraveling the atomic composition of all matter, whether biological or inorganic. As observed by the National Research Council (2001),"Because all essential biological mechanisms ultimately depend on physical interactions between molecules, physics lies at the heart of the most profound insights into biology."

It follows that, to prepare students for the emerging age of nanoscience and molecular biology, the traditional course sequence must be reversed to physics first followed by chemistry and then biology." This drastic change has been most forcefully advocated by Nobelist Leon Lederman (2001), who has led the way to map out its implications for the whole curriculum (Bardeen and Lederman, 1998). We agree completely with Lederman's rationale, but we see grave practical difficulties in making the reform work. At the very least, the physics course needs to be thoroughly redesigned to make it a suitable introduction for chemistry, and the chemistry course needs to be revised to take advantage of the prerequisite physics. Moreover, middle school physical science needs to be reformed to prepare students for physics in the 9^{th} or 10^{th} grade. All these reforms must be implemented simultaneously to achieve a course sequence that is smoothly integrated across grade levels. The present project will address this massive problem by incorporating the necessary reforms in curriculum content and pedagogy into a professional development system that prepares teachers and supports in a nationwide community of like-minded colleagues.

We focus first on *energy* as a major unifying theme for the entire science curriculum. As recognized in the *National Science Education Standards* (NSES, 1996), *structure of matter* is an essential concurrent theme, for energy without matter is like the smile of the Cheshire cat without the cat. However, atomic structure has many problem aspects that cannot be adequately addressed until students have a scientific energy concept. Indeed, energy has been the principal guide in research that has unraveled the atomic structure of matter. This calls to mind an analogy with investigative reporting. Deep Throat advised Bob Woodward to "Follow the money!" to get to the bottom of the Watergate mystery. Likewise, researchers and students are well advised to "Follow the Energy!" in investigating the structure of matter.

Of course, everyone agrees that energy should be well understood by all high school students as part of their basic education in science. Otherwise, as adults they will not be able to produce reasoned accounts or sound decisions about everyday phenomena or public policy. Indeed, more or less standard treatments of energy are prominent throughout the K-12 curriculum and generally in alignment with state and national science standards. By and large, the textbooks, the schools and the teachers are satisfied that the subject of energy is well covered. It is taken for granted that students have mastered basic energy concepts and can use them to explain phenomena in the world about them. *However, educational research tells a different story!*

During the last two decades science education researchers have documented a plethora of student difficulties in using energy to explain their world, even in the province of typical school science after conscientious instruction. Recently the insights gleaned from this research have been incorporated into the design of a new assessment instrument, the *Energy Concept Inventory* (ECI), which provides a detailed profile of student and teacher understandings about energy. Results from applying this instrument (reviewed below) could hardly be more dismal. For example, though all graduating high school students are likely to know the mantra, “Energy can neither be created nor destroyed,” most of them believe that energy can be produced or disappear or can exist as “pure energy” apart from matter. Many of them associate energy with life in unscientific ways or grant to “coldness” the same ontological status as energy. Overall, the data shows that energy instruction in the schools has many serious deficiencies that can only be corrected by significant reform of curriculum design and instructional practices.

Turning from energy to our second major theme, we recall that Richard Feynman, in his famous *Lectures on Physics,* argued that the single most important discovery of physics is that *matter is made of atoms*. It is noteworthy that this discovery was not made by a single individual or group. It is the outcome of diverse research by legions of physicists and chemists, not to mention contributions by philosophers and mathematicians. The search for atoms culminated in the first half of the 20^{th} century with the invention of quantum mechanics and *atomic theory* capable of explaining the periodic table of the elements. This provides the foundation for modern materials science and the molecular explanation for life, beginning with the double helix model for DNA discovered in 1953.

As the *atomic-molecular theory of matter* is essential to science and technology of the 21^{st} century, it deserves a central place in the K-12 science curriculum. However, the content of school science has hardly changed in many decades, while advances in science and technology have continued at an implacable pace. The standard high school physics course, for example, remains mired in 19th century mechanics, optics, heat, sound, electricity and magnetism. Although that is fundamental science of enduring importance, it needs to be reconstituted and enriched to lead students into the modern age of science and technology.

Though textbooks make frequent allusions to atoms and electrons in disconnected pockets scattered throughout the curriculum, they seldom approach the scientific goal of valid explanations for properties of matter. This project will develop a more systematic approach, including explicit formulations of

- generic principles for *structure of matter theory*, and
- *model-based explanations* for properties of materials

Developing a coherent science curriculum centered on atomic-molecular theory is not an easy task. But it is a central problem for science education research aimed at integrating physics with chemistry and ultimately biology. It requires well-defined specifications for the models that students should learn and the prerequisites needed to learn them. Though scientists move fluently from one model to another in studying a material system, most would be hard-pressed to articulate precisely what models they are using and how models fit together to form a coherent picture of the system. To surmount that problem, this project will assemble experienced researchers in physics and chemistry to work with expert teachers on incorporating their scientific insights into the design of a model-based curriculum.

Mindful of the essential role that mathematics plays in contemporary science, our curriculum reform will be designed for horizontal coordination with mathematics courses centered on the *models and modeling* theme. “Modeling” is recommended in the NCTM Standards (2003) as a unifying process strand for the mathematics curriculum, but little has been done to coordinate it with reforms in the science curriculum. This project will contribute to bridging this unfortunate barrier between academic disciplines by explicit integration of middle school physical science and mathematics and coordination of algebra with ninth grade physics.

Having identified the need and general direction for K-12 STEM education reform, we turn to the main objective of this proposal, creating an engine to drive continuous reform. Ultimately, all reform is local and the teacher is the agent of educational change. Accordingly, our problem is to equip, inspire and support teachers in this endeavor. This proposal explains how to do it. Indeed, the next section provides proof of concept from fifteen years of NSF support.

We are well aware that successful reform requires buy-in by schools and school districts. However, they lack the means for equipping teachers to implement reform. Our approach is to create an independent professional development system to equip and support teachers, and offer it to schools as a professional development service. We have plenty of takers already, including large educational systems such as the *Math and Science Partnership of Greater Philadelphia*, the state of Rhode Island and the nation of Singapore.

II. Project Goal and Research Question

This is a research and development project focused on **design, implementation** and **evaluation**.

> **Project goal:** *To create an **effective professional development system** to drive reforms in course content and pedagogy of the K-12 physical science curriculum.*

More specifically, to prepare teachers for implementing reform the project will create a sequence of workshops that

1. introduce exemplary course content within an integrated ***curriculum framework*** and
2. equip them with the proven ***modeling pedagogy*** for science teaching.

A curriculum framework differs from a curriculum in allowing multiple options in implementing its various components. This allows for diversity and adaptability in implementation as well as ease in upgrading with new curriculum materials and activities.

Teachers who have taken at least one modeling workshop and have adopted the modeling approach to science instruction call themselves **modelers.** There are about 2,500 modelers nationwide already. To support the community of modelers for continued professional growth and STEM reform we will create and maintain a *Modeling Wiki.*

Details of the professional development system are described in subsequent sections, and their field-testing, of course, constitutes a set of project subgoals. We contend that the curriculum framework and course designs are integral parts of the system. *Indeed, the single most important lesson learned in science education in recent decades may be that science content and pedagogy are inseparable.* (Unfortunately, an unhealthy separation between science and education is institutionalized in many universities.) Consequently, a substantial portion of this project must be devoted to aligning course content with the curriculum framework and pedagogy, followed by field-testing and implementation in Workshops that foster cooperation and collaboration among science and math teachers.

The operative word in our project goal statement is "***effective.***" Accordingly, development and implementation components of the project must be complemented by an evaluation component to answer the main

> **Research question:** *How **effective** is the modeling professional development system at promoting STEM education reform***?**

A satisfactory answer requires measures of student learning and teacher buy-in. Specific instruments to be used for this evaluation are described below.

III. Science and Math Literacy in Curriculum and Assessment

In a landmark publication, *Science for All Americans* (Rutherford & Almgren, 1990), AAAS Project 2061 defined scientific literacy as the central goal of public STEM education. This was followed by a more detailed framework in *Benchmarks for Scientific Literacy* (1993). Now, more than a decade later, it is hard to detect a trace of this framework in the textbook-driven public education or the policies of the U.S. Department of Education.

Fortunately, the goals of scientific and mathematical literacy have been taken up with renewed vigor at the international level in creation of the *Programme for International Student Assessment* (PISA) by the Organisation for Economic Cooperation and Development (OECD). To date, PISA has assessed well over a million students in 60 countries. The 30 member nations of the OECD along with 27 partner nations that participated in the most recent testing cycle account for roughly 90% of the world economy. As usual, the United States did not perform very well, but that is not a point we want to make.

The important point is that design of the PISA assessment instruments is guided by a well-crafted *Framework for Scientific, Reading and Mathematical Literacy* (Cresswell & Vassayettes) developed by outstanding international teams of domain experts. This framework is simpler and more practical than the Benchmarks, though it captures all the essential aspects of science and math literacy, and it has the great advantage of intimate ties to an internationally credible education assessment program. Accordingly, we highly recommend the *Pisa Framework for Scientific, Reading and Mathematical Literacy* as a guide for any STEM education initiative in the United States. Moreover, we begin that advocacy by adopting it as a core component of our curriculum framework and professional development program. We have already cleared with PISA officials that we will be free to use PISA questions in summative evaluation of our project, and we will have access to the large PISA data base to assess the significance of our results. For lack of space, we cannot review details of the PISA framework here. The main implication for our curriculum design is that PISA math-science assessment items are situated in real world contexts.

The AAAS Benchmarks will remain a valuable resource for curriculum design, but we are mindful of a serious flaw noted by math educator Patrick Thompson (1994). It seems that Benchmarks has inadvertently promoted the unhealthy separation between math and science that exists in our schools. In consequence, most math teachers haven't the vaguest idea what constitutes science literacy. This flaw is corrected in the PISA literacy framework, which emphasizes the intimate connection of math literacy to science. This connection is emphasized in the modeling component of our curriculum framework.

IV. Models, Modeling and Modeling Instruction

The name *Modeling Instruction* emphasizes making and using conceptual models of physical phenomena as central to learning and doing science. Adoption of "models and modeling" as a unifying theme for science and mathematics education is recommended by both NSES and NCTM Standards as well as AAAS Project 2061. However, to our knowledge, no other program has implemented that theme so thoroughly as the *Modeling Instruction Project* for physics (Section II). Our long-term goal is to extend it to the entire STEM curriculum.

A thorough analysis of the introductory physics course (Hestenes [10]) reveals that a handful of basic mathematical models provides the essential structure for the entire subject. Here is the list along with a few hints of applications.

Basic Mathematical Models:

1. **Constant rate** (linear change): graphs and equations for straight lines (proportional reasoning, constant velocity, acceleration, force, momentum, energy, etc.)
2. **Constant change in rate** (quadratic change) graphs and equations for parabolas (constant acceleration, kinetic and elastic potential energy, etc.)
3. **Rate proportional to amount**: doubling time, graphs and equations of exponential growth and decay (monetary interest, population growth, radioactive decay, etc.)
4. **Change in rate proportional to amount:** graphs and equations of trigonometric functions (waves and vibrations, harmonic oscillators, etc.)
5. **Sudden change**: stepwise graphs and inflection points (Impulsive force, etc.)

These models characterize basic quantitative structures that are ubiquitous not only in physics but throughout the rest of science. Their applications to science and modern life are rich and unlimited. Accordingly, we regard skill in using these models in a variety of situations as an essential component of math and science literacy. We will cultivate this skill deliberately and systematically with repeated activities throughout the STEM curriculum.

In this project, integration of mathematics with physics will be most strongly emphasized in grades 8 and 9, but it will be implicit throughout the curriculum. Utilizing modeling instruction, abstract mathematical concepts such as *variable*, *function* and *rate* will be explored within the context of mathematical models, applied concretely in physics and deployed to other subjects (i.e. economics, biology).

By direct experience, students will learn there is much more to a scientific model than the abstract structure of a mathematical model. In a scientific model variables must be related to observable experience and quantified with measurement procedures. Here they will see another role for mathematics: statistical concepts such as mean, standard deviation, and error analysis are applied in the process of matching models to data collected by students using calculators, computer interfaces and measurement probes. Technology facilitates measurement and data-gathering, thus shifting the focus to data interpretation, model identification and analysis.

The ***modeling process strand*** incorporates a student-centered instructional approach into our curriculum framework. It includes *structured inquiry techniques* developed in the Modeling Instruction Project and basic skills in mathematical modeling, proportional reasoning, quantitative estimation, and data analysis. This contributes to the development of critical thinking and communication skills, including the ability to formulate well-defined opinions and evaluate or defend them with rational argument and evidence. It is expected to produce significant improvement in student scores on standardized reading, writing and mathematics tests as well as in higher-order thinking.

Implementation in Modeling Instruction:

A few words about Modeling Instruction are needed to appreciate the unique features most responsible for its success. Its big difference from other approaches is that *all stages of inquiry are structured by modeling principles.* Typical inquiry activities (or investigations) are organized into ***modeling cycles*** about two weeks long [8].

The teacher subtly guides students through the activities with **modeling discourse [**10]: which means that the teacher promotes *framing all classroom discourse in terms of models and modeling.* The aim is to sensitize students to the structure of scientific knowledge, in both declarative and procedural aspects.

The culmination of student modeling activities is reporting and discussing outcomes in a whiteboard session [8, 10]. This may be where the deepest student learning takes place, because it stimulates assessing and consolidating the whole experience in recent modeling activities. *Whiteboard sessions have become a signature feature of the Modeling Method*, because they are flexible and easy to implement, and so effective in supporting rich classroom interactions. Each student team summarizes its model and evidence on a small (2ft $\times$ 2.5ft) whiteboard that is easily displayed to the entire class. This serves as a focus for the team's report and ensuing discussion. Comparison of whiteboards from different teams is often productively provocative. The main point is that class discussion is centered on visible symbolic inscriptions that serve as an anchor for shared understanding [17, 18].

Primacy of modeling over problem solving.

In Modeling Instruction, problem solving is addressed as a special case of modeling and model-based reasoning. Students are taught that the solution to a problem follows directly from a model of the problem situation. The modeling cycle applies equally well to solving artificial textbook problems and significant real world problems of great complexity. ***This approach is readily transferred to mathematics teaching****, as math teachers who attend our workshops learn!*

The modeling method, with its emphasis on coherence and self-consistency of the model, is especially-well-suited to detection and correction of ill-posed problems, where the given information is either defective or insufficient. Moreover, students are thrilled when they realize that a single model generates solutions to an unlimited number of problems. Indeed, the Modeling Workshops teach that six basic models suffice to solve almost any mechanics problem in high school physics. Modeling promotes expert problem solving behavior in students [19,20].

V. Why Modeling for Physics First?

As forcefully argued in the introduction, updating the curriculum to reflect advances in science and technology requires inverting the traditional science course sequence to place physics in the ninth grade, the so-called *Physics First* sequence. Strong advocacy for Physics First has come from many scientific quarters. Thus, in an official policy statement on Physics First (2002) the AAPT recognizes that "Physics First has the potential to foster greater scientific literacy and to help integrate physics, chemistry and biology." Simply moving 12th grade physics to 9th grade is not recommended, however; rather, the statement emphasizes that major revisions in the high school curriculum will be necessary to realize the potential of Physics First. This project provides a vehicle for introducing such reform on a national scale.

Though interest in Physics First is increasing throughout the nation, the success of attempts to introduce it has been spotty and largely unsatisfactory, mainly, we contend, because of inadequate curriculum materials, course design and teacher preparation. For example, in concession to widespread mathephobia among students and the general populace, many schools have adopted a "Conceptual Physics" approach that aims to teach physics without mathematics. We see this as a serious mistake, contending that mathephobia is better addressed by strengthening the connection between math and science rather than weakening it. Indeed, we contend that ninth grade physics should play a central role in developing mathematical literacy for all students. We are well aware of doubts that ninth grade students are sufficiently mature for ninth grade physics, so we present some unpublished data here as proof of concept that Modeling Instruction, at least, can make it work.

The data are supplied by Rex Rice, one of the most accomplished modelers in the country. After he participated in Modeling Workshops (1995-97), the performance of his students was evaluated with the FCI and MBT. His scores are still among the highest achieved by any modeler in the country, comparable to those of college students in Eric Mazur's course at Harvard and graduate physics at ASU. Consequently, he was well qualified to adapt the modeling materials developed for 11^{th} and 12^{th} grade physics to a 9^{th} grade physics course.

Rice has been a physics teacher at Clayton public high school in suburban St. Louis, Missouri for nearly twenty years. In the last decade he has succeeded in moving his entire school to a Physics First sequence. This required training new teachers in physics modeling instruction and persuading chemistry and biology teachers to accept it.

The following data from 2001-02 are for 148 students in ninth grade physics taught by four different teachers using Modeling Instruction (20% of the students were bussed from inner city St. Louis). One teacher was brand-new to physics, with a degree in biology and several years' experience teaching science in elementary school. He took our 3-week Modeling Workshop in summer 2001, had a job for the rest of the summer, and then began teaching. The other three teachers were experienced physics teachers, including Rex Rice and others who had participated in one Modeling Workshop within the previous two years.

Their student FCI pretest and posttest scores were as follows:
For 89 students in Regular Physics (30% from inner city)

Pretest: 20%	Posttest: 44%	SD: 17.8%

For 57 students in Honors Physics

Pretest: 28%	Posttest: 71%	SD: 15.9%

For the 58 students of the new teacher the posttest score was 43%; compared to 47% for the experienced teacher. In view of the standard deviation, a 5% difference is insignificant.

In view of the huge body of FCI data from high school to graduate school, these data are extremely significant. Compare them with the data in Figure 1, for example. Pretest scores ranging from 20% (a random guessing score) to 30% for the best students are typical for students at all age levels into college. It tells us that no one learns physics from everyday experience without some formal introduction to the subject. For Regular Physics the posttest scores are higher than typical scores for conventional 11^{th} and 12^{th} grade physics, even though the main teacher is a novice with degree out of field, and, more important, even though the students are from the bottom 70% of the class, whereas conventional physics draws from the top 25%. Compared to conventional physics, the 71% posttest score for expert modeling instruction is simply *superb*! Rice has documented that FCI scores continue to improve, averaging more than 90% for his incoming senior AP-B students (compared to a typical score near 60% for AP students under traditional instruction).

This is compelling evidence that modeling instruction for 9^{th} grade physics students is significantly more effective than traditional physics instruction for 12^{th} grade students. Moreover, the chemistry and biology teachers at Clayton have become champions of the inverted Modeling Physics First sequence.

An important subgoal *of this project is to* **replicate** *and build on Rex Rice's success!* One of our first acts will be to join with Rex Rice and other modelers with related experience [21, 22] to produce a compelling article on "Modeling for Physics First." This should help convince school district officials who might be skeptical that such an implementation can be successful.

VI. Course Content, Curriculum Framework and Workshop Design

Thematic structuring to achieve a coherent curriculum is advocated in the National Science Education Standards (1996) and by the National Research Council (1999). Though our thematic framework is intended for the entire K-12 curriculum, we will concentrate on developing and field-testing it at the most critical junctures, namely, the interfaces of ninth grade physics with middle school science on the one hand and a subsequent chemistry course on the other. Accordingly, we will create a three course sequence of six modeling workshops in physical science, physics and chemistry bound into a coherent whole by a science process thread of *models and modeling* and a science content thread of *energy and structure of matter*.

Fortunately, draft materials for modeling workshops in these courses have already been created and pilot tested as spin-offs of the long-standing Modeling Instruction Project. Our main problem in development will be shaping given materials and activities to a learning progression with high coherence and quality over the three year span. Even so, we are always looking for better materials, including software, so a portion of development time will be devoted to reviewing materials created by other projects. As in the past, we will team up with outstanding developers of research-based materials, such as the Concord Consortium (2008). Our objective is to incorporate the best materials we can find into a coherent course sequence.

We know that there is not a unique set of best materials, so we continue to extend our (already large) repertoire of alternative course materials and activities to support individual teacher preferences and local conditions. This contributes to the flexibility of the curriculum to meet local needs. Of course, that flexibility is essential to continued upgrades of the STEM curriculum. Realization of this demand for *flexibility* to support local needs and continued upgrades will be greatly facilitated by creating the *Modeling Wiki* described below.

The K-12 science curriculum is largely shaped by textbooks, and publishers are clamoring to adopt them to the *ad hoc* requirements of state science and math standards. This is a huge barrier to systematic STEM education reform, and this project aims to create a viable alternative. Though we are not opposed to textbooks in principle, we have not found any that are suitable for our courses. We recommend some physics and high school textbooks to teachers for their personal reference or token assignment of a textbook that is often required by schools. However, the most widely used middle school textbooks are scandalously bad (Hubisz, 2003). We are confident in recommending one venerable old textbook (Haber-Schaim, 1982) and one new (Goldberg, 2007), but they do not satisfy many of our requirements for course design below. We look to the *Modeling Wiki* to ultimately free us from textbook hegemony.

A. Middle School Physical Science and Mathematics

This workshop (course) series addresses conceptual underpinnings for physics and chemistry that are important components of scientific literacy even for students who do not continue with the recommended sequence of more advanced courses. The course is intended for integration with middle school mathematics so we will encourage both science and math teachers to attend our workshops, especially in teams from the same school. The course is designed for grade 8, but can easily be spread out over grades 7 and 8. We are keenly aware of competing state requirements to include earth and space science or biology in these grades, but we contend that the math in these grades can be more efficiently addressed by integrating it with physical science in the way we propose.

The course emphasizes *proportional reasoning* as a starting point for developing the concept of *function* and in relationship to *graphing* and *modeling motion* and money contexts. This is an ideal prelude to our central mathematical theme of *quantitative reasoning with models*.

Quantitative reasoning with number and unit goes hand-in-hand with *modeling and measurement*, which couples the mathematics to the science (Lesh & Doerr, 2003a,b). Our workshop fleshes this out with a hands-on introduction to basic physical variables, including time, position, velocity, mass, density, temperature and energy. Proportional reasoning is an essential component of quantitative reasoning, so our evaluation scheme will be designed to compare results of instruction in both.

Here is a working outline of topics to be addressed in the physical science course. As always in modeling instruction, all essential concepts are introduced and developed through specific student activities.

1. Modeling Geometric Properties of Matter: size, shape and place.
    a. Measurement of length
        i. Measurement as comparison: standard rulers and units
        ii. Additivity and equivalence of lengths (congruence)
        iii. Accuracy, uncertainty and propagation of error
    b. Shapes and boundary size
        i. Circle: circumference vs. radius and diameter
        ii. Polygons: rectangle and perimeter
    c. Measurement of area: dimension and size
        i. Rectangular objects: multiplicative relation of length to area
        ii. Irregular objects: additivity of parts and areas
        iii. Area of circle: approximation by polygons
    d. Measurement of volume
        i. Units, dimension and additivity
        ii. Volume of irregular solids and liquids
        iii. Graphical relation between volume and height
    e. Maps as models of place, size and shape
        i. Position vs. distance
        ii. Scaling and shape invariance
2. Physical properties of matter
    a. How much stuff? Mass as quantity of matter
        i. Measurement by balancing
        ii. Additivity and choice of unit
        iii. Conservation of mass (under change of size/shape, melting, dissolving, etc.)
    b. Kinds of stuff:
        i. Density as a distinguishing property of material kinds (eg. alcohol on water)
        ii. Density of solid, liquid, gas
        iii. Is there a smallest part? Atoms (estimation of atomic size from thin film)
    c. Systems: boundaries and environments
        i. System diagrams
        ii. Open and closed systems (matter exchange)
3. Motion and Interaction
    a. Particle model of motion (displacement and motion maps)
    b. Measurement by comparison of motions
        i. Clocks as standard motions: units for time
        ii. Time vs. time interval
        iii. Position-time graphs: slope as velocity

c. Constant and variable velocity
    i. Measurement with motion sensors: graphical representation
    ii. Qualitative concept of acceleration
d. Kinetic energy as quantity of motion
    i. Change in collisions
    ii. Energy conservation and transfer
e. Agents and interactions
    i. Long and short range interactions (gravity and contact)
    ii. Attraction and repulsion (magnetic and electric)
f. Potential energy and energy conservation
    i. Falling body, pendulum and springs
    ii. Quadratic functions and their graphs
    iii. Graphical model of binding interactions with repulsion & attraction

4. Energy & change (observations and qualitative explanations)
    a. Heating and cooling as energy exchange
        i. Thermal energy as kinetic energy of particles (expansion of gases)
        ii. Thermal contact, conductivity and equilibrium
        iii. Thermometers: temperature as measure of thermal energy
        iv. Energy exchange by radiation
    b. Internal energy = thermal energy + interaction energy
        i. Thermal expansion of solids
        ii. Change of state
    c. Chemical change
        i. Molecular models of materials
        ii. Energy from chemical change
        iii. First look at the Periodic Table

B. Energy Wprkshops for Physics First.

Although the energy thread will run through the entire curriculum, it will be treated most intensively in two workshops on the ninth grade physics course focused on *Energy and Structure of Matter*. These workshops will be attractive to both physics and chemistry teachers at any level, whether or not they are interested in broader curriculum reform. Some of the course topics could be included in either physics or chemistry courses, so the importance of integrating the courses is obvious. The workshops are also recommended for teachers of ninth grade algebra, as they will include explicit designs for coordinating (if not integrating) math with physics.

Our design of the workshops is guided by the need to teach physics as a foundation for chemistry, whether the ninth grade course be 'physics first' or physical science. In particular, the Newtonian emphasis on force and motion will be reduced in favor of internal energy and energy transfer, which play much greater roles in chemistry. The general energy conservation law (First Law of Thermodynamics) will be introduced from the beginning by modeling particles with internal energy. This decouples energy and momentum laws (which are inextricably linked in Newtonian mechanics). The emphasis will be on changes in systems that occur as a result of an interaction, rather than on the details that occur during an interaction. Thermodynamic systems, few-particle systems, and fluid systems will be treated in a unified way. Then the dynamics of interactions will be explored.

A key strategy in course design will be development of *models for macroscopic systems and processes that can be transferred by analogy to model atomic-molecular systems* and processes as directly as possible – thus to help students develop intuitions for the imperceptible in terms of the perceptible.

One of the great lessons learned from *Modeling Instruction* is that science pedagogy cannot be separated from science content. *Pedagogical reform requires curriculum reform!*

Incorporating modeling instruction into an energy first approach that replaces the usual force-and-motion first approach requires a formidable reconstruction of the curriculum. Fortunately, much of the work has been done for us already by Prof. Wendell Potter and his collaborators (Potter et. al. 2000, 2004). Over many years they created and thoroughly tested an energy first reformed course for algebra-based college physics. The pedagogical design and course content are so similar to what we need for our Energy Workshop that adapting it will be straightforward.

A bonus of adapting Potter's course is that he has impressive longitudinal data on more than 8000 biology majors showing that his students do significantly better in upper division courses than a control group of students who took a conventional physics course, and he has evidence attributing the difference to thinking patterns promoted in his course. We expect our ninth grade energy intervention to have a similar impact on subsequent chemistry and biology courses.

In developing our Energy Workshop, challenging problems arise in selecting, sequencing and structuring the subject matter for optimal coherence and learnability. Another challenge is that the workshop materials developed must be usable in many settings for many different kinds of students. Of course, strong emphasis will be placed on the process of developing models and using models to make predictions about the real world.

Energy storage and transfer

A stronger emphasis on energy, especially on *qualitative reasoning with energy diagrams and bar charts,* is needed to establish a solid foundation for energy arguments throughout the high school science curriculum. Thus, we adopt energy storage and transfer as a unifying theme that binds the various topics into a coherent conceptual system.

Qualitative reasoning based on the energy concept will be emphasized first, with the more quantitative development following. The concept development will rely heavily on the use of diagrammatic tools such as energy bar charts (cf. Alan van Heuvelen's *ALPS kits*), energy flow diagrams (similar to those used to describe thermodynamic processes), and potential energy diagrams to describe energy storage and transfer, giving continuity to the tools of discourse from physics to chemistry.

Here is a brief description of the innovations we propose and the rationale behind them:

1) Incorporating thermodynamics in mechanics and throughout chemistry. As Sherwood [E31] and Arons [E32] have observed, thermodynamic questions arise in the most elementary phenomena of mechanics, such as sliding friction, and textbook treatments are frequently wrong. The problem begins with the fact that Newtonian particles have no internal degrees of freedom, yet thermodynamics is about internal energy. We submit that the simplest way to solve this problem is to extend the class of models in introductory mechanics to include particles with internal structure and hence internal energy. That is, we model objects as *particles* with internal structure. This is a departure from treatments in standard textbooks, which do not introduce the concept of internal energy until objects are modeled as systems of structureless particles. While this is not wrong, it is very complicated and achieves little. For example, even for simple models of internal force, the equations of a many-particle system are too difficult to solve in closed form, and furthermore a correct treatment requires quantum mechanics. Our approach is simpler: it simply admits that an object can have internal structure so that internal energy can be correctly discussed in mechanics, but leaves the details of that structure unspecified, to be discussed when appropriate or needed. This approach is not as radical as it may at first seem: particles with internal structure are used frequently in other branches of physics, such as relativistic physics, for example. In that sense, we are setting the table for advanced course work (see also below).

By allowing objects to be modeled as particles with internal structure and thus internal energy, we have decoupled energy conservation from momentum conservation. That is, standard textbooks often derive the work-energy theorem from Newton's 2nd Law. However, the concept of internal energy is not derivable within that framework. Again as pointed out by Arons [E32] and Sherwood [E31], the work-energy theorem is thus often incorrectly applied in introductory mechanics problems dealing with sliding friction. In our approach, momentum conservation will still be governed by Newton's 2nd Law, but energy conservation will be governed by the 1st Law of Thermodynamics. From the outset of the course, energy storage and transfer will be discussed in the context of the 1st Law of Thermodynamics. Again this is not as radical as it may at first sound – the decoupling of energy conservation from momentum conservation is central to advanced course work (quantum mechanics, thermodynamics, relativistic physics). Thus, we are making the students' experience in their introductory course more aligned with later course work. Indeed, the ubiquitous nature of energy conservation has led Alonso and Finn [E33] to coin the phrase "The Equation of Everything" for the 1st Law of Thermodynamics. This figurative expression nonetheless captures the students' imagination and is a bit less imposing than the "1st Law of Thermodynamics." We plan to adopt it in the units we develop.

We believe the benefits of the approach we have described above are manifold: (i) our approach provides a resolution to the problem of how to correctly treat friction in energy processes as discussed by Arons [E32] and Sherwood [E31]; (ii) thermodynamics is often presented to the students as *disjoint* from mechanics, thereby again incorrectly portraying knowledge in physics as *fragmented*. Thermodynamics is also fragmented in chemistry with energy changes involved in changes in temperature, phase, and bonding treated in an unrelated manner. Our approach begins to rectify this issue, presenting mechanics and thermodynamics (as presented in both physics and chemistry) in a more coherent framework; (iii) the idea of particles with internal structure opens the door to and intertwines with our structure of matter theme, thereby presenting physics and chemistry as a *coherent*, rather than fragmented, body of knowledge.

2) Use of Diagrammatic Tools. A key issue for students in describing energy processes is correctly *bookkeeping* energy storage and transfer (to use a money analogy, how much energy is stored in each account before and after the process, and what energy "transactions" were made). Therefore, we propose to develop an energy strand running through both physics and chemistry that will rely heavily on diagrammatic tools to help students first reason qualitatively about energy storage and transfer. The diagrammatic tools we will emphasize and further develop include the following: *(i) energy pie charts*. The energy of the system is represented by a pie (circle) with the various modes of energy storage (kinetic, potential, internal) represented as pieces of the pie. Energy transfer into or out of the systems is depicted by the pie getting larger or smaller; *(ii) energy bar graphs.* Each energy storage mode is represented by a bar of a certain height. Students are asked to draw bar graphs for the initial and final states of the system and account for any energy transfer into or out of the system or within the system by comparing the initial and final bar charts; *(iii) energy flow diagrams.* As the reader may have deduced, the previous two tools are better suited for describing energy *storage* than energy transfer. A diagrammatic tool is needed to better describe both the internal transfers of energy within the system and the external transfer of energy between the system and the environment. Such a tool exists in energy flow diagrams used in thermodynamics. We will use such diagrams to represent the flow of energy in mechanical and chemical processes as well. Use of these diagrams for more traditional mechanics problems will again better prepare the students for their use in later courses and will present a more coherent approach to energy across the science curriculum; and *(iv) potential energy diagrams*. Potential energy diagrams will be used to develop the idea of potential (as noted below) and to develop the idea of a "bound" system. A goal of the latter development is as a prelude to energy level diagrams in chemistry. Facile use of the qualitative tools is essential for correct quantitative descriptions of energy storage and transfer by students.

3) Stronger emphasis on potential. In fashioning the energy strand, we will place a strong emphasis on potential energy diagrams *as well as* the concept of *potential*. Educational research shows that exposure to and practice with the idea of potential in a mechanical context significantly improves subsequent student learning and understanding of electrical potential (Brewe, [E34]). As students move on to chemistry, a solid understanding of electrical potential and potential energy changes will provide the foundation on which conceptual understanding of bonding and electrochemical phenomena can be built.

To summarize: A deep understanding of energy is necessary to make sense of the material universe, whether one approaches it macroscopically through the study of mechanics or microscopically in studying behavior of atoms. To this end, students will be asked to describe energy storage and transfer in situations that are exemplars of the content model being developed. Student analysis will be guided by the 1st Law of Thermodynamics, which will be developed as an integral part of the first models of the course. The students will first be asked to describe the process qualitatively using the tools described above, which will be developed as needed in the units. The idea of particles with structure will be introduced at appropriate points in the model development of each course. Quantitative descriptions of energy transfer will grow out of the reasoning students build through the use of qualitative tools.

C. Remodeling Chemistry.

Sad to say, the standard high school chemistry course begins with a whirlwind tour of internal structure of the atom, without providing either a rationale for the need to know this structure, or more than a cursory treatment of the evidence used to support the current view. As a result, the chemistry course relies heavily on rote learning, because the atomic theory needed for conceptual understanding requires a physics course. A physics course before chemistry is helpful but not sufficient to solve this problem. It is equally important to clarify the structure of chemistry by defining the models needed to explain particular chemical properties. Only from well-defined models can precise inferences be made. *Models that explain structure of the periodic table of the elements and mechanisms for chemical change are of central importance.* Pedagogically acceptable models will appeal to empirical evidence for a progressively more refined model of matter without resorting to quantum mechanical explanations that students are not prepared to understand. For example, empirical evidence is sufficient to infer the existence of quantized energy levels, so a model of the atom that accounts for the interaction of light and electrons can be developed without including a quantum mechanical justification. At the same time, our modeling chemistry course cultivates math literacy by stressing proportional reasoning over rote use of algorithms to solve a wide variety of problems (stoichiometry and gas laws).

As continuations of learning progressions originating in the preceding workshops the chemistry workshop will address the following crucial topics at least:

I Particulate structure of matter
Macroscopic vs microscopic descriptions. Compounds, elements and mixtures.
Explanation of (observed) macroscopic properties with microscopic models.
Systematic explanation of details with models of increasing complexity.
Macroscopic evidence for microscopic structure (ionic vs molecular substances).

II Energy and kinetic molecular theory
Visualizable models (macroscopic analogs) for solids, liquids and gases.
Energy storage modes and transfer mechanisms.
Interaction energy and phase change.
Distinction between heat and temperature.

III Stoichiometry
The mole concept – relating how much to how many.
Using equations to represent chemical change.
Non-algorithmic approaches to chemical calculations.

IV Energy and chemical change
Attractive forces vs chemical bonds.
Kinetic energy, chemical potential energy and ΔH.

Conceptual mastery of all these topics is essential for working knowledge of the **periodic table** as an embodiment of knowledge about the atomic structure of matter, which should surely be one of the ultimate objectives of a chemistry course. Chemistry education research shows that this objective is rarely achieved under traditional instruction. (See below for discussion of an essential component of that research concerning energy.) Understanding of the periodic table does not come all at once, so we aim to develop it within a learning progression on structure of matter that begins with middle school physical science.

VII. Evaluation with Concept Inventories.

The successful evaluation of student learning in physics using the *Force Concept Inventory* (FCI) will be extended to a coherent evaluation system able to track growth in student learning throughout the new modeling curriculum. The core of the evaluation system is a battery of four *Concept Inventories* tied to the major conceptual strands in the curriculum framework: Besides the FCI, a validated *Energy Concept Inventory* (ECI) with a significant body of baseline data is now ready for comparative studies [E1]. A *Matter Concept Inventory* and a *Chemistry Concept Inventory* are under development and will be ready for use within the first year of this project.

We aim to develop the Concept Inventories into an evaluation system that can be used by others for both formative and summative evaluation. As they stand, the Inventories systematically survey essential concepts in each of the content strands, so they are suitable for summative evaluation. *For the purpose of formative evaluation*, we will subdivide the inventory concept coverage to create a battery of graded instruments to help teachers monitor learning progress throughout the courses, as we have done successfully with the FCI in the past. *A crucial research issue is to ascertain just how much students can learn about energy and structure of matter at each grade level*. The complexity and import of that issue is revealed in the detailed discussion of the ECI below. *We hypothesize that our systematic approach to energy and structure of matter using modeling pedagogy will produce significant learning gains in these conceptual domains*.

Designs for all the Concept Inventories follow the proven design for the FCI, which originated with the Modeling Project [5]. The suitability of the FCI as an evaluation instrument is clear from the striking results reported in Section IIIA. Others cite the FCI as producing the most convincing hard evidence of need to reform traditional physics instruction and the impact of teaching grounded in educational research (Hake 2002; Saul & Redish 1998).

<u>Energy Concept Inventory</u> (ECI)

Of all the Inventories, we regard the ECI as the most significant for measuring overall success of our curriculum innovations, because energy is an essential concept for biology and chemistry as well as physics, and our baseline ECI data (reviewed below) reveals an abysmal grasp of energy concepts by almost all students at all grade levels from middle school through university physics [E1]. The net effect is to reduce the role of energy in the traditional curriculum to meaningless jargon. Above all, we aim to demonstrate that our instructional framework is a significant step toward solving this desperate problem.

The complete ECI will be used for summative evaluation at the end of the physics and chemistry courses. A subset of ECI questions, called the *Basic Energy Concept Inventory* (BECI), will be used to evaluate the earlier stages. Questions on the BECI require no specialized knowledge and no scientifically technical language. No ECI item is worded in technical terms, and only qualitative analysis is required.

Design and validation of the ECI is complete [E1], after a five-year development process closely informed by science education research, though some questions may be added or modified to address "coverage issues. We have also accumulated a substantial body of baseline data. A summary of the results is appropriate here, as it provide primary motivation and justification for the present project, as well as evidence for the efficacy of the ECI.

Results from 2000 students in grades 9, 10, 11, and 12, more than 200 university students in physics courses, and 185 high school teachers of the physical sciences indicate that students at every level and most science teachers cannot use energy to account for common school science phenomena in the standard biology, chemistry, and physics curriculum. For example, seven hundred ninth grade students in a suburban school averaged about 25% on the BECI, and their conception of energy was very inconsistent.[Glenbrook North HS 2005] We gave the BECI to twenty-five ninth grade physical science and biology teachers in an urban school district, and they averaged about 45%. Although students' conception of energy becomes more consistent the older the group surveyed, 600 high school juniors and seniors answered only one-third of the ECI questions correctly. One hundred eighty-five teachers of high school physics and chemistry enrolled in our summer graduate courses at ASU scored almost twice as high, averaging about 60%, although a few scored above 90%. Most of these teachers have taken at least one Modeling Workshop, and they score at mastery level on the FCI. Their relatively low score on the ECI indicates a strong need to improve energy instruction in Modeling Workshops.

Preliminary statistics on these 185 teachers indicate that the ECI is very well-developed and reliable: for a group of 91 teachers, the estimate of internal consistency reliability (Cronbach's alpha) was .86. For another group of 34 teachers, it was .87. This is more than satisfactory for making inferences regarding groups of examinees - potentially an excellent instrument for conducting research. Most ECI items show high levels of discrimination (examinees who do well overall do well on a particular item and those who do poorly overall do not - this is important if we expect that getting items correct actually reflects having the knowledge being measured).

Like the FCI, the ECI is a multiple-choice test of the subject's ability to discriminate between scientific concepts and "common sense" alternatives that are highly plausible on grounds of everyday experience. The high validity of the ECI ensures that "common sense choices" are strong indicators of deficiencies in the scientific concepts. Like the FCI, the ECI incorporates a systematic *survey of all dimensions of the energy concept* compared with a systematic *taxonomy of alternative conceptions* (Appendix B, Table 2).

Of course, the alternative conceptions are *misconceptions* from the scientific point of view, but the "due process" of scientific method dictates that they should be regarded as reasonable hypotheses until they are disconfirmed by evidence and argument. Indeed, we hold the main reason that unscientific ideas about energy are so persistent is that conventional instruction fails to give them their "day in court" where they can be critically evaluated and dismissed by students themselves. That insight played a major role in the design of Modeling Instruction to deal successfully with force concepts, so we expect it to be equally important for energy instruction.

Energy is a complex concept, so it cannot be described in a single, simple statement. For students to have a fully functional energy concept, they must understand its four basic conceptual dimensions outlined in Appendix A (Table 1). That analysis of the energy concept was used to guide the selection of items for the ECI, and it will guide the systematic treatment of energy in our Workshop.

Table 3 shows the average ECI scores for three significant student populations: 325 incoming freshman and 273 juniors and seniors attending a suburban academically-oriented high school, and 117 college students from two typical state universities who took the ECI near the end of a one-year calculus-based physics course.

The ECI is a multiple choice test with 5 choices for each item, so 20% is a random score on the test. The freshman BECI score of 22.9% suggests that they had learned nothing at all about energy in middle school. The juniors and seniors had just completed high school physics, so their score of 35.7% indicates that they had learned little about energy in high school. The university score of 45.4% is not more impressive, especially considering the selection effect that presumably filters out weaker students from high school. Note how the Kuder-Richardson score (KR-20) in Table 3 increases with each population until it reaches the credible value of 0.81.

Table 3. Summary Statistics for the ECI

New HS Freshmen Statistics (BECI)		*High Schools Statistics* (ECI)		*Universities Statistics* (ECI)	
Mean	22.9%	Mean	35.7%	Mean	45.4%
Standard Dev.	8.2%	Standard Dev.	12.8%	Standard Dev.	16.2%
Range	52%	Range	66%	Range	71%
Minimum	0	Minimum	14%	Minimum	11%
Maximum	52%	Maximum	80%	Maximum	83%
KR-20	0.03	KR-20	0.70	KR-20	0.81
Count	325	Count	273	Count	117

<u>Other evaluation instruments and procedures</u>: Besides the Concept Inventories, we will test for specific math skills, such as proportional reasoning and quantitative analysis, that are emphasized in our curriculum. Whenever possible, we will adopt or adapt instruments created by

other researchers so we can take advantage of their insights and results. The emphasis will be on instruments with strong baseline data to support quantitative comparisons.

To evaluate degree of classroom implementations of the curriculum and changes in teaching practice, we will employ two teacher surveys adapted from well-developed surveys long in use by the Modeling Project (so we have background data for comparison). The first is administered at the beginning of the workshop while the second is administered online after teaching the course during the academic year. In addition, we plan to correlate test scores with onsite monitoring of the instruction by an experienced observer using the Reformed Teaching Observation Protocol (RTOP) (Piburn et. al., 2000).

VIII. A Modeling Wiki for continuous STEM education reform

This project will pioneer a new enhancement of the national cyberinfrastructure to support continuous K-12 STEM education reform. A new kind of wiki, called the *Modeling Wiki*, will be developed to facilitate interaction within the community of modeling teachers and give them direct access to the currently best available modeling curriculum materials, downloadable for immediate use in their teaching. Wikis are optimal tools for threaded discussions and information search on the internet.

We expect the Modeling Wiki to evolve over time to not only become *the place* to access modeling materials, but also fulfill some of the functions for support and discussion currently served by the modeling listserv and its archives, aid teachers in curriculum development and planning, and host a dynamic online community that collaborates on new material. The present project will extend the Wiki along these lines as opportunity permits, but the main objective will be to put the Wiki on a secure foundation.

As a first step, all curriculum materials developed for *Modeling Instruction* will be translated into a collaboratively editable wiki documents that will be open to all modeling teachers for revision and improvement. This will make the curriculum responsive to the experience and best thinking of the entire modeling community. Submissions to the wiki will be regularly reviewed by an expert editorial board of modelers and researchers that will release endorsed versions of the curriculum to make current best practices and the most up-to-date materials available to all.

As soon as it is up and running, the Modeling Wiki will be adopted as the primary distribution tool for the continuously evolving curriculum of the Modeling Instruction Project. It will keep teachers up-to-date on new curriculum developments so they can make informed choices about scope and sequencing of topics as well as contribute their own discoveries and materials to the modeling knowledge base. It will provide teachers with the security of using a vetted, regularly updated version of the modeling materials, and enable them to view relationships among curricular elements and compare their chosen curricular sequence with other suggested curricular "paths."

Individuals in the nationwide community of modeling teachers have voluntarily contributed their expertise and energy to review and refine the existing curriculum materials as well as create new materials to suit their individual purposes. After a decade of classroom use, the community has spawned numerous updates and revisions of the original curriculum materials. A few modeling teachers maintain websites with their modifications that are frequently visited by other modelers seeking new updates and perspectives on the curricular materials.

In addition, ASU has maintained a set of modeling listservs for 12 years (1800 current subscribers). These listservs have served as fertile forums for discussion about the modeling curriculum, and they have been the genesis for numerous adjustments in the curriculum, from changes as small as the wording of individual problems to large changes in classroom practice or curriculum scope and sequence.

The active role of technology in refining the *Modeling curriculum* to date is clearly evident in the collection of listserv compilations on the *Modeling Instruction website:* http://modeling.asu.edu. Here, suggestions, techniques and adjustments from a decade of discussion among modelers have been collected into 300 compiled listserv discussion threads. Many of these compilations include important curricular adjustments used by expert modelers that have not yet been incorporated into the modeling curriculum materials. Numerous more extensive updates to the curriculum have also been created and submitted by the modeling community directly to ASU and to the *American Modeling Teachers' Association* (AMTA). These submissions represent valuable contributions to the curriculum.

The distributed nature of all these efforts to refine the Modeling Curriculum has greatly complicated the process of determining and distributing the best updates to the curriculum. As a result, materials used as "best practices" modeling instruction in physics have become fragmented, and many modelers are unable to benefit from the excellent curricular improvements made by others.

The Modeling Wiki will remedy these difficulties by making use of the national cyberinfrastructure available to all modeling teachers. The resulting wiki will be hosted by the National Science Digital Library (NSDL) ComPADRE (Communities for Physics and Astronomy Digital Resources in Education) Pathway, which will connect the Modeling Instruction curriculum to its infrastructure and resources of the NSDL. The curriculum elements will be developed and modified using a specialized NSDL version of the MediaWiki software. ComPADRE will also help develop tools for navigation and personalization of the modeling curriculum as well as a toolset for visualizing relationships among the elements of the curriculum. (See letter by ComPADRE Director Bruce Mason in supplementary documents.)

For quality control, top-rated submissions to the wiki will be reviewed by an expert editorial board of modelers and researchers that will release endorsed versions of the curriculum reflecting the best curriculum at the time of review. These endorsed versions will be regularly released but will remain static between review periods.

IX. Results from Previous NSF Support

The present project is a continuation of systematic *STEM Education R&D* that has been ongoing for more than two decades. Success of initial work in physics education stimulated extension to chemistry and middle school physical science along with institutionalization in a graduate program for STEM teacher professional development. Fifteen years of continuous NSF funding for the Modeling Instruction Project ended three years ago, but the project has been sustained since by state funding in Arizona and elsewhere across the country. As its entire history is relevant to the present project, we review it briefly here.

Modeling Instruction: The physics education R&D work undergirding this project has been concerned with: (a) developing a coherent instructional theory, (b) applying it to the design and conduct of instruction, and (c) developing validated instruments to assess the outcomes.

Foundations for the project were laid in references [1] through [4], and they provided the primary justification for subsequent NSF funding. Results from support by the three NSF grants are reported in references [5] through [14]. The following is a summary of results relevant to the present project.

A. Modeling Theory

Modeling theory is grounded on the thesis that scientific activity is centered on *modeling*: *the construction, validation and application of conceptual models to understand and organize the physical world.* Accordingly, instructional design is centered on *models*, as units of coherently structured scientific knowledge, and *modeling*, as the core of scientific method. Full implementation of modeling theory in science instruction is a huge task, because it requires a thorough analysis and reconstruction of the curriculum. Although details have been worked out fully only for physics [3, 7, 10, 14], the *epistemological and pedagogical framework of modeling theory is applicable to all the sciences* [15, 16]. Thus we have the basis for an integrated approach to all science instruction.

Modeling Instruction has much in common with *Realistic Mathematics Education* (RME), a teaching and learning theory in mathematics education developed by the Freudenthal Institute in the Netherlands (Freudenthal, 1991, 1993).

B. Evaluation of Physics Instruction

The *Force Concept Inventory* (FCI) is one of several evaluation instruments developed in the Modeling Instruction Project for comparative evaluation of alternative methods of physics instruction [1, 5, 6, 9, 12, 13]. Within the physics community, the FCI has been cited as producing the most convincing hard evidence of need to reform traditional physics instruction and of the impact of teaching grounded in educational research (Hake 1998, 2002; Saul & Redish, 1998).

Besides the extensive survey by Hake (1998) we now have FCI data on roughly 30,000 students of 400 physics teachers in high schools, colleges and universities through the United States. This large data base presents a highly consistent picture, showing that the FCI provides statistically reliable and discriminating measures of minimal performance in mechanics. It has enabled evaluation of modeling instruction with high statistical significance.

C. How effective is modeling instruction?

In comparison to traditional instruction, under expert modeling instruction high school students average more than two standard deviations higher on the FCI.

Figure 1 summarizes data from a nationwide sample of 7500 high school physics students involved in the Modeling Instruction Project during 1995–98. The average FCI pretest score is about 26%, slightly above the random guessing level of 20%, and well below the 60% score which, for empirical reasons, can be regarded as a *threshold* in the understanding of Newtonian mechanics.

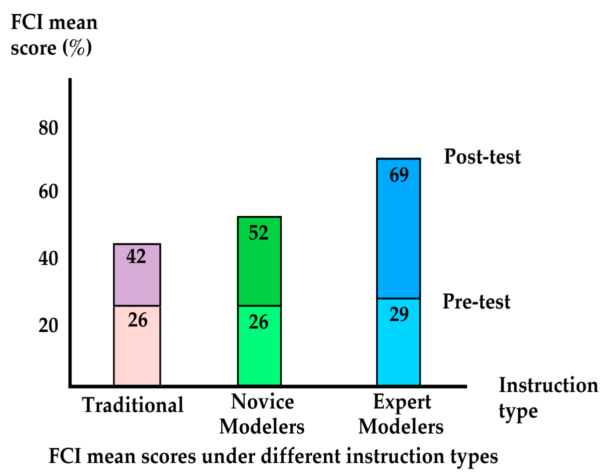

Fig 1

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%, still well below the Newtonian threshold. This corresponds to a normalized FCI “Hake gain” of (42 – 26)/(100 – 26) = 22%, in agreement with Hake’s results. To the surprise of many, this gain has been shown to be largely *independent of the instructor’s subject knowledge, experience and teaching style* [1].

High school teachers participating in the Modeling Instruction Project begin a shift from traditional instruction to modeling instruction in their first three- or four-week summer workshop. After their first year of teaching posttest scores for students of these n*ovice modelers* are about 10% higher, as shown in Fig. 1 for 3394 students of 66 teachers. Students of expert modelers do much better. For 11 teachers identified as expert modelers after two years in the Project, posttest scores of their 647 students averaged 69%. This corresponds to a Hake gain of 56%, more than double the gain under traditional instruction. After two years in the Project, gains for students of under-prepared teachers are comparable to gains for well-prepared teachers. Underrepresented minorities and females have comparable gains.

D. External Evaluation of the Modeling Project

The Modeling Instruction Project has been evaluated by two Panels of Experts commissioned by the U.S. Department of Education. In September 2000, the Modeling Project was rated as one of seven exemplary or promising K-12 educational technology projects out of 134 projects reviewed. In January 2001, the *Modeling Instruction Project was the only high school science project to receive an **exemplary** rating*, out of 27 projects reviewed. Ratings were based on these criteria: (l) Quality of Program, (2) Educational Significance, (3) Evidence of Effectiveness, and (4) Usefulness to Others.

E. Institutionalization of Modeling Instruction <http://modeling.asu.edu>

The Modeling Instruction Project is institutionalized at ASU in a full-fledged summer graduate program expressly designed to meet the needs of physics teachers and leading to a *Master of Natural Science* (MNS) degree in physics. From 2002 to 2005 the program was funded by the NSF to make it available to teachers throughout the United States; each summer 125 to 150 in-service teachers participate. Responses from both teachers and professors have been overwhelmingly positive. A *North Central Accreditation Academic Program Review Committee* evaluating the ASU physics department reported in May 2005: "One of the important ways that ASU is currently elevating science education in Arizona is its unique Master of Natural Science (MNS) program for in-service teachers. *There appears to be no comparable program at any other university in the United States, and it stands as an exemplary model of how physics departments can improve high school physics education*."

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