Empowering Teachers for STEM Education

David Hestenes

To drive rapid, deep and sustained K-12 STEM education reform nationwide, teachers need strong links to the physics community!

The national crisis in K-12 STEM education is thoroughly documented, and calls are loud and clear for immediate action to maintain the status and competitiveness of the United States in the global economy. [1] Even so, the crisis continues to deepen despite efforts of the U.S. government to address it.

The problems of STEM education reform are many and difficult, but one does not have to look far to see that the crux of the matter is a dearth of well-qualified teachers. Ultimately, education in the schools boils down to a transaction between teacher and students, and the quality of that transaction depends primarily on the expertise and resources of the teacher.

The shortage of qualified STEM teachers is staggering! The best available data are for physics teachers, [2, 3] which is all the more significant because physics is central to the STEM curriculum. *The nation has about 27,000 high school physics teachers, but only a third of them have a degree in physics or physics education, and the production rate of new teachers barely matches the replacement rate for this group.* The remaining two-thirds consists of crossover teachers from other majors, mostly with no more preparation than two or three semesters of general physics; most are drafted by their principals into teaching physics, and their most common degree is biology. A few are PhD's in physics or engineering, but even these are under-qualified, because they lack pedagogical knowledge needed for effective teaching.

A closer look reveals further deficiencies in teacher qualifications. Well-trained teachers specializing in physics are often drafted to teach chemistry or mathematics, so the problem of inadequately qualified crossover teachers cuts both ways. And in rural schools there is seldom more than one teacher for all the STEM subjects, if indeed physics and chemistry are even offered. Obviously, since the supply of new qualified teachers is such a trickle, **the only possibility for massive improvement in the qualifications of teachers is professional development of teachers already in the classroom.** (Box 1)

Schools and school districts are ill-equipped to conduct the necessary professional development on their own, because they lack the necessary *expertise* in science and technology as well as the *resources* to keep up-to-date with advances in science curriculum materials and pedagogy. The problem is most severe in rural and urban schools with "high-need" students. Fortunately, a practical means to address this problem is at hand.

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The 2014 APS Excellence in Physics Education Award to *High School Modeling Instruction* [6] serves as timely recognition of a new approach to STEM education reform — one that emerged from the physics community and will depend on its support for ultimate success. My purpose here, as founder of the *Modeling Instruction Program*, is to describe its current status and how it can be coupled to the physics community to create a **powerful engine to drive nationwide K-12 STEM education reform. Reform will be**

- **rapid** if it focuses on *empowering teachers already in the classroom*;
- **deep** if it is anchored in discipline-based research;
- **sustained** if it is linked directly to the physics community for continual renewal and adaptation to the rapidly changing world of science and technology.

Physics must take the lead in extending reform in physics education to integrated reform of all the STEM disciplines.

FOUNDATIONS FOR PHYSICS EDUCATION REFORM

Education reform on a large scale requires institutional mechanisms to maintain it. I submit that three such mechanisms are essential, and I am pleased to report that robust versions of all three are already in place and ready to deploy. The first is the *American Modeling Teachers Association* (AMTA) [7], which has organized physics teachers across the country into a cohesive community of practice. The second is *Physics Education Research* (PER), which has grown into a viable subdiscipline of physics, with its own conferences and journal [8] and faculty positions in many physics departments. The third is the *Physics Teacher Education Coalition* (PhysTEC) [9], an APS-AAPT partnership dedicated to improving and promoting physics teacher education.

Before we can discuss how these three can work together for STEM reform, we need some background that explains what they are about. Since the AMTA is the new kid on the block, I concentrate on its evolution and grounding in PER.

Shocked by the specter of Russian Sputnik, in 1957 the U. S. government committed serious funding to reform introductory physics teaching, beginning with the *Physical Science Study Committee* (PSSC) led by MIT's Jerrold Zacharias and Francis Friedman. [10] Thus began a golden age of NSF support for curriculum reform and intensive summer workshops for in-service teachers culminating in work by physicist Robert Karplus in the mid-1970s. [11] This ended suddenly in 1980, when one of the first acts of President Ronald Reagan was to emasculate NSF funding for education.

At about the same time I was stimulated by Karplus' foray into Piagetian psychology to publish an article on the "science of teaching" in a physics journal. [12] That had the unintended consequence of drawing me into a decade of PER in collaboration with two outstanding graduate students, Ibrahim Halloun and Malcolm Wells. This research had two major outcomes:

The first was development and validation of the *Force Concept Inventory* (FCI), which has become a standard PER instrument for evaluating the effectiveness of physics instruction. [13] It has been translated into 21 languages. The original results suggesting serious deficiencies in conventional physics instruction have been repeatedly confirmed, and the FCI is widely used to evaluate innovations in physics teaching. [14]

The second was development and testing of a new approach to physics teaching called *Modeling Instruction,* based on research experience in physics and insights from cognitive science. [15]

I was so impressed with Malcolm's doctoral dissertation on implementing Modeling Instruction in his high school physics class [16] that I applied for NSF funding to passed on his methods to other teachers. By that time NSF had recovered from the Reagan purges and was prepared to resume funding for the program of summer workshops for physics teachers that began with PSSC. Malcolm had attended all those workshops and incorporated what he learned in his teaching. Moreover, he had learned how to conduct a workshop to confer teachers with ownership of the product and confidence in its potency. The workshops he led were thus an unqualified success. Through Malcolm Wells, Modeling Instruction is a direct descendent of PSSC! Tragically, he did not live to see the great flowering of Modeling Instruction that followed.

With more than a decade of substantial NSF support, Modeling Instruction continued to develop new curriculum materials, refine the pedagogy, create new Workshops and expand into a thriving national program. To date, more than 3,000 high school physics teachers have taken at least one intensive 3-week summer workshop. Discounting teachers who have since retired, that amounts to about 10% of all the physics teachers in the U. S. Including other Modeling Workshops in physical science, chemistry and biology, more than 6,000 STEM teachers have participated in the program.

When NSF funding for Modeling Instruction ran out in 2005, the teachers took over, creating a nonprofit organization of their own, the *American Modeling Teachers Association* (AMTA), to keep the program going. Without missing a beat, teachers and supportive faculty have continued to drum up local funds, so the AMTA has managed to maintain a steady offering of more than 50 workshops for some 800 new teachers each year. Dues-paying membership in the AMTA has surpassed 1600, and the scope of AMTA activities is growing. Thus, the AMTA is fully prepared to play its part in nationwide STEM education reform.

OF MODELS AND MODELING

Members of the AMTA affectionately refer to themselves as ***"modelers."*** They are united by a common vision of good science and science teaching, so they want to share and cultivate it further.

Every physicist knows that models mediate between theory and experiment, as well as engineering design and applications. Accordingly, ***Modeling Instruction*** is both a science pedagogy and a curriculum design centered on (1) ***scientific models*** *as the content core* of each science and (2) ***modeling*** *as the procedural core* of science. Here the term *'modeling'* is to be understood broadly to include all aspects of making and using scientific models.

To promote precision in scientific discourse and design of instruction, we define the term *'model'* precisely as "a *representation of structure* in a given system." Thorough explication of meaning for this definition is a job for *Modeling Theory* (Box 2). However, students learn the meaning indirectly by modeling specific systems and examining how representations are constructed and interpreted.

For example, the first high school course on the "science of motion" is organized around *five basic models*: constant velocity (free particle), constant acceleration (constant force), simple harmonic motion (Hooke's law), uniform circular motion (central force), collision (impulsive force). Student mastery of these models and how to use them for inference, prediction, explanation, planning and design is the main objective of the course. Textbooks are of little help, so the AMTA distributes thoroughly tested instructional materials tailored to the specific tasks.

The course devotes two weeks to each model. The first week cycles students through all phases of modeling a specific system, including design of an experiment, measurement of variables, representation and analysis of data with graphs, figures and equations, presenting and defending conclusions. Modeling workshops are designed to develop teacher skill in subtly guiding students through this process to take ownership of the outcome. Thereby, each student should come away with his/her own version of the model, vetted by comparison with personal models of other students. Moreover, after two or three model development cycles most students have internalized the process, so when presented with a new situation they set about developing a model with little guidance from the teacher. The teacher can then concentrate on deepening their understanding of models and how they fit into theory.

Newton was the first to develop theory from a modeling cycle [21]. In accord with his claim in the Preface to his *Principia*, his method is simply this: *From the motions (Kepler's Laws) infer the forces; from the forces (Newton's laws) deduce the motions.* I call this *Newton's Modeling Cycle*.

The second week of a modeling cycle aims to induce students to abstract the model from the specific situation in which it was learned by presenting them with analogous situations to model. The ultimate goal is to lead students to mastery of the five basic mathematical models in Box 3, though that is not easy to reach. After students have acquired a repertoire of mathematical models, they can see problem solving as a special case of modeling. The solution to every textbook problem is a model. David Pritchard at MIT has documented his success in teaching a modeling approach to problem solving. [22]

Though Modeling Instruction was first developed for physics, it is a flexible, evolving, research-based approach to integrate pedagogy and content in any scientific domain. Integrating the STEM disciplines helps identify models and modeling techniques they share and thereby strengthen interdisciplinary learning. Teachers are encouraged to incorporate their unique knowledge and experience into a personal teaching style and share it with others.

PhysTEC finds MODELING

About 300 colleges and universities have signed on as members of PhysTEC. How can they be activated to support nationwide STEM education reform?

The *National Task Force on Teacher Education in Physics* (T-TEP), commissioned by PhysTEC and the AIP, has recently produced a definitive report on the state of physics teacher education (PTE) across the U.S. [23] Overall, the picture is abysmal, but a few bright spots serve as exemplars for substantial improvement. The chief finding is that, without exception, successful PTE programs are led by a personally committed faculty champion, usually with little institutional support.

The T-TEP report profiles exemplary PTE programs at eleven institutions. All of them employ practices with PER backing. More than half employ some form of Modeling Instruction. Experienced modelers have been hired as Teacher-In-Residence or tenure-track faculty to prepare physics majors for a possible teaching career. Besides increasing the output of teachers, modelers have contributed to a revitalization of physics teaching throughout the department. One way has been by mentoring “Learning Assistants,” high-performing undergraduate students recruited to serve as peer instructors in introductory physics courses. On a larger scale, PhysTEC has engaged the AMTA to offer an online course in physics pedagogy to coalition institutions. [24]

Perhaps the most successful PTE program has been championed by Laird Kramer and Eric Brewe at Florida International University (FIU). They attribute that success to integration of Modeling Instruction throughout the physics teacher education program: Modeling Instruction is used in the Intro Physics course and the training of Learning Assistants. A Modeling Workshop serves as a class in Teaching Methods and links pre-service to in-service teachers. This continues in student teaching with a Modeling teacher. And finally induction into service is managed by FizMo, the Modeling physics LTA. Recruitment into the Modeling Teacher Community is centered at FIU. The FIU president is such an enthusiastic supporter that he forcefully advocated Modeling Instruction as an exemplary STEM education program in a presentation to the U.S. President’s Advisory Council (PCAST).

The linking of pre-service to in-service teacher education at FIU is a first step in the right direction. Data in the T-TEP report clearly show that the problem of professional development for in-service teachers is even more critical than pre-service teacher production. The number of PTE graduates from physics departments (200) combined with those from schools of education is less than 500 per year nationwide. On the other hand, more than 3,000 new teachers are needed each year to compensate for retirements, dropouts and increasing demand for physics courses. The problems are linked and can best be solved together.

A CALL TO ACTION

The T-TEP report issued a “call to action” by the physics community and physics departments in particular. The case has been made that the physics community must take responsibility for the education of teachers in physics. As the problem is national, a concerted community effort is needed to address it, and physics departments have a critical role to play, but they need not go it alone. PhysTEC has created a supportive infrastructure and identified effective steps to improve recruiting and teaching physics majors as well as PTE. I am arguing here for expanding PhysTEC’s mission to include professional development for in-service teachers and coupling it strongly to the in-service program. The AMTA is prepared to help build and support a local community of in-service physics teachers.

PhysTEC has only limited funds, devoted mostly to identifying and cultivating best practices. But physics departments need not wait for grants to get started. Funding requirements are so modest, they can be handled in-house if administrators are on board. Indeed, university administrations are more aware than ever of the STEM education crisis, so they are likely to welcome opportunities to weigh in.

The first simple step is to hire a teacher-in-residence (TIR) and consult with PhysTEC peers about the most beneficial assignment of duties. The AMTA may be helpful in identifying a pedagogically well-qualified teacher for the position. It has contact with many retired teachers, who are very able and adaptable.

The next step is to link the physics department to local in-service teachers. Of course, there must be a “go to” faculty member in position to marshal department resources to serve teachers. But I recommend a more aggressive step: hiring a second TIR (full-time or part-time) to seek out contacts with teachers and survey the health of the local STEM community. The ultimate goal is to foster organization of teachers into a robust *Local Teacher Alliance* (LTA) positioned to collaborate with the physics department to improve STEM education locally. The AMTA should be involved from the beginning, to advise and assist in setting up LTA functions and to integrate the LTA into the national Modeling community. The AMTA will also help with summer Modeling Workshops for the teachers, if not locally then at other universities.

The AMTA has many examples of very successful LTAs and is prepared to share what makes them tick. An essential element is a few high-functioning teachers at the center of the LTA, though support by university faculty has been a great help in some cases. To start with, it will be helpful (perhaps essential) if the TIR is one such high-functioning teacher. In any case, the TIR should start by ferreting out good programs that are already functioning in local communities or for teacher-leaders who might be willing to form such programs. “Empower them . . . provide places for them to meet or hold summer workshops, help them (or teach them) to write grants. Insofar as it is possible, make each teacher feel like an *insider* in the science community . . . someone who plays an important part in the work that scientists are able to do . . . part of the *team* if you will. There will be no new physicists without physics teachers:” so says one very high-functioning modeler! Certainly, helping to energize an existing community with strategic resources is much easier than creating a new community from the ground up.

The range of TIR activities benefiting the university and the community it serves is limited only by the TIR’s initiative and support. An essential TIR duty will be to organize teachers in the LTA for induction and mentoring of new teachers. Beyond that, the TIR can broker teacher and student contact with university faculty and programs. Also, the TIR can help teachers with a variety of extracurricular science clubs, projects and summer camps for students. The bottom line is that the TIR can construct and maintain a direct pathway connecting high school students, through teachers, to university science faculty and programs; the AMTA is prepared to help as needed. Though a working exemplar of such a pathway is yet to be built, the Modeling program at FIU may be a good first approximation.

The T-TEP report proposes a national network of *Regional Centers in Physics Education* to address the problems of teacher preparation and professional development. That may be a good idea, but funding is problematic. It will be better to press ahead immediately with initiatives at committed universities, which may ultimately strengthen the case for Regional Centers.

THE PHYSICS IN STEM EDUCATION

To serve as an authoritative guide for deep and coherent STEM education reform, the National Research Council (NRC) has recently published *A Framework for K-12 Science Education* [25]. The “Framework” was developed by a distinguished committee of the National Research Council (NRC) led by physicist Helen Quinn. The committee has done an excellent job of updating previous curriculum recommendations and broadening them to include engineering and technology, with a balanced emphasis on scientific inquiry and engineering design.

A second document, the *Next Generation Science Standards* (NGSS) has recently been published to guide adoption of state STEM education standards. [26] It was developed in a process managed by Achieve Inc. (a nonprofit education reform organization led by a Board of Directors of governors and business leaders) in partnership with the *National Science Teachers Association* (NSTA) and other stakeholders.

Following the NRC Framework, the NGSS organizes the STEM curriculum into a system of "*performance expectations*" indexed by subject and grade level. These expectations are supposed to serve as "clear and specific targets for curriculum, instruction and assessment." The NGSS recommends that "*all students* should be held accountable for demonstrating their achievement of *all performance expectations*." This sets a worthy goal of science literacy for all students. Implementation is another story!

As the NGSS does not define a curriculum, it leaves states and local districts with the responsibility of providing more detailed guidance to classroom teachers. Here's the rub! By and large, education administrators from the state superintendent down to school principals are not qualified to make good decisions about STEM curriculum and instruction. The result is predictable, as we have seen it before. The curriculum will be mutilated to serve special interests. To increase teacher accountability, standards will be interpreted as rigid measures of teacher performance, with student testing to separate good teaching from bad. Teachers will be frustrated and discouraged.

There is an alternative. Teachers can be put in charge of working collaboratively to implement a coherent STEM curriculum throughout their school. The AMTA can cite many examples where this has worked beautifully. Unfortunately, it can cite more examples of teacher frustration, where the teacher does not have due respect of the principal or leeway for creative innovation. That can be changed by embedding the teacher in an active LTA connected to a local physics department. For that association can validate the teacher's expertise and support teacher initiatives with the authority of acknowledged experts in science. With help from PhysTEC, the AMTA is prepared to set this up immediately anywhere in the U.S. To be sure, many schools and school districts will balk at giving substantial autonomy to teachers. But there are plenty of others eager to adopt a proven approach to STEM education. In the long run, their results will carry the day.

On the matter of STEM curriculum, the AMTA is way ahead of the game. Having inherited the entire Modeling Instruction Program, the AMTA already has a well-developed curriculum in physics, chemistry and biology (in progress), in full accord with the NRC Framework. Indeed, Helen Quinn told me that emphasis on models and modeling in the Framework was a direct influence of Modeling Instruction. AMTA curriculum materials are under continuous development and refinement by expert teachers, who are open to every opportunity for input from science professionals. Consequently, the AMTA can respond quickly to teacher requests for help in adapting materials to a unique situation. Contrast this with the standard science course shaped and bound for the duration to a commercial textbook.

The AMTA has already taken decisive steps toward creating a fully integrated K-12 STEM curriculum united by common threads of models, modeling, energy and structure of matter. As already advocated by Leon Lederman's project ARISE [27] and the AAPT [28], this requires inverting the usual high school science sequence to a logical "*physics first*" sequence, with grade 9 physics preparing for grade 10 chemistry, which leads to grade 11 biology. While "physics first" is highly controversial, with many attempts to do it ending in failure, and even physics educators recommending a "conceptual physics" version that avoids mathematics, the AMTA has documentation for many examples of strong success and great benefits for the entire science curriculum.

There are good reasons why physics should play a leading role in the STEM curriculum. It is no accident that physics was the first science to develop historically. Physics is the science most closely related to our basic perceptions of matter, motion and light. The science of force and motion should be taught first, because it relates directly to the student's sensory experience. It provides the foundation for quantitative methods in the rest of science, and it stands as the first exemplar of scientific method. *Quantitative reasoning* with number and unit goes hand-in-hand with *modeling and measurement*, which couples mathematics to science.

WHAT TEACHERS NEED

Empowering teachers is the key to STEM education reform!

The crucial need for greatly expanded professional development programs to cultivate teacher expertise is discussed in Box 4.

More than anything, teachers need to be integrated into the community of scientists as respected colleagues in ways that strengthen their expertise, their credibility and their impact in the schools.

Teachers themselves should be the local experts on the STEM curriculum and how to teach it. They should be advising their principals and school districts on what needs to be done, rather than the other way around. To command that authority, teachers need the direct support from the scientific community that a *Local Teacher Alliance* can provide. Only then can they freely implement up-to-date STEM education in their schools.

Physicists must take the lead in bringing all this to pass, because they have unique access to resources for building the necessary infrastructure. As we have seen, a crucial first step for a physics department is to establish an LTA linked to the AMTA. Then colleagues from other disciplines can be invited to join in expanding the LTA from physics to a larger STEM LTA or a coalition of LTAs for different disciplines.

With their direct connections to STEM teachers and students, LTAs are ideal vehicles for university *Outreach Programs* as well as sponsoring student symposia, summits & retreats. In short, LTAs can be powerful mechanisms for bonding universities to their communities.

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Historical note: EMERGENCE OF MODELING INSTRUCTION

When I was hired at Arizona State University (ASU) in 1966, the physics department had the unusual feature of including five tenured faculty in science education, a vestige of conversion from a teacher's college in 1958. Consequently, I learned about NSF programs for science education reform without even trying. Though I was not especially interested in teaching *per se*, I had a long-standing interest in cognitive science stemming from my undergraduate degree in philosophy, and my colleague Bill Tillery introduced me to the impressive work of Robert Karplus in developing the *Science Curriculum Improvement Study* (SCIS) for elementary school students. This stimulated me to teach a graduate seminar on science education research and publish an article on the "science of teaching" in *The Physics Teacher* [12].

Unforeseen consequences were swift and surprising. First, the Director of the EHR Division at NSF made my article required reading for all EHR personnel and brought me into contact with saavy Program Officer Raymond Hannapel before the whole science education division was emasculated by President Ronald Reagan. Second, without consulting me, my department chair assigned me to supervise a dissertation in physics education research by Ibrahim Halloun, who had come on a fully funded fellowship from Lebanon for just that purpose.

Thus, I was suddenly thrust into physics education research. Fortunately, I had plenty of ideas to pursue. In particular, I had just finished writing a mechanics textbook/monograph that organized the subject around models and modeling. [32] So I set myself the task of extending that approach to a modeling pedagogy. Only many years later did I fully appreciate how close this was to the approach of Karplus. I attribute this coincidence to our common experience in theoretical physics research. I hold that modeling pedagogy is grounded in the conduct of scientific research.

I had also collected informal evidence of a significant *mismatch* between student understanding of physics and what professors thought they had been taught. So I set Halloun the difficult task of creating and validating an instrument to measure the mismatch. The results of testing more than 1,000 students in University Physics taught by four different professors were surprising even to me: The mismatch was large at the beginning of the course, though most of the students had taken high school physics. It had been reduced by less than 15% at the end of the course and the result was the same within 1% for all four professors, though they differed widely in teaching style and experience. The editor of the AJP was so impressed that he accelerated publication. [33] Subsequent refinement and extension led to the *Force Concept Inventory* (FCI), which is still a staple of *Modeling Instruction* today. I was urged by colleagues to make minor revisions in the FCI to wording that they thought was misleading. I was opposed because I did not think it would make a statistically significant difference. Subsequent data analysis proved me right. I still recommend use of the original FCI so there are no questions about comparison with the original large body of FCI data.

Halloun was one of the first to earn a physics PhD specializing in *Physics Education Research* (PER). Since completing his doctorate in 1984, Halloun has returned to his native Lebanon, where he has established a flourishing program in Modeling Instruction for the Arab States. [34]

Before I was done with Halloun, Malcolm Wells appeared at my office door, pressing me to direct him in a PER dissertation. Malcolm was a mature high school physics teacher who had eagerly participated in all the NSF-sponsored summer workshops for physics teachers from the beginning with PSSC. He had incorporated the best of PSSC activities into an integrated lab-based physics course and had experimented with the most up-to-date ideas on inquiry-based instruction, including Karplus' "Learning Cycle." Still, he felt that something was missing, and he would not be satisfied with a thesis that did not make a genuine advance in the teaching craft. We met off and on for some two years to banter about what his thesis topic might be, including an emphasis on modeling as proposed in the preprint for a paper of mine. [15] This led to replacing the "Learning Cycle" with a "Modeling Cycle," which has since continued to be refined as a core component of Modeling Instruction. Suddenly, when Malcolm saw the data on student misconceptions in Halloun's thesis, his course became clear.

Malcolm's thesis is a landmark in PER. [16] As controls for assessing his new teaching, he had data on his own previous teaching as well as that of a well-matched peer teacher. He did not change any of the content or activities in his course; he changed only the way he organized activities and interacted with his students. With subtle guidance by Malcolm, students were put in charge of designing their own experiments, formulating models to explain their results and defending their conclusions against Malcolm's probing Socratic questioning. In short, he induced students to clarify their own thinking about challenging physics by publicly articulating and refining it. The newly completed FCI was used in evaluation. The comparative gains it measured were unprecedented.

I was so impressed that I contacted Ray Hannapel, who had survived the Reagan purges, about NSF funding to see if Malcolm's magic could be passed on to other teachers. In 1989 Hannapel approved a two-year pilot project for "proof of concept." Though the second year was essential to work out an unforeseen glitch in the first, the outcome was a fully developed **Modeling Workshop** for teachers of high school physics with any background, weak or strong. Malcolm contributed a complete system of thoroughly vetted curriculum materials, student activities and pedagogical practices, and he set a high standard for conducting workshops. His preparation was so thorough that the Workshops continued smoothly without him after his sad demise.

As described in the second section of this paper, Modeling Instruction continued to grow and thrive with more than a decade of substantial NSF support. But funding does not make a program work; people do that! I must single out two people, in particular, who have been absolutely essential to success of the Modeling Program. Jane Jackson resigned from a tenured faculty position in physics to devote full-time, year-round and often without pay, to managing the Program. She managed details in organizing hundreds of Workshops: selecting sites and workshop leaders, recruiting participants, arranging housing and allocating funds. More importantly, she has taken every opportunity for personal contact with teachers and maintained a "modeling listserv" as a forum for discussing issues about teaching. She has detailed knowledge about teachers and their schools in nearly every state. In short, she has cultivated the social cohesion necessary to transform a program of professional development workshops into a community of teachers with a shared vision of good teaching.

Larry Dukerich was trained as a chemistry teacher, but transformed into a physics teacher in Malcolm's pilot workshop. Without fanfare, he has slipped into the mantle of Malcolm Wells as selfless, dedicated leader among teachers, attending to every detail in the design and execution of Modeling Workshops. Many other chemistry teachers pressed into teaching physics have taken a Modeling Workshop to prepare for it. On witnessing the effectiveness of Modeling in physics, they called for the same in chemistry. Dukerich answered. With some grant support and consultation with a professor of chemistry education, but mostly with his own time and effort, he has created a Modeling Workshop for high school chemistry that is now much in demand. Similar developments are underway for biology and middle school science. These are crucial steps toward creating an integrated K-12 STEM curriculum.

Though the Modeling Instruction was a mature, thriving program by year 2000, three doctoral students of mine have since stepped in to raise it to higher levels. Colleen Megowan was the prime mover in creating the AMTA, and without her leadership it would probably not exist today. Duane Desbien has raised Modeling teaching techniques to the highest level and promoted modeling in community colleges. Eric Brewe is leading the incorporation of modeling techniques into university physics teaching and, together with colleague Laird Cramer and help from PhysTEC [9], has developed Florida International University into the nation's leading center for Modeling Instruction in teacher education.

Today, the AMTA has grown so large that it includes many outstanding teachers I have never met.

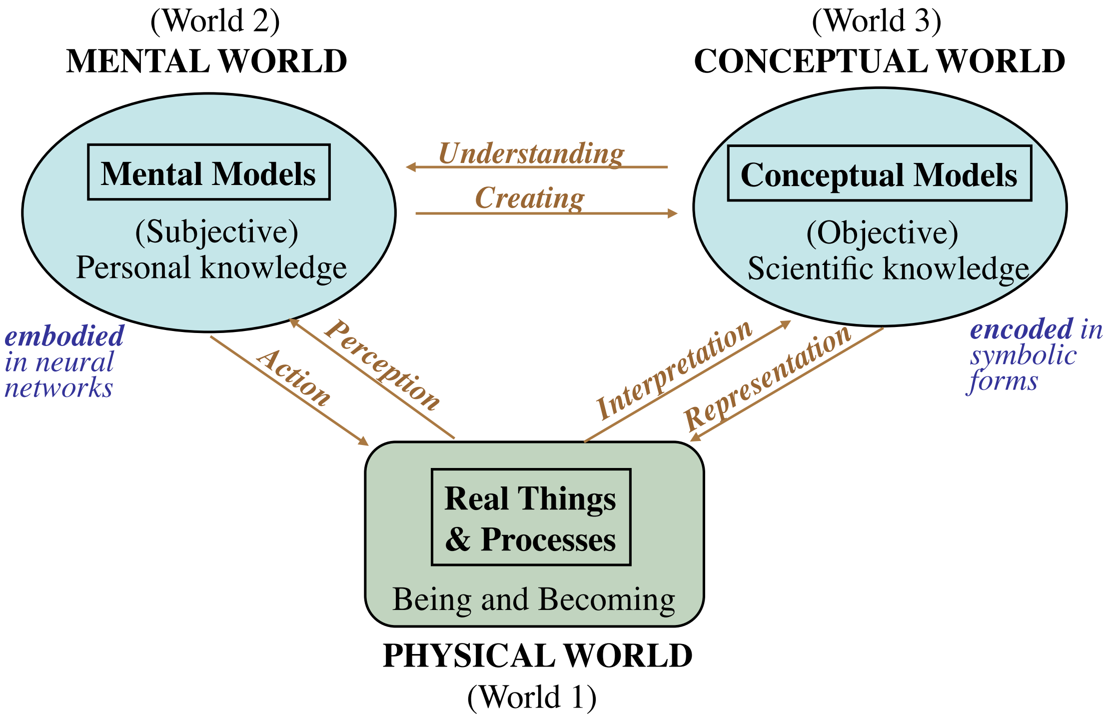
Box 1. Primacy of teacher professional development

The Glenn Commission (2000) [4] concluded:

"We are of one mind in our belief that the way to interest children in mathematics and science is *through teachers* who are not only enthusiastic about their subjects, but who are also steeped in their disciplines and who have the professional training—as teachers—to teach those subjects well. *Nor is this teacher training simply a matter of preparation; it depends just as much—or even more—on sustained, high-quality professional development*."

Furthermore: *Research shows that teaching method is the most important factor in student learning!* Stigler and Hiebert [5] expressed it well in their updated 2009 preface to *The Teaching Gap* (1999), their TIMSS study of 8th grade math instruction in the U.S.A, Japan, and Germany: ". . . most policy efforts to improve classroom teaching focus on teachers rather than teaching, attending mostly to who is in the classroom instead of on what they do when they get there. Most policy work aimed at improving teaching has focused on recruiting better teachers: increasing the qualifications of teachers, making the certification processes more rigorous, and improving the salaries and working conditions for teachers. *Little attention has been paid to the methods these teachers will use to promote better student learning. The distinction between teachers and teaching is an important one. In fact, we believe that until U.S. educators understand and appreciate the difference, classroom teaching will not change much."*

Box 2. Modeling Theory for Physics Instruction



Modeling Theory [15, 17, 18] makes a crucial distinction between the 'mental models' we think with and the 'conceptual models' of science we aim to teach. Both model types represent objects and states in the physical world. But cognitive research with the FCI and other means shows that they are often incompatible. Accordingly, a major problem of science instruction is to induce alignment of student mental models with conceptual models of science. Such alignment is called "understanding." To address this problem, Modeling Theory calls on multidisciplinary research in cognitive science.

The human cognitive capacity for creating, manipulating and remembering ***mental models*** has evolved to facilitate coping with the environment, so it is central to "common sense" thinking and communication by humans. Human culture has expanded and augmented this capacity by creating ***semiotic systems***: Representational systems of signs (symbols, diagrams, tokens, icons, etc.), most notably spoken and written language. Science and mathematics has further extended the use of symbolic systems deliberately and systematically. Science differs from common sense in its objectivity, precision, consistency, coherence & systematics, but the *cognitive mechanisms for mental modeling are essentially the same for science and common sense*.

Research in cognitive linguistics and psychology supports the ***central thesis*** that *language does not refer directly to the world but rather to mental models or components thereof!* Words activate, elaborate or modify mental models, as in *comprehension of a* *narrative*. *Mental models represent states of the world*, not perceptions; they are *schematic*, representing only some features of things, and *structured*, consisting of elements and relations among them. *Elements are typically objects* (or reified things) with *idealized properties* (such as points, lines or paths). Object models are always *placed in a background* (context or *frame*), and they are modeled separately from the frame so they can move around in it. *Structured external representations, such as language and mathematics* (**symbolic forms**), support construction of mental models.

Box 3. Five basic mathematical models

Constant rate (linear change): graphs and equations for straight lines (proportional reasoning, constant velocity, acceleration, force, momentum, energy, etc.)

Constant change in rate (quadratic change) graphs and equations for parabolas (constant acceleration, kinetic and elastic potential energy, etc.)

Rate proportional to amount: doubling time, graphs and equations of exponential growth and decay (monetary interest, population growth, radioactive decay, etc.)

Change in rate proportional to amount: graphs and equations of trigonometric functions (waves and vibrations, harmonic oscillators, etc.)

Sudden change: stepwise graphs and inflection points (Impulsive force, etc.)

These models are ubiquitous, with rich and unlimited applications to science and modern life. Skill in using them in a variety of situations is an important component of math and science literacy. However, their treatment is haphazard at best in high school, and even in university mathematics they are not treated systematically until a senior course in differential equations. Calculus courses are so concentrated on mechanics of the subject, that they overlook the fact that calculus serves science through differential equations. To give these basic math models the prominence they deserve, high school math must be integrated with science. That will not be easy because of profound cultural barriers between math and science.

The very concept of rate is problematic in many math textbooks, as shown by their haphazard treatment of units, often ignoring them completely. One consequence is conflation of ratios with fractions; hence failure to recognize that rates are comparisons of change in one quantity with respect to change in another, or that defining such quantities is a problem of measurement in science.

Since physics requirements for math majors were dropped after World War II, whole generations of mathematicians have grown up with profound ignorance about science. Consequently, in the U.S. at least, *most high school math teachers have little insight into relations of math they teach to science* in general and physics in particular. Here is a bit of data to support that contention: We administered the FCI to a cohort of some 20 experienced high school math teachers. The profile of their scores is telling, with the highest score barely reaching the threshold of 60% required for a modicum of physics understanding. *Half the teachers missed basic questions about relating data on motion to concepts of velocity and acceleration*. **This chasm between math and science, now fully ensconced in the training of teachers, may be the single most serious barrier to significant secondary science education reform.**

A promising effort to address this problem is the middle school program Physics Union Mathematics (PUM) at Rutgers University. [19] However, many states have signed on to the *Common Core State Standards Initiative*, [20] which promotes a mathematics curriculum that is independent of the science curriculum, though the *Next Generation Science Standards* recommends alignment with it.

Box 4. Cultivating Teacher Expertise

Development of expertise in any domain requires ten years (or 10,000 hours) of deliberate practice! This striking conclusion of K. Anders Ericsson [29] from extensive research across many domains is widely accepted. [30] Its surprising implication for teachers is that years of classroom teaching experience will not improve teaching expertise! The crucial factor in any skill development is *deliberate practice*: examining your performance, asking how you can improve it, and then taking specific actions to change. To promote such practice should be the main purpose of professional development for teachers.

The expertise of a master teacher and the effort needed to acquire it is vastly underestimated by nearly everyone. A rough comparison of opportunity for deliberate practice in the training of scientists and teachers is given in Fig. 4. Without quibbling over details, it seems clear that opportunity differs by at least a factor of two!

Fig. 4. Professional preparation for teachers compared to scientists

	4 yr. college			Total prep.
Scientist:	3 in major	4-7 in grad school	2-3 as post-doc	**≈ 10 yrs.**
Teacher:	2 in major	teaching begins, sporadic prof. dev.		**≈ 3 yrs.**

Red numbers indicate years with strong opportunity for deliberate practice.

If we are to have a truly potent STEM teacher workforce, the huge deficiency in professional preparation must be made up. The most promising solution is a strong professional development program supported by the scientific community and the nation's universities. Every teacher I know thinks the typical professional development offered by schools is a trivial waste of time. What teachers need is the kind of intensive summer multi-week workshops offered by the AMTA. But even more is needed, for each teacher's professional development should be extended over many years, if not decades. Teachers need lifelong professional development opportunities. That includes the fine programs at national labs like Brookhaven and Fermilab, and graduate studies for teachers like the MNS program at ASU. [31]

Finally, teachers deserve full pay while participating in summer professional development. They are true professionals and should be treated as such. Of course, the bottom line is how to pay for all this. The truth is, there is plenty of wasted money sloshing around the educational system. It would be nice to see the federal government channel funds in this direction. But states and school districts can get things moving locally. And here is a worthy cause that the private sector can sink its funding teeth into. Who will step up?