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Abstract

Transforming Teacher Knowledge: Modeling Instruction in Physics

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I show that the Modeling physics curriculum is readily accommodated by most teachers in favor of traditional didactic pedagogies. This is so, at least in part, because Modeling focuses on a small set of connected models embedded in a self-consistent theoretical framework and thus is closely congruent with human cognition in this context which is to generate mental models of physical phenomena as both predictive and explanatory devices. Whether a teacher fully implements the Modeling pedagogy depends on the depth of the teacher's commitment to inquiry-based instruction, specifically Modeling instruction, as a means of promoting student understanding of Newtonian mechanics. Moreover, this commitment trumps all other characteristics: teacher educational background, content coverage issues, student achievement data, district or state learning standards, and district or state student assessments. Indeed, distinctive differences exist in how Modeling teachers deliver their curricula and some teachers are measurably more effective than others in their delivery, but they all share an unshakable belief in the efficacy of inquiry-based, constructivist-oriented instruction. The Modeling Workshops' pedagogy, duration, and social interactions impacts teachers' self-identification as members of a professional community. Finally, I discuss the consequences my research may have for the Modeling Instruction program designers and for designers of professional development programs generally.

Acknowledgements

This dissertation would not have been possible without the willing and gracious cooperation of the physics teachers who are the subjects of this research. They welcomed me into their classrooms and into their practice. Each one of them said they wished that teachers would have more opportunties to observe one another if only to promote meaningful dialogue that might help improve the craft. I owe them a debt of gratitude that this dissertation can repay but a small fraction.

I am indebted also to the staff of the Modeling Instruction in High School Physics program at Arizona State University, especially Dr. David Hestenes, director, and Dr. Jane Jackson, co-director. They granted me access to datafiles that were instrumental to this project and helped find my subjects. The contribution of the Modeling Instruction program to the cause of improved student learning in physics and, now, chemistry, physical science, and biology, is incalculable.

I would like to thank my advisor, Dr. Bill McDiarmid, for his insightful comments and always ready editor's pen. He kept me on track and focused on the essential issues. More importantly he helped me eschew obfuscation so as to not be perceived a smartypants. I am grateful also to the members of my reading committee, Drs. Mike Copland, Paul Hill, and Mark Windschitl, whose unique and sometimes disparate perspectives enriched this work.

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Introduction

During the years 1995 through 2000 (and intermittently thereafter) the Views About Science Survey (Halloun & Hestenes, 1996 – see Appendix 9) was administered to thousands of high school and college science students and also to many teachers and instructors. Halloun & Hestenes describe the "VASS" as "a survey of student views about science for the purpose of assessing the influence of these views on learning." They used survey data to develop "profiles" with respect to respondents' views about science. At the extremes are "expert" and "folk" views and in between is a "mixed" or "transitional" view. I will go into more detail about this survey later, but suffice it to say that Halloun & Hestenes found that college instructors generally hold "expert" views about science, high school teachers do so as well but not as consistently, and most students considerably less so.

As a matter of course this survey was administered to the high school teachers attending the summer leadership workshops (1995-1999) conducted by the Modeling Instruction in High School Physics program and thus to the six teachers who are the subjects of this study (see http://modeling.asu.edu). These teachers completed the survey in 1998, during the first of two consecutive summer workshops. Their average profile was 86% expert, 10% mixed, and 4% folk, only slightly below the college instructor average profile of 90% expert reported by Halloun & Hestenes. What was of more interest to me, however, was whether there were any significant differences in my subjects' responses to this survey and whether these differences manifested themselves in teachers' classroom practices and, in particular, with respect to the extent to which a teacher implements the Modeling Instruction (Wells, Hestenes & Swackhamer, 1995) pedagogy which lies at the heart of this study. The short answers are yes and no.

The teachers in this study disagreed most in their responses to survey question 21: "The laws of physics are: (a) inherent in the nature of things and independent of how humans think vs. (b) invented by physicists to organize their knowledge about the natural world." According to Halloun & Hestenes, the "expert" response option is "Towards 'Only (b)'," what some philosophers of the nature of science would call the "constructivist" perspective as distinguished from the "empiricist" (folk) perspective implied by alternative (a). Choices are along a seven-point scale: two of the teachers selected an "expert" option, three teachers selected a "folk" option, and the last teacher selected a "mixed" option. What is interesting about these responses is that I would judge five of the six teachers full-fledged "Modelers," which is to say they embraced the Modeling pedagogy at the workshops and do so to this day. It is the teacher who selected a "folk" option who (now) least implements Modeling and the teacher I judge most expert that selected a "mixed" option.

As one might expect, the teachers also disagreed in their responses to question 22: "The laws of physics portray the real world: (a) exactly the way it is vs. (b) by approximation." This time four teachers selected the so-called "expert" view (b), including the most expert Modeler and the non-Modeler; and the teachers that had selected a "folk" option for question 21, but who are nevertheless Modelers, now chose "folk" and "mixed" options, respectively. So, except for the non-Modeling teacher, the teachers' responses are consistent across the two questions, that is, Modeling teachers generally held onto to their views whether "expert" or "folk." It would seem that the non-Modeling teacher is conflicted in his views about science.

As a point of information, my subjects were unanimous in their responses only to question 2: “If I had a choice: (a) I would never take any physics course vs. (b) I would still take physics for my own benefit.” I leave it to the reader to contemplate which was the teachers’ choice.

When I queried the teachers about their views of the nature of science and scientific knowledge, it was quite clear they believe that there is *something* inherent in the nature of things independent of how humans think that makes inventing laws to organize knowledge about the natural world a reasonable thing to do, and nature (or our experience of it) seems to behave in a sufficiently consistent, repeatable manner so as to sustain the validity of these laws. Most of the principles that they teach have withstood the tests of time and scientists and engineers have been able to manipulate nature in profound ways and open new lines of inquiry based on these very same tenets. Though no teacher fully espoused one point of view over the other, the two positions are fairly well represented in two teachers’ statements below (both of whom I judge to be Modelers):

> Scientists believe that numbers represent the truth. Scientists get their numbers from measuring things and then they try, they use different techniques to evaluate what those numbers mean. We do that because we can make good predictions with numbers that are useful to us, they enhance our health, our welfare, and so this is something important to study and learn about because we're interested in our health and welfare.
>
> It's a way of understanding the universe around you by testing ideas for validity: does this work, in what situations does this work, what situations doesn't this work; the process of building these models whether they're mental or physical that approximate what's going on, that work in certain situations but not necessarily in every situation. I guess the process of learning science and constructing that scientific knowledge is the process of building the models, testing them in different situations; could be actually in the lab, could be mentally, thinking about will that work here or there.

In other words, whether a teacher believes the laws of physics portray the real world exactly the way it is or by approximation, they all believe there is something quite real behind them. What is more, contrary to the work of some science education researchers (e.g., Tsai, 2006), this belief has no apparent impact on a teacher’s ability or inclination to implement Modeling, an emphatically constructivist-oriented pedagogy. So what does?

This research project was guided by the following three questions:

1. How and to what extent does the design of the Modeling pedagogy induce conceptual change in teachers’ conceptions of physics content and pedagogy?
2. What factors, including teachers’ beliefs and background as well as their participation in the community of discourse embodied by the workshops and the Modeling program generally, influence their implementation of the Modeling pedagogy in their classrooms?

3. How might the program be redesigned to increase the number of high performing teachers and, similarly, how might teachers be supported after completing a workshop so as to reach high levels of implementation?

I will show that the Modeling physics curriculum is readily accommodated by most teachers in favor of traditional didactic pedagogies. This is so, at least in part, because Modeling focuses on a small set of connected models embedded in a self-consistent theoretical framework and thus is closely congruent with human cognition in this context which is to generate mental models of physical phenomena as both predictive and explanatory devices. Whether a teacher fully implements the Modeling pedagogy will be shown to depend on the depth of the teacher's commitment to inquiry-based instruction, specifically Modeling instruction, as a means of promoting student understanding of Newtonian mechanics. Moreover, I will show that this commitment trumps all other characteristics: teacher educational background, content coverage issues, student achievement data, district or state learning standards, and district or state student assessments. Indeed, distinctive differences exist in how Modeling teachers deliver their curricula and some teachers are measurably more effective than others in their delivery, but they all share an unshakable belief in the efficacy of inquiry-based, constructivist-oriented instruction. I will also examine the impact of the Modeling Workshops' pedagogy, duration, and social interactions on teachers' self-identification as members of a professional community. Finally, I will discuss the consequences my research may have for the Modeling Instruction program designers and for designers of professional development programs generally.

Modeling Instruction in Physics

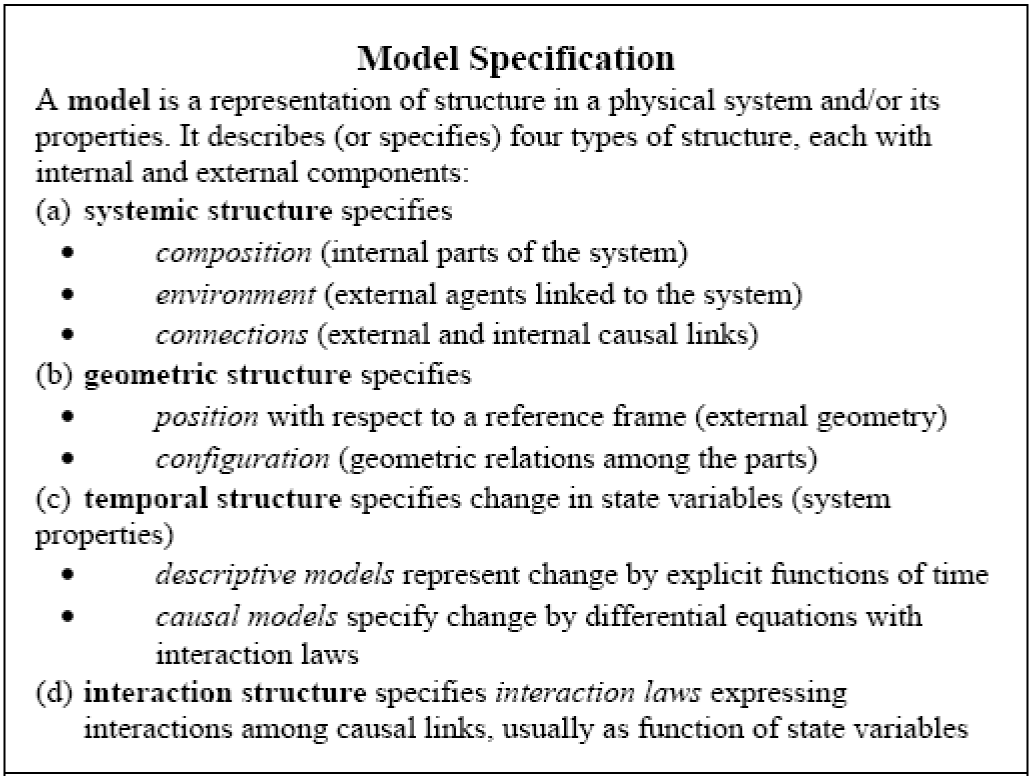
The Modeling Method of Instruction in High School Physics (Wells, Hestenes & Swackhamer, 1995) was designed by an exceptional high school physics teacher, Malcolm Wells, under the direction of David Hestenes at Arizona State University. How Malcolm came to develop the Modeling Method is a fascinating story in its own right and the reader is referred to the article cited above for the details. Modeling instruction incorporates the work of Karplus (1975) and his "learning cycle," a pedagogical model he originally developed to help elementary teachers teach science concepts. Much work and research on learning cycles has been conducted since then and nearly every K-12 science educator by now is familiar with one iteration or another of what has come to be called an "inquiry approach" to science teaching. Karplus's original learning cycle had three stages: exploration, explanation, and application (Karplus, 1977). The thrust of the model is that "science learning should be a process of self–regulation in which the learner forms new reasoning patterns. These will result from reflection, after the pupil interacts with phenomena and with the ideas of others" (Sunal & Sunal, 2000). Latter-day educators have expanded Karplus's model into the now ubiquitous "5E" learning cycle model: engagement, exploration, explanation, elaboration, and evaluation (e.g., Bybee, 1989), but the epistemological foundation is the same.

Modeling Instruction and its "modeling cycle" (Wells, Hestenes & Swackhamer, 1995; Hestenes, 1987; Hestenes, 1992; Hestenes, 1995; Hestenes, 2006; Halloun, 2004) is well-situated in this tradition, but it has a few unique features. First is an overarching emphasis on the development of well-defined, comprehensive, and systematic conceptual models of physical phenomena. Hestenes (2006) gives us two reasons for this:

> The great game of science is modeling the real world, and each scientific theory lays down a system of rules for playing the game. The object of the game is to construct valid models of real objects and processes. Such models comprise the content core of scientific knowledge. To understand science is to know how scientific models are constructed and validated. The main objective of science instruction should therefore be to teach the modeling game.
>
> Cognition in science, math, and everyday life is basically about making and manipulating *mental models*.

That is, the content of scientific knowledge is *conceptual* models (that are subject to objective validation) and the content of personal knowledge is *mental* models. Thus, *modeling* should be the "main objective of science instruction" because it is how science is done, and *Modeling* should be an effective pedagogy because it is congruent with human cognition. The critical distinction made here between conceptual and mental models is the difference between symbolic representations (e.g., graphs, mathematical formulae, diagrams) of physical realties developed alone or in concert with other observers as explanatory and/or predictive devices and the mental constructions individually derived directly from sensory perception of the same physical realities but without the "intermediary of symbolic forms" (Hestenes, 2006). The box below is from

Hestenes (1995); it is a synopsis of what should be the end product of science instruction, a complete "model specification" which is embedded in the context of a specific physical theory.



Model Specification

A model is a representation of structure in a physical system and/or its properties. It describes (or specifies) four types of structure, each with internal and external components:

(a) **systemic structure** specifies

- *composition* (internal parts of the system)
- *environment* (external agents linked to the system)
- *connections* (external and internal causal links)

(b) **geometric structure** specifies

- *position* with respect to a reference frame (external geometry)
- *configuration* (geometric relations among the parts)

(c) **temporal structure** specifies change in state variables (system properties)

- *descriptive models* represent change by explicit functions of time
- *causal models* specify change by differential equations with interaction laws

(d) **interaction structure** specifies *interaction laws* expressing interactions among causal links, usually as function of state variables

The major assumption of this research project, therefore, is that by attending Modeling Workshops physics teachers are exposed to both a new theory (for them) of learning, which restructures their conceptions about *learning* physics, and a new physics pedagogy, which restructures their conceptions about *teaching* physics.

The second distinctive feature of the Modeling pedagogy is the Modeling Cycle. The Modeling Cycle has been designed specifically to help promote *conceptual change* (Posner et al, 1982) by creating an environment in which student misconceptions can be confronted and then resolved via a series of carefully structured experiences and dialogues. This aspect of Modeling surely must find its epistemological and pedagogical antecedents in the works of education researchers such as Bruner (1960), Vygotsky (1978), and Arons (1977, 1990), if not directly, then at least as a consequence of their profound reshaping of the fundamental principles of teaching and learning that have so slowly rippled down to us in these latter days. Bruner's constructivist theories, Vygotsky's "zone of proximal development," and Arons' insistence that physics students have the opportunity to verbalize their understanding have each become inextricably entwined in the Modeling pedagogy. Their work is mostly beyond the scope of this paper except insofar as acknowledging the debt owed by those of us who came after.

As I describe the phases of one Modeling Cycle, it is critical that the reader understand that participants experience the complete sequence of Modeling Cycles over the course of the four-week Modeling Workshop in nearly the same manner it is intended they deliver the curriculum in their own classrooms. This sort of "immersion" is consistent with the recommendations of professional development researchers such as Hawley & Valli (1999); Etkina (2005); and

Loucks-Horsley, Love, Stiles, Mundry & Hewson (2003). More is said about the professional development program in Study Context, below.

The Modeling Cycle has two stages, model development and model deployment. "**Stage I** is designed to lead students systematically through the four main phases of model development: description, formulation, ramification and validation. **Stage II** is devoted to deployment of the model developed in Stage I to a variety of new physical situations in a variety of different ways" (Wells, Hestenes & Swackhamer, 1995). Each of these stages is further divided into phases. The list of phases is taken from Halloun (2004), but the descriptions are based on my own training at Modeling Workshops and experience as a Modeler.

Stage I – Model Development

1. *Exploration*: Demonstration

In the *Exploration* phase of Stage I students first are presented with a "paradigm experiment," that is, some sort of demonstration, hands-on activity, video depiction, or computer-based activity that manifests the as yet unspecified physical principles to be discovered. This may be as simple as a toy truck moving across a table or as complicated as a modified Atwood's machine. An important feature of this phase is that it is a "carry-forward" from the previous modeling cycle, that is, it is the next logical step in building up a coherent theory (storyline) in the relevant physics sub-discipline. The teacher solicits from the class "everyday social language" descriptions of the system under scrutiny thereby activating students' prior knowledge. All observations are accepted and duly recorded by the teacher for all to see. Eventually, and this may well require that the teacher ask directing questions to refocus students' thinking towards what the teacher knows are the relationships to be developed, a student makes a pertinent, but preliminary observation. For example, a student might say the toy truck is moving at a "constant speed." The teacher then (gently) challenges that one student to be more explicit: What do you mean by "constant speed"? This give and take continues until teacher and students are satisfied that a sufficiently complete description of the system has been generated. The teacher now leads the class in a discussion to narrow the list of observations by identifying duplications, removing obvious non-sequiturs, and zeroing in on the salient features of the system.

2. *Exploration*: Nominal models

The discussion shifts now to developing preliminary explanatory models. This phase is initiated by asking students to consider what parameters might be descriptive of and/or account for the system's behavior. In this phase the teacher often challenges students to explain their theories or at least more precisely define the terms they use to describe their models. The intent here is *not* to correct the students' models per se, but rather to assist the students in making their thinking clear to the class and to themselves, typically by asking probing questions or paraphrasing students' responses.

3. *Model Adduction*: Plausible model

The next step involves guiding the class to a consensus as to the quantitative parameters that *appear* to affect the behavior of the object (system) under scrutiny and to discard those that do not. Some extraneous "parameters" may survive this process, especially when student experience (or intuition) with the system is limited. The teacher sometimes has to assume a more authoritative posture here to bring the discussion to a timely close, to restrict the number of extraneous parameters for efficiency's sake, and to give the parameters their scientific labels, even though their (preliminary) functional roles were previously established. At the close of this phase the class should have developed at least one test of the functional relationships between the specified variables.

4. *Model Adduction*: Investigative design

Now it is time for the students to design an experimental test(s) to attempt to establish the relationships between the variables. Students are organized into groups for the purposes of designing, conducting, and analyzing their experiments, and for presenting them as well. Students are engaged in group conversations as they struggle to work out all the challenges associated with designing and setting up the experiment and collecting data. This is a crucial first step in the process of model formulation because it is at this point that students confront their prior conceptual models and they often need help organizing their thinking. The teacher circulates around the room, mostly providing guidance in the form of directing questions or restating students' questions and only rarely answers questions directly, usually about the proper use of test equipment.

5. *Model Formulation*: Investigation and initial model formulation

Once students have collected experimental data they are expected to prepare a graphical representation of the characteristic relationships and to generate a (preliminary) mathematical model in anticipation of presenting their findings to the class (usually on a dry-erase "whiteboard," but there are other equally suitable media).

The teaching sequence now enters the pivotal phase of initial model formulation – student presentations. There are a variety of ways for staging the presentations, but, in the end, the goal is to create a "safe" environment, one that fosters respectful student self-expression and promotes robust classroom discourse. Typically one student from each group is designated by the teacher to stand at the front of the class and defend the group's results which include a brief summary of the experimental procedure (if applicable) and a thorough explanation of their graphs and mathematical derivations. They also must explain any other representational devices that may be depicted, such as free-body or other vector diagrams. The use of multiple representations increases the likelihood that some aspect of the model specification is accessible to every student.

The key feature of the whiteboard presentations is the questioning that follows. Anyone in the class is free to ask questions of the presenter but the teacher generally holds his or her own questions until the students have had their chance. Thus, the teacher serves initially as moderator; sometimes helping students phrase or rephrase their questions, sometimes helping the presenter with his or her responses. Most students ask questions seeking information or explanation, but more confident students often attempt to challenge the presenter on the validity of their graph or mathematical formula or their model formulation. On rare occasions a question can spark a class-wide discussion and the teacher should be prepared to take a back seat.

The crux of the Modeling Method, its very heart, lies in the interaction between the student-presenters, their student-colleagues, and the teacher during the Model Formulation phase and later during the Model Deployment phase. *These* are the best opportunities in the cycle for the teacher to probe for individual student understanding and to make the "story" available for all the students in the class.

6. *Model Formulation*: Rational model extrapolation

After the students' presentations are complete and the model specification has evolved as far students can take it on their own, it is time for the teacher to step in and continue the development of the scientific story. The goal, of course, is to reach a developmentally appropriate level of closure, to the point that all relevant aspects of the model specification have been defined, delineated, differentiated, and decontextualized.

Stage II – Model Deployment

7 & 8. *Model Deployment:* Elementary and Paradigmatic deployment

The purpose of model deployment is to provide students with opportunities to more fully integrate the model specification into their conceptual profiles by applying their new perspective in novel situations, thus establishing the model as a generally applicable scientific rule. Deployment activities typically include problem sets and "deployment labs." The problem sets are carefully designed to illuminate the different aspects of the model specification and are implemented in a fashion similar to the procedures for the investigative phases of model development, i.e., students work in teams and present whiteboards. A deployment lab can be a new experiment, a demonstration, or even a computer simulation, but the cycle begins immediately in the investigative phase (step 6) and with no moderation by the teacher.

It is during the deployment phase that whole-class discussions about the model are most likely because by this time many students will have had sufficient exposure to the "scientific view" to have begun to appropriate the model. They are more confident in their use of school science social language and are more willing to challenge and test their colleagues' paradigms and representations.

9. *Model Deployment*: Paradigmatic synthesis

Paradigmatic synthesis is the culminating phase in the development of a model *qua* model. That is, it is a very intentional, explicit validation of the model itself as being an accurate representation of the physical phenomenon under scrutiny. "It is…a systematic recapitulation, following modeling schemata, of a model and its building blocks, as well as of tools, processes and underlying tenets involved in model construction and deployment" (Halloun, 2004, p. 230).

From this description of the complete Modeling Cycle, it is only reasonable to propose a list of traits for the "ideal" Modeler that we might have a standard by which we can compare Modeling as well as non-Modeling teachers. Hestenes (see, for example, Wells, Hestenes & Swackhamer, 1995) and Halloun (2004) have done much theoretical work in this area, based in large part on their informal observations of Modeling teachers and their students, and several former and current Modeling teachers have written research-based dissertations on Modeling that have added to this body of knowledge (see http://modeling.asu.edu for a complete listing).

A comprehensive enumeration of these traits is Halloun's (1998) Modeling Instruction Survey (MIS) which is a 100-item taxonomy of Modeling behaviors (see Appendix 7). The survey was designed to be administered to teachers who had completed Modeling Workshops so as to estimate the extent to which a teacher implements the Modeling pedagogy in his or her physics classes. Halloun hoped to correlate MIS data with the Force Concept Inventory, the Mechanics Baseline Test, and other measures of student learning to validate the instrument and identify "essential" Modeling behaviors. Some preliminary work in this regard had been done, but the correlations were not definitive and forces beyond their control required the Modeling Instruction program staff set this work aside. Based on my own analysis of Halloun's limited data, access to which was graciously granted by the Modeling program staff, my own practice, and my practical knowledge of teachers and teaching, I winnowed Halloun's list to 49 items I believe are strongly indicative of Modeling behavior. I used my list as a guide during classroom observations to supplement the Reformed Observation Teaching Protocol (Sawada, Piburn and Falconer, Turley, Benford & Bloom, 2000) I employed during this project. I also used these items, plus 11 additional items identified post hoc, to generate scores for the three of my subjects who completed the survey in 1998 and again for all six of my subjects who completed the survey as part of this research project. More is said of the MIS and the items I selected, below, but as an aid to the reader I will take the liberty to provide a summary of essential Modeling practices.

1. A deep understanding of student misconceptions in physics and how they manifest themselves in student talk and student-generated representations (i.e., diagrams, graphs, and formulas such as on whiteboards, homework, and tests) so as to inform teacher-mediated classroom discourse (i.e., Socratic questioning).

2. Considerable skill in managing classroom discourse itself, that is, knowing what "communicative approach" (Mortimer & Scott, 2004) to use in each phase of the Modeling Cycle and especially knowing when to intervene and when to step back.

3. The ability to create an environment that supports students' collaborative construction of conceptual models, promotes student-to-student interactions, and deemphasizes the authoritative role of the teacher. This means developing a "learning community" within the class that can induce and sustain student model assimilation and internalization.

4. An appreciation of the nature of science and of physics, in particular, as a model building enterprise and of the nature of such models themselves; that they have specific operational domains, structures, and compositions and exist within the framework of a well-defined theory (Halloun, 2004). The teacher should be well-versed in the underlying physics of the models he or she presents, how they fit together, and how to maintain a coherent storyline from concept to concept.

Pedagogical Content Knowledge and Conceptual Change

Domains of Teacher Knowledge

Beginning with Shulman (1986), many authors have created categorization schemas for teachers' knowledge domains (see, for example, Grossman, 1990; Morine-Dershimer & Kent, 1999; Carlsen, 1999; and Etkina, 2005). Although the models vary in some specifics, they agree generally to divide teacher knowledge into three broad categories: 1) general pedagogical knowledge and 2) subject matter knowledge which are foundations for 3) pedagogical content knowledge (PCK). Some researchers (e.g., Grossman, 1990 and Morine-Dershimer & Kent, 1999) add a fourth knowledge category that relates to the general and specific educational contexts in which teachers work, but I prefer Carlsen's (1999) depiction that instead embeds the teacher in his or her larger educational environment – akin to Schwab's (1982) milieu, that is, "the context within which learning takes place." Although these contexts can profoundly affect teachers' knowledge and practice (sometimes proscriptively so), they are not amenable to this sort of generic analysis. That is, even though school environments are often categorized broadly by many education researchers and statisticians as, for example, "inner-city," "rural," and "suburban," or "advantaged" and "disadvantaged," along with the baggage these conceptions of school carry with them, I maintain these contexts are sufficiently diverse that it is more productive to analyze their impact on teachers' practice on a case-by-case basis. Nevertheless, it is at least worth mentioning here that the subjects of this study all live and work in relatively privileged communities, which is partly a consequence of studying physics teachers. This is because junior/senior physics typically is a high status college-prep elective course in most high schools and is offered only on an occasional basis in many rural and inner-city schools. However, inasmuch as this study focuses on teachers rather than on their students, I believe my findings will be widely applicable – certainly wherever physics is taught.

I do not intend to challenge these models of teacher knowledge or their ontological and epistemological underpinnings, but some researchers suggest that both the categories themselves and the distinctions between them may be problematic. Holder (2004), for example, contends that PCK as a construct "is not based on scientifically-based research" and consequently PCK may be more a politically expedient creation intended to influence the direction of teacher accreditation programs than it is an authentic genus of teacher knowledge. The implication is that it is sufficient to characterize general pedagogical and subject matter knowledge and then to inquire as to how these knowledge bases interact in teachers' practice.

Segall (2004), on the other hand, sees the interrelationship between content (subject) and pedagogy as inextricable. That is, to speak of PCK as merely a domain of teacher knowledge is to ignore the pedagogical nature of the content itself. Segall is not making a connection between *how* one teaches and *what* one teaches, which is, of course, the *raison d'etre* of Modeling Instruction, he is making a statement about the texts (written media) that are offered to students. The classic example here might be high school history textbooks which have been notorious for marginalizing people and events that do not fit the prevailing (re)construction of history. But the concept extends to all texts in all subjects – someone (other than the teacher) has made a decision about what is worthy of inclusion and how it shall be depicted. At least two layers of pedagogy are at play here: the teacher-mediated classroom pedagogy and the texts themselves. Segall has much more to say about the intentional, regulatory nature of pedagogy, and that by choosing what to teach and what *not* to teach a teacher confers a privileged status on one world view over others, but his main argument is that content is itself pedagogical because content is not just about some*thing*, it is also for some*one*. Segall therefore suggests that "teacher education's focus on pedagogical content knowledge should move beyond the idea of teaching students how to pedagogize pedagogically free content to helping them recognize the inherently pedagogical nature of content and its implications for (and in) teaching." This dichotomy has even been somewhat of an issue within the Modeling community with respect to the suitability of "standard" physics textbooks most of which are considered Modeling-unfriendly in that they present the material in a manner not supportive of a constructivist-oriented, inquiry-based pedagogy.

Both Hooker (2004) and Segall (2004) therefore see the apparent distinctions between the domains of teacher knowledge listed above as vague at best and at worst as obfuscating other, more important issues in education. Although this all may be true, this conception of pedagogy really adds nothing to the task at hand: making content comprehensible for learners. Teachers *can* change their pedagogy without substantively changing content and do so regularly – that is the whole point of reflective practice, in particular, and some aspects of education reform. Of course, many changes in pedagogy and content do go hand in hand. But if such changes can and at least sometimes do occur independently of one another, the separation of teacher knowledge into distinct domains does indeed serve both epistemological and practical purposes. On the one hand we can describe what teachers do and should *know*, and on the other what they can and should be able to *do*.

General Pedagogical Knowledge

General pedagogical knowledge, then, consists of discipline-independent forms of knowledge, such as knowledge about learners and learning, classroom management, and general principles of curriculum, instruction, and assessment (Carlsen, 1999). These are the forms of knowledge that a teacher derives initially from his or her own experiences as a student (Lortie's (1975) apprenticeship of observation) and then in a teacher training program; they evolve and mature with teaching experience (one would hope) and with additional training. General pedagogical knowledge also is influenced by teachers' personal beliefs and perceptions about themselves, students, parents, society, the world, and about education and their role as teachers (Morine-Dershimer & Kent, 1999). Presumably, general pedagogical knowledge is what enables teachers to teach *outside* their content areas, a fate almost all secondary teachers face at one point or another during their careers; there are procedures and techniques that can be applied across a wide spectrum of courses, albeit with varying degrees of effectiveness. In fact, some of the teachers I observed have successfully adapted the physics Modeling pedagogy for their other, non-physics classes, including biology. It could thus be argued that they had thereby "generalized" the Modeling pedagogy.

Subject Matter Knowledge

Subject matter knowledge is the content of the discipline itself, be it physics, chemistry, English, what have you. Subject matter knowledge consists of the substantive and syntactic structures (Schwab, 1962; Carlsen, 1999) of the discipline, what some researchers identify as declarative and procedural knowledge (see, for example, Gess-Newsome, 1999), as well as the nature of the discipline. Researchers here are referring to what constitutes scientific knowledge and the rules by which such knowledge is both acquired and validated. As for the nature of the discipline, in science this might be the difference between an “empiricist” perspective, wherein science is conceived as a body of revealed, immutable facts to be memorized, and a “constructivist” perspective in which scientific knowledge is considered as tentative, collaborative, and proceeding according to generally accepted conventions (Tsai, 2006). How teachers conceive of their subject inevitably influences their practice; it affects what they believe is worthy of teaching and learning. Similarly, the depth and richness of teachers’ subject knowledge affects the facility with which they can access and make accessible the structure and connections within the discipline via suitable representations, analogies, and metaphors.

For most teachers, subject matter knowledge is primarily obtained in school, usually at the high school and undergraduate levels, often presented in the didactic style with which every reader is undoubtedly familiar. Other sources of subject matter knowledge can broaden and enrich a teacher’s background: independent study, print and other visual media; non-teaching work experience, etc. But it is this narrow, didactic style of teaching that sits square in the crosshairs of contemporary education reform, especially in science, and the old aphorism that “teachers teach as they were taught” has become both warning and opportunity. Very few undergraduate science programs make any attempt at a thematic approach that would weave ostensibly related courses into a coherent presentation of the discipline or make transparent the epistemological underpinnings that frame contemporary understandings of the field. It is “left to the reader” to work out the organizing principles, though a well-designed science methods course can be helpful in this regard for pre-service teachers. This situation is succinctly addressed by the National Research Council’s (1999) call to arms in *Transforming Undergraduate Education in Science, Mathematics, Engineering, and Technology*, which says, in part, “in addition to mastery of the specific subject matter taught in a course, success would be defined and measured by the degree of understanding and appreciation gained by students of both general scientific concepts and of the scientific approach to understanding natural processes (Vision 3).” This sentiment permeates the entire document: undergraduate education in STEM for majors and non-majors alike should do more than emphasize mere content, it should tie together the otherwise disjointed view of a given discipline as well as its relationships with other disciplines.

It should therefore come as no surprise that new teachers (and under-prepared teachers generally) rely heavily on textbooks for the content and structure of their classes because their only other sources of guidance are their general pedagogical knowledge and what they can remember, piecemeal, from their college course work. Consequently, these teachers have difficulty planning their curricula, recognizing and responding to student difficulties, and handling student questions. In the words of McDiarmid, Ball & Anderson (1989), “staying one chapter ahead doesn’t really work.”

Some programs, as suggested by *Transforming Undergraduate Education*, are now taking advantage of recent research on teaching and learning and are actively engaged in programs of undergraduate and teacher education reform. For example, several recent National Science Foundation-funded initiatives, such as PhysTEC (http://www. phystec.org), encourage and support the redesign of introductory-level STEM courses, especially courses likely to have pre-service teachers enrolled, so as to be more constructivist-oriented and inquiry-based. An intriguing science portfolio program for chemistry majors at Berea College in Berea, Kentucky provides an overarching structure to foster students’ development into professional scientists, life-long learners, and competent communicators (Roecker, Baltisberger, Saderholm, Smithson & Blair, 2006). Such programs have spawned related efforts at many institutions and some in-service teacher professional development programs.

Pedagogical Content Knowledge

Finally, pedagogical content knowledge represents the union of general pedagogical knowledge and subject matter knowledge in the context of a specific discipline. Carlsen (1999) identifies four components of PCK in science: knowledge of students' common misconceptions, knowledge of specific science curricula, knowledge of topic-specific instructional strategies, and knowledge of the purposes for teaching science. To this list Etkina (2005) would add knowledge of assessment methods which has become an increasingly important aspect of teachers' practice primarily because of the move toward standards-based instruction and a renewed emphasis on formative assessments designed to inform instruction. The epistemological thrust is from the general to the specific; but the critical aspect of PCK, the thing that makes it a legitimate domain of teacher knowledge, is an understanding of the learning challenges unique to the discipline and how to meet them. In the case of this project, this means first and foremost understanding how students learn (or do not learn) physics.

Any changes in the foundational knowledge domains must ripple through to PCK itself. A deeper apprehension of the content, new insights into student learning, a shift in epistemological perspective will, as a matter of course, affect a teacher's practice (Tsai, 2006). The interaction between the domains is reciprocal. For example, changes in topic-specific curricula or instructional strategies, either or both of which can be externally mandated or self-motivated, can require a restructuring of pedagogical and subject knowledge. Such changes are often associated with programs of professional development, but they can also be the result of reflective practice.

Conceptual Change

This brings us finally to the central question. A long-standing criticism of both pre-service teacher preparation, including core A&S classes and in-service professional development programs, is that they usually do not induce the depth of conceptual restructuring in teachers' knowledge and beliefs that ultimately results in meaningful and sustained reform in teachers' practice (Richardson & Placier, 2001). (I am restricting my comments to small-scale, focused programs of professional development directed at relatively small groups of teachers, such as high school physics teachers, though I believe there are many issues in common between these programs and their larger counterparts. The critical difference between them is essentially one of un-coerced teacher choice and, consequently, teacher motivation.) Why is this so? What is the source of this apparent inertia, this resistance to change in teachers' practice, and what can overcome it? I hypothesize that teachers are, in this regard, no different than their students; in order to assimilate a significant revision to their world view they must undergo *conceptual change*. I hypothesize further that the conceptual change is concerned mostly with teachers' views on the nature of physics, how students learn physics, and their roles as physics teachers. (We do know, however, that many of the teachers who attended Modeling Workshops, especially those teachers under-prepared in physics, significantly increased their subject matter knowledge, just as it is hoped will their own students, but in this paper I am emphasizing teachers' conceptions of physics *teaching*.)

The gist of the conceptual change theory of learning is well known to many science educators, especially those who espouse a constructivist-oriented approach to teaching. The theory describes the "the process by which people's central, organizing concepts change from one set of concepts to another set, incompatible with the first" (Posner et al, 1982, p. 211). The argument is that humans “construct” knowledge via organizing principles inherent to human perception and cognition, presumably from birth onward. The knowledge so constructed constitutes the content of our “conceptual ecologies.” But, because we cannot perceive everything (beyond our sensory capabilities) or because mental processing stops when a "satisfactory" potential has been achieved (i.e., the model is "good enough"), we draw inferences based on incomplete information or partial understanding. “Cognitive conflict” arises when one or more pre-existing conceptions are contradicted by new experience, the so-called “discrepant event.” “Accommodation” of a new conception occurs under the following conditions:

1. There must be dissatisfaction with existing conceptions
2. A new conception must be intelligible
3. A new conception must appear initially plausible
4. A new conception should suggest the possibility of a fruitful research program

“The central commitment of the conceptual change learning model is that learning is a rational activity that can be defined as coming to comprehend and accept ideas because they are seen as intelligible and rational; the ‘ahaa’ experience is of utmost importance in learning” (Suping, 2003). Interestingly, the conceptual change model says nothing about the external validity of the new conception, only that it has to *appear* “plausible” and “fruitful.” In such a context it is easy to see learning as an ongoing series of cognitive conflicts and accommodations. Posner et al. (1982) therefore suggested that to help students replace naïve/incorrect conceptions in science teachers should design their curricula so as to expose students to conceptual conflict and to devise strategies that would help them accommodate scientifically aligned conceptions.

I have appropriated the conceptual change model of learning from the rather extensive universe of theories of learning for the following reasons: it was developed specifically to provide an explanatory framework for understanding students’ learning of science concepts, so it seems reasonable to apply it to science teachers’ learning in this context; there is a rich peer-reviewed research literature base to support it; there is physical evidence from cognitive science that conceptual change is a tenable model for describing mental processes that can be associated with this theory of learning (Dunbar, 2001); it is consistent with the epistemology of Modeling instruction; and, in particular, it can explain the “transformative” nature of the learning experiences reported by many teachers who have attended Modeling Workshops.

Other theories of learning could probably contribute to this study; learning is far too complicated to be completely explicated by any one theory. But more to the point, a few studies have considered the roles of various factors that affect student learning *within* the conceptual change framework. This is sometimes referred to as “warm” vs. “cold” conceptual change theory (Pintrich, Marx & Boyle, 1993) distinguishing between purely rational (cold) and socio-emotionally mediated (warm) models of learning. For example, in a study of science students learning about density, Kang, Scharmann, Noh & Koh (2005) examined the interplay of several cognitive and motivational variables as predictors of students’ conceptual understanding transitioning from an “undifferentiated weight-density concept into a scientific density concept.” They administered tests of logical thinking ability, field dependence/independence (FDI), meaningful learning approach, failure tolerance, mastery goal orientation, and self-efficacy of which only FDI and failure tolerance were statistically significant predictors of conception post-test scores. Failure tolerance is probably not an issue for teachers in this context, but it might be interesting to consider the effect of FDI.

Abd-El-Khalick & Akerson (2004) found similarly that not only is conceptual change mediated by various motivational and cognitive factors but also by cultural factors. Their study of the development of elementary pre-service teachers’ views about the nature of science revealed, among other things, “that students who viewed science and religion as opposing enterprises rather than as two different ways of knowing” did not show growth in the sophistication of their views about science. As is mentioned elsewhere in this dissertation, I will have some cognitive and attitudinal data that were collected from teachers during and shortly after their participation in the Modeling Workshops that may be useful, at least tentatively, in identifying some of these factors. Correlating these data with classroom observation and interview data should be more fruitful.

An important aspect of the Workshops is that they are also venues for socially mediated conceptual change. They are an instance of “professional community” in which teacher learning occurs in a social context through shared discourse and meaning making. Spillane (1999), for example, describes a relatively complex environment of “enactment zones,” which are not unlike Vygotsky’s (1978) “zones of proximal development.” Enactment zones are where “teachers notice, construe, construct and operationalize the instructional ideas advocated by reformers;” they are “the space where reform initiatives …interact with the world of practitioners and ‘practice’.” Teachers are more highly motivated to change their core practice when their “enactment zones extend beyond their individual classrooms to include rich deliberations about the reforms and practising the reform ideas with their fellow teachers and other experts” (p. 170). For Spillane, these deliberations can occur both formally and informally, in conversations between teachers during recess as well as with experts during an occasion of professional development. To Spillane’s list I would add “conversations” that occur over the Internet via the Modeling listserv, not to the extent that such virtual conversations promote conceptual change (which is possible), but rather to the extent they help nurture and sustain the sense of community among subscribing teachers (Rheingold, 1994; Ellis, Oldridge & Vasconcelos, 2004).

Cast in the framework of conceptual change theory, the fundamental premise of this research is that the traditional (whether behaviorist or empiricist) perspective is in its very essence based on a “naïve” conception of learning, that is, physics teachers have misconceptions about teaching and learning just as do their students about physics. The critical misconception in this case is that a didactic teaching style is an effective pedagogy for promoting student assimilation of physics concepts. The discrepant event that should be the source of teachers’ cognitive conflict is students’ chronic and apparently irremediable inability to master these concepts. Teachers have found a variety of strategies for accommodating this dissonance, the most important historically being to blame the students for lack of wit or perseverance or their previous science and math instructors. Over many years, physics teachers have evolved the notion that their discipline is really just for the “best and the brightest” and their job is to weed out “inferior” students. But in the face of so much research that places the blame on the pedagogy, many teachers have found themselves ethically unable to perpetuate the charade and have sought a new accommodation. To resolve their cognitive conflict, many teachers have turned to alternative conceptions of learning and teaching in the form of constructivist theories. A wide range of constructivist pedagogies now are available to the physics teacher, most of which have shown some success compared to traditional teaching styles (see, for example, Boller, 1999). These pedagogies generally emphasize a shift in the teacher's role from "sage on the stage" to "guide on the side." One such pedagogy, Modeling Instruction in Physics, has, in many cases, proven remarkably effective at inducing conceptual change so as to progress the conceptual ecologies of practitioners *and* their students. However, variations in teachers' implementation of the Modeling pedagogy and student achievement demand a close investigation of possible mediating motivational and cognitive factors, as suggested by the works cited above, as well as other organizational factors.

Research Methods

The focus of this study is the transformation of in-service high school physics teachers' subject and pedagogical content knowledge as a direct consequence of completing the two-summer Modeling Workshop professional development program. In particular, I investigated whether and to what extent teachers' participation at the Workshops induced conceptual change so as to reorganize their conceptions of physics teaching and learning *and* subsequent teaching practices. Such investigations typically depend heavily on teachers' self-reports on their beliefs, subject knowledge, and teaching practices both prior to and since attending the Workshops. However, the Modeling Instruction program staff has collected considerable longitudinal data on participating teachers *and* their students. I have teachers' and students' pre-Workshop scores on the Force Concept Inventory (FCI; Hestenes, Wells &. Swackhamer, 1992 and (revised) Halloun, Hake, Mosca & Hestenes, 1995), a 30-question multiple choice test of Newtonian mechanics which has become *the* standard assessment instrument in introductory physics courses worldwide; teachers' pre-Workshop Views About Science Survey data (VASS; Halloun & Hestenes, 1996); teachers' Participant Experiences survey data (PE; Halloun et al, 1997; a teacher self-report of Modeling implementation administered at the second summer session of the Workshops), and at least two years of students' pre- and post-instruction FCI data. In addition, I obtained teachers' applications to the Modeling Instruction program which includes personal statements describing their personal goals and views about education. These data plus interview and observation data should provide sufficient convergent information to explore the relationship between teachers' participation in a Modeling Workshop and the changes I hypothesize in teachers' knowledge domains.

This study was somewhat unusual. As I will show below, these teachers faced no significant external interference in their implementation of the Modeling pedagogy. Put briefly, however, physics is typically an elective course taught at the junior/senior level, that is, after most students have survived their states' high-stakes assessment. Exempt from this pressure, physics teachers enjoy a certain benign neglect from the powers that be and generally do not have to conform to any school, district, or state instructional guidelines as to content or methodology. Therefore, the manner and extent to which a teacher employed Modeling instruction was entirely a personal and professional choice. This means we have a lens through which to examine teachers' beliefs and practice that is unobscured by such confounding factors. We are thus in a position to compare "apples to apples," as it were, and make distinctions between the teachers in this study that are the direct result of their individual predilections.

Settings and Participants

School Context

Despite the fact that over the years various Modelers have reported (via the Modeling listserv and on Participant Experiences surveys) problems with schools' scheduling practices, scheduled and unscheduled class interruptions, limited laboratory equipment (computers especially), and resistance to the Modeling curriculum itself from school administrators, science department chairs, department colleagues (especially other, non-Modeling physics teachers), parents, and students, none of these factors proved to be significant obstacles for the teachers in this study much beyond the introduction phase (about two years). Additionally, though some teachers' students (juniors) do have to sit for their state's student learning assessment, which ostensibly could have placed constraints on the content the affected teachers must cover and consequently affect the pacing of the course in such a way as to inhibit a full deployment of the Modeling pedagogy, the Modelers in my study found ways around these requirements. On the other hand, some of the teachers reported no interference at all and even immediate, enthusiastic support for their adoption of the Modeling pedagogy.

School and class demographics were definitely factors in how a teacher implemented the Modeling pedagogy but not in an obvious manner. With the exception of the performing arts charter school, the demographics of the classes, all of which were "regular" algebra-based junior or junior/senior physics classes, were no less than 90% white, upper middle class with a ratio of about two-to-one boys to girls. This ratio was reversed at the charter school (which is consistent with the demographics of the school itself). That high school physics classes are mostly populated with white students (only about 22% of Black students and 21% of Hispanic students take a physics class in high school; Neuschatz & McFarling, 2003) is beyond the scope of this dissertation, but this fact does raise serious questions about the efficacy of the Modeling pedagogy for underrepresented populations. Moreover, Modeling Instruction program staff do have data that indicate minority students in Modeling classes generally underperform compared to their white peers. However this may be, the criteria that seemed to most influence teachers' presentation of the curriculum was their estimation of their students' mathematical aptitude and, of course, the extent to which teachers felt their students had mastered the physics concepts under study. I will discuss this in a later section, but in sum, it should be understood that, for the most part, the students of these teachers were among the best in their respective schools and the teachers themselves were unfettered with respect to the delivery of their instruction.

Study Context

The subjects of this of analysis are practicing public high school "regular" physics teachers who completed two 3-week Modeling Workshop sessions over two consecutive summers during 1998 and 1999 under the auspices of the Modeling Instruction in High School Physics program at Arizona State University. Five of the six teachers attended the same series of workshops on the west coast and the sixth teacher attended workshops on the east coast. Appendix 1 shows the typical Modeling curriculum (Mechanics is presented during the first summer session and Waves, Sound, Light, and Electricity & Magnetism during the second summer session), and

Appendix 2 is a sample syllabus for a 4-week session on Mechanics (prepared by Jane Jackson, co-Director, Modeling Instruction program).

The professional development program has teachers "model" their way through a year's curriculum just as would their students, including designing and conducting all the experiments, preparing and presenting whiteboards, and completing the various "model deployment" activities (but not homework or "end of unit" assessments). The workshop leaders enact the teaching role and emulate the various styles of teacher discourse through each modeling cycle. Workshops typically begin with the administration of the Force Concept Inventory and the Mechanics Baseline Test (Hestenes & Wells, 1992; a 26-question, quantitatively-oriented assessment), followed by some readings, lectures, and discussions about research in physics education, constructivist pedagogy, guided inquiry, models, and the modeling cycle. It then takes three weeks, eight hours a day, to complete a semester's curriculum. As teachers work through the curriculum, time is allotted for group deconstruction of every aspect of a lesson: the physics, the models, the pedagogy, materials, the use of computer technology, whiteboarding, styles of discourse (especially questioning techniques), assessment – everything. Workshop leaders take pains to provide for social occasions, such as group outings and dinners, to give the participants some respite from a hard day's work, but also to promote a sense of community. Upon completing a workshop not only do teachers have a fully developed semester's curriculum *and* pedagogy to take back to their classrooms, they also have been inducted into the community of Modelers.

It is these two characteristics, duration and curriculum, that most distinguish Modeling Workshops from other programs of professional development. Few workshops for physics teachers last more than one week and most are but a single day. There are literally dozens of these one- or two-day workshops; from all-day "take away" workshops (in which teachers develop a lesson to take back to school), to sessions just for physics teachers at AAPT, NSTA, AVS, etc., annual and semi-annual meetings, to "local physics alliance" workshops such as the Physics Teacher SOS New Teacher Workshops conducted by the Northern California/ Nevada section of AAPT. One of the "premier" series of workshops, the Physics Teaching Resource Agents "summer institutes" (see http://www. aapt.org/ptra) held in conjunction with AAPT summer meetings, are only a week long. The famous Woodrow Wilson Foundation summer institutes (see http://www. woodrow.org/lpt/LPTnational.php), which concluded in 2003, lasted from two to four weeks but focused on specific topics in physics and physical science. The Physics by Inquiry summer institutes here at the University of Washington (see http://www.phys. washington.edu/groups/peg/ 2007institute.html) are an exception. These workshops last for five weeks (plus several weekly evening sessions during the school year), and teachers are typically expected to make a two- to three-summer commitment to the program. This hands-on, inquiry-oriented program emphasizes improving the physical science content knowledge, science process knowledge, and nature of science literacy mostly for grades 4 through 9 teachers, but it is open to all K-12 teachers. However, the curriculum is not designed to be transferable to the classroom.

As mentioned earlier, a spate of initiatives intended to reform pre-service physics teacher education, such as PhysTEC, have been implemented at at least two dozen institutions and the list is growing. Besides introductory level and methods course reform, these programs include pre-service physics teacher recruitment, master teachers whose duties specifically include undergraduate course revisions and designing of physics faculty professional development, mentoring for pre-service and novice teachers, early teaching experiences, and multi-institution collaborations. More college courses are designed for pre- and in-service teachers at many "non-reformed" institutions, but these are mostly content- rather than pedagogy-oriented courses. The point is few other multi-week, immersion physics instruction training programs exist for pre- and in-service physics teachers besides Modeling Instruction (and closely related programs, such as the Master of Natural Science degree program for in-service teachers at ASU). Moreover, many of the programs that *are* designed specifically for pre-service physics teachers that exist within an increasing number of A&S physics departments directly or indirectly incorporate Modeling or Modeling-derived pedagogy in their pre-service methods and in-service professional development courses (see, for example, PHY620 at Buffalo State College, PHY 311 at Illinois State University, or 15:256:552 (Teaching Physical Science) at Rutgers University).

Participant Selection

The subjects are a representative sample of six from the entire population of about 175 teachers who have completed the Workshop sequence described above, who currently teach at least one regular physics class, and for whom I have most or all of the following data: the teacher's application to the Modeling Instruction program, student FCI data for the teacher's regular physics class(es) taught prior to the first Workshop, the teacher's pre-Workshop FCI and VASS scores, the teacher's Participant Experiences survey data, and at least two year's of student FCI pre- and post-instruction scores following the first (Mechanics) Workshop.

Because I am interested in how participation in the Modeling Workshops might induce conceptual change in teachers that ultimately may affect their classroom practice, I decided to use the results from the Participant Experiences Survey that was completed early in the second summer workshop (that is, after a year's experience with Modeling), and the first post-workshop student FCI scores to establish a baseline from which I could compare teachers' initial implementation of the Modeling pedagogy and use as a reference point for changes in pedagogy and student achievement over time. I use the pre-Workshop student FCI scores to flesh out each teacher's pre- vs. post-Workshop instructional profile, but given that the focus of this research study is the pedagogical impact of the Workshops, the first post-Workshop student FCI scores are more germane for selecting participants. Thus, to identify the population of potential subjects I generated a scatterplot of average first-year normalized student FCI gains ([Posttest % – Pretest %]/[100 – Pretest %]) by teacher vs. an average score of selected items from each teacher's Participant Experiences survey (see Appendix 3) responses, that is, the items directly related to the degree to which a teacher reported he or she is implementing the Modeling pedagogy. I selected items 1-8 (4 and 6 were reversed), 10-13, 19, 23-25, 27-31, and 42 and 43. Appendix 4 is a scatterplot for the 1998-1999 cohort (with teachers' identification code numbers), that shows the distribution of teachers across these dimensions of (self-reported) implementation vs. student achievement (FCI gains). The circled identification codes denote those teachers who met the selection criteria specified above and agreed to participate in this study. The invitation to participate was extended by the Modeling Instruction program staff on my behalf, so I had no contact with potential subjects until they had agreed to do so, at which time I was given their contact information.

Data Collection Strategy and Procedures

I adopted an interpretive, "observer as participant" approach in this study following Erickson (1986, p. 121), Merriam (1998, p. 101), and Glesne (1998, p. 44) in the sense that 1) I interacted only minimally with teachers and students during classroom observations; 2) I interviewed teachers after each observation and conducted one extended interview with each teacher; 3) I interacted with the teachers informally between and after classes during which times we "talked shop," but never did I divulge anything substantive about the purposes of my research except to say that I was observing teachers who had completed the Modeling Workshop sequence; and 4) I myself completed the workshop sequence in 1996 and have been a committed Modeler ever since. I wanted to investigate what it means for teachers to have assimilated both the conceptual and pedagogical perspectives that are the foundations of Modeling. Thus, there is what the teacher reveals to me via the VASS, the Participant Experiences Survey (administered spring 1998), and a Modeling Instruction Survey (self-administered and mailed to me after I left the school – see below), and the extended interview, and, on the other hand, there is what he reveals to me via his classroom practice during classroom observations. My task is to attempt to reconcile and interpret these interrelated but not identical representations of teachers' pedagogical content knowledge in the context of the Modeling construct.

Moreover, inasmuch as I have been a practicing Modeler since 1995 I am in a position to discover and disclose aspects of Modeling Instruction that are probably inaccessible to other researchers. This suggests this project may be an example of a "revelatory" case study (Yin, 2002) in that these data should provide some unique insights into a specific program of professional development and its impact on teachers.

Classroom Observation

The classroom is where a teacher's pedagogical content knowledge is made manifest so it is there the connections between knowledge, beliefs, and practice must be realized. I observed every class, regular physics or otherwise, of each teacher over (at least) three consecutive days. This was enough time to observe any one phase of a modeling cycle and to get a good sense of each teacher's pedagogical style. Some teachers incorporate aspects of Modeling into all their classes, some do not. I tried to be the proverbial fly on the wall, more or less, during classroom observations so that the "performance" could unfold in a completely natural way, but every teacher reported being conscious of my presence to some extent. However, in only one case did a teacher admit deviating from his routine practice. On the other hand, except for the occasional exchange of salutations, one or two student inquiries as to the reason for my attendance in class (I was introduced to every class as a researcher "observing teachers who had attended Modeling Workshops," but some students were more curious), and one or two inquiries on my part about this or that experimental apparatus, students seemed generally oblivious to my existence.

During the classroom observations I used the Reformed Teaching Observation Protocol (RTOP; Sawada, Piburn and Falconer, Turley, Benford & Bloom, 2000; see Appendix 6). The RTOP is a well-validated instrument that was developed at ASU for the Arizona Collaborative for Excellence in the Preparation of Teachers (ACEPT). ACEPT was a large-scale, NSF-funded program aimed at reforming teaching in introductory level STEM courses, that is, courses likely to be populated by pre-service teachers. The RTOP was utilized to evaluate the extent to which instructors had “reformed” their instruction consistent with the constructivist perspective adopted by the collaborative, and Modeling Instruction program staff have themselves used the RTOP to observe modelers. However, since the RTOP is not a Modeling-specific instrument, I prepared detailed field notes and reanalyzed the class presentation utilizing Halloun’s (1998) 100-item Modeling Instruction survey (MIS; see Appendix 7) and made my own judgments about how well the presentation was aligned with Modeling principles. This questionnaire was piloted with 80 teachers during the 1998 Workshops and the results were correlated, albeit weakly, with student FCI scores from 1997 and 1998, but it is not a validated instrument. Nevertheless, it does provide a comprehensive taxonomy of Modeling activities and I am confident that with my own 11-year’s experience as a Modeler I was able to use it effectively.

Interviews

Following each classroom observation (but no more than once per day) I conducted short, semi-structured interviews (see Appendix 5: Interview Protocols) with each teacher to elucidate the teacher’s perspective on the extent to which the lesson just observed was aligned with the teacher’s own learning goals. One question did ask the teachers to reflect on the changes in their presentation of the topic since attending a Modeling Workshop. Several of the teachers commented that these interviews forced them to reflect on their rationales for a given lesson, whether or not it was part of the “accepted” Modeling curriculum (which is also to say that some of the teachers have made their own modifications to the Modeling curriculum).

The interviews were digitally recorded on a mini disc recorder and the files were subsequently downloaded on a computer. Transcription of the interviews was accomplished using playback software to replay aloud each audio file while I repeated orally each word which was transcribed in turn using another software application. I replayed each interview as necessary to check and correct the transcription text files.

Following Baxter & Lederman’s (1999) admonition that “if a single researcher is to be involved, withhold all assessments of knowledge structures until after classroom observations have been completed” because there is the possibility that the assessment itself will act as a treatment, the extended background interviews were conducted following the last classroom observation and post-observation interview. These were semi-structured interviews (see Appendix 5: Interview Protocols), similarly transcribed, of each teacher “to capture the perspectives of program participants” (Patton, 1980, p. 196). The interview questions have two foci. The first several open-ended questions probed the teacher’s background and beliefs about the nature of science and science teaching that underpin the teacher’s practice. It is well know among education researchers that teachers’ beliefs comprehensively affect all aspects of their pedagogical practices, from the content they choose to teach (even in the face of district or state mandates), how they teach it, to how they relate to their students. For example, Tsai (2006) found that science teachers’ “beliefs about learning science, teaching science, and the nature of science are closely correlated” and affect their receptiveness to certain pedagogies. He contrasts teachers who adopt an “empiricist” versus a “constructivist” orientation, an approach I hypothesized might be a useful lens to frame the connections between teachers’ knowledge and beliefs and classroom practices.

In the empiricist perspective, “scientific knowledge is a discovery of an objective reality external to ourselves and discovered by observing, experimenting or application of a universal scientific method” which, if done carefully, “will produce infallible knowledge” (Tsai, 2006). Teachers who adopt this perspective tend to have a didactic teaching style and conceive of the teacher’s role as the transmitter of an established body of facts. The constructivist perspective, on the other hand, emphasizes “the tentative nature of science knowledge, the theory-laden quality of scientific exploration, and the role of conceptual change in progressive development of scientific understanding” (Tsai, 2006). In addition, Hashweh (cited in Gess-Newsome, 1999, p. 76) found that constructivist-oriented teachers are more likely to recognize and are better able to attend to student alternative conceptions of content.

My subjects have all completed the two-summer sequence of Modeling Workshops which have a decidedly constructivist slant. Nevertheless, it seemed reasonable to suppose that teachers who had adopted a more or less empiricist stance prior to attending a Workshop and, in particular, had a “traditional” lecture/demonstration teaching style, would probably have more difficulty accepting and implementing the Modeling pedagogy, at least initially, compared to more constructivist-oriented teachers. I hypothesized, therefore, that this conflict between beliefs and practice should be reflected in both a teacher’s VASS and Participant Experiences survey scores and his students’ short-term FCI gains. I suspected that teachers’ beliefs would probably span the spectrum between the two extremes and might even be a superposition of both perspectives depending on the situation. As it turns out, however, teachers’ beliefs are generally polarized at the two extremes, with the possible exception of one teacher. As I indicated in the Introduction, however, this distinction between teachers’ beliefs about the nature of science, while present, does not appear to affect their pedagogy in a consistent fashion and so does not serve as a reliable indicator of the extent to which a teacher will choose to implement Modeling. The implication is that, contrary to Tsai’s (2006) findings, beliefs other than about the nature of science that hold more sway for these teachers in terms of their classroom practices.

The remaining interview questions were directed at Modeling itself; the impact of attending a Workshop on the teacher’s beliefs and practice and the personal and organizational factors that may affect a teacher’s implementation of the Modeling pedagogy. And, as is often the case with semi-structured interviewers, I pursued potentially fruitful lines of inquiry beyond the direct scope of the interview questions as they presented themselves during the interviews.

The situation of the possible influences of an empiricist vs. a constructivist orientation on teachers’ practice is complicated by (at least) two other considerations that should be elucidated by these later questions. First are the organizational factors to which I have already alluded. Second, it is a matter of fact that it takes time for teachers to learn a new pedagogy, especially a constructivist-oriented, discourse-heavy pedagogy such as Modeling that is very different than that to which most physics teachers are accustomed. My subjects all confirmed that this was the case, more for some than for others, however, and one teacher eventually discontinued Modeling entirely except for a few weeks early in the year. Participant Experiences survey data and anecdotal reports by Modeling “graduates” indicate that the biggest obstacle for new Modelers is managing classroom discourse – it represents both a new skill set and mindset for most teachers. The point here is that though a teacher may well have adopted a more constructivist perspective as a result of completing the Workshop sequence, it took time for him to master the new curriculum. This fact must be considered in drawing any conclusions about the teacher's practice. It is still the case, however, that some teachers do attain high levels of implementation and student achievement relatively quickly, including one teacher in this study, and it is important to try to uncover contributing factors.

Data Analysis

This is a mixed methods study utilizing both qualitative and quantitative data to illuminate various aspects of teachers' beliefs and practice. The analysis of the quantitative data associated with this study was fairly straightforward as all the assessment and survey instruments have been previously validated by their authors. The one exception to this is Halloun's (1998) Modeling Instruction Survey, as mentioned above. I did use an abridged form of this instrument to generate a quantitative score for comparative purposes so as to provide some insights into the teachers' current views about their implementation of the Modeling pedagogy, but it was more useful as a source of codes to aid in the analysis of the qualitative data, both classroom observations and interviews. I describe each of these instruments in some detail below, but briefly the Force Concept Inventory, Participant Experiences Survey, Views About Science Survey, and Reformed Teaching Observation Protocol and their uses have all been described above: a single or composite score or a pre-post gain can be calculated and the assessment results can be compared and correlated with one another and with the qualitative data. Even though the FCI and PE were used primarily to identify potential subjects, these instruments plus the VASS and MIS also provide useful teacher background data that can be compared to the classroom observation and interview data for consistency purposes and as a sort of baseline for measuring apparent growth in a teacher's implementation of the Modeling pedagogy. For example, teachers who started their journeys as Modelers with relatively low student FCI gains may now be realizing much improved student achievement. Having background data collected during the Modeling Workshop may help reveal specific areas of growth in teachers' pedagogical content knowledge.

Table 1 is a listing of the preliminary data obtained by the Modeling Instruction program staff during 1998 and 1999 and presented in roughly chronological order. The Baseline Student FCI scores are the scores earned by the teachers' regular physics students in the spring prior to the first Modeling Workshop. Thus, it represents some measure of the effectiveness of teachers' pre-Modeling pedagogy. It is interesting to note that Charley, who now Models only in a limited fashion, had the highest pre-Workshop student FCI scores. It is also clear from these data that, at least superficially, there is not much difference between the teachers on the VASS, FCI, and MBT. The Modeling Instruction Survey was administered on a voluntary basis in 1999 and some teachers did not complete it. Note that the 1999 FCI posttest scores, that is, after the first (Mechanics) Workshop, all are higher than the pre-Workshop scores. The Modeling Instruction program staff report that this is usually, but not always, the case (my own first post-Work-shop scores were lower!).

The RTOP form has spaces for notes and observations as well as for scale scores and, as mentioned above, the qualitative observation data was analyzed using Halloun's (1998) Modeling Instruction Survey to generate an informal measure of the alignment of the observed lesson with Modeling principles. The coding scheme for interview data is derived directly from the interview questions and the corresponding responses following the analytical logic described in

Coffey & Atkinson (1996). Each question has an intent, an underlying proposition that is being probed, which in turn suggested an applicable code. That is, by paying “close attention to the categories of expression that the informant actually uses” (p. 40) and the conceptual framework of the study (and with Halloun’s Modeling Instruction Survey as a guide), I was able to generate a list of relevant codes. Once I coded the data I followed standard qualitative analytical procedures as in Miles & Huberman (1994) with respect to relative frequencies. My goal is to combine the various data sources to paint a picture of each teacher. Of the quantitative data, FCI gains are by far the strongest measure of a teacher’s expertise as a Modeler. The classroom observation and interview data are most important in terms of identifying the factors that contribute to this expertise and how it was attained. Tables 2 and 3 depict the quantitative data. Appendix 8 is a graph of teachers’ average FCI gains since the Workshops. Note that there is no data for “Charley,” who did not submit any FCI data, “Edward” did not submit any FCI data after 2002, and “Frank (H)” are data for “Frank’s” honors physics classes and are included for comparison purposes only.

I should say a word here about potential researcher bias. I was in the first cohort of the Modeling Workshops, 1995 -1997, and I wholeheartedly subscribe to the philosophy and pedagogy of the Modeling Method. Unchecked, my biases may have influenced how and what I recorded during classroom observations and how I interpret the data whatever their sources. In other words, as a confirmed Modeler, it is conceivable that in consciously or unconsciously comparing my conceptions of teaching and learning (i.e., Modeling as I see it) with those of the teachers I observed and interviewed, I may have been looking only for what I expected to see or for what I *didn’t* see. As a result, I may have judged a teacher’s classroom performance against my perceptions of how I present the same lesson in my own classroom rather than on its own merits. Similarly, I have my own views about the nature of science and science teaching. However, Modeling, as presented in Modeling Instruction Workshops, is a well-defined pedagogical framework with a well-defined curriculum and an extensive research literature base. Adhering strictly to the Modeling construct developed by Hestenes and Halloun and observing good research practices (such as multiple data sources) should mitigate the likelihood of unwarranted assertions and conclusions. Notwithstanding these comments and despite my sincere efforts otherwise, a degree of advocacy for Modeling Instruction will undoubtedly insinuate itself into this dissertation for which I ask the reader’s forgiveness.

Study Limitations

An important limitation of this study is a lack of contrasting cases. It would have been useful to observe and interview teachers who had completed the Workshops but elected to not implement the Modeling pedagogy at all or ceased Modeling completely after just one or two years. Perhaps they faced insurmountable organizational obstacles or they could not master classroom discourse management in their particular situation, or maybe their physics background was inadequate to the task. Anecdotal data for all three instances have been reported on the Modeling listserv. Of course, such teachers would be exceedingly difficult to find. Also, as I note above, my subjects were all white males of a certain age teaching mostly white children of privilege. Studies of female teachers and teachers of color as well as teachers with students of color and/or students from disadvantaged families would have been interesting. Data on such teachers and their physics classes would add to our understanding about the interplay of teachers’ beliefs in conceptual change learning theory and its role in programs of professional development, as well as about the Modeling pedagogy itself. I would have to design a somewhat different study because the Modeling Instruction program staff stopped collecting the “pre-study” data I employed at the close of the Leadership Workshops in 1999, but it could be done.

In addition, I regret the limited time I had to observe some of the teachers, especially Edward and Frank. In both cases, I would have been very interested to see what came next. If I had it to do again, I would ensure that my visits were long enough to observe a full Modeling cycle that I might get a better sense of teachers’ classroom discourse management over the entire range of Modeling activities.

Table 2
Study data set. All raw data obtained directly from participating teachers.

Teacher	3-day RTOP Average %	Modeling Instruction Survey[a] (summer 2007)	Long-term Student FCI Averages %		
			Pre	Post	Gain
Allan	90	135/2.3	24.4	50.3	33.9
Brian	80	148/2.5	35.8	66.4	47.7
Charley	70	149/2.5	n/a	n/a	n/a
David	84	130/2.2	37.8	65.8	45.0
Edward	71	96/1.6	30.4	72.0	59.8
Frank	87	114/1.9	26.0	52.4	35.6

a. Modeling Instruction survey score based on 60 selected items from 100 questions (see text); presented as score and average. Response options range from 1 to 5; low score most consistent with Modeling philosophy.

Table 3
Longitudinal data formatted for ease of comparison

Teacher	Modeling Instruction Survey		Baseline Student FCI (spring '98) %	Long-term Student FCI Averages %		
	1999	2007		Pre	Post	Gain
Allan	185/3.1	135/2.3	39.3	24.4	50.3	33.9
Brian	n/a	148/2.5	43.7	35.8	66.4	47.7
Charley	n/a	149/2.5	49.7	n/a	n/a	n/a
David	n/a	130/2.2	35.0	37.8	65.8	45.0
Edward	145/2.4	96/1.6	n/a	30.4	72.0	59.8
Frank	168/2.8	114/1.9	41.7	26.0	52.4	35.6

Evaluation Instruments

Force Concept Inventory

The Force Concept Inventory (Hestenes, Wells &. Swackhamer, 1992 and, revised, Halloun, Hake, Mosca & Hestenes, 1995) has its origins in several investigations of students' misconceptions in physics conducted at the dawning of physics education research. "The Initial Knowledge State of College Physics Students" (Halloun & Hestenes, 1985) and "Common Sense Concepts about Motion" (Halloun & Hestenes, 1985) were early attempts to identify, quantify, and assess student misconceptions in Newtonian mechanics to serve several diagnostic, placement, and evaluative purposes that might inform instruction in light of the chronically abysmal performance of students in introductory-level physics courses. These investigations included countless hours of one-on-one and focus group conversations with physics students at all levels – high school to graduate school – from which were constructed carefully crafted conceptually-oriented multiple-choice questions to probe students' understanding. The key feature of these questions was the incorporation of powerful "commonsense" distractors extracted from the painstaking research described above. The questions went through many iterations of piloting, refinement, and retesting eventually evolving into the FCI. The FCI itself was initially administered to over 1500 students in high school physics classes, including those of Malcolm Wells in Arizona and Greg Swackhamer in Illinois, and in introductory physics classes at Arizona State University, the Ohio State University, and Harvard University. Student scores on the FCI also were positively correlated with student performance on tests of quantitative ability such as the Mechanics Baseline Test described below. The FCI has since been administered to over 200,000 students in many countries and in at least 16 languages. It has been the subject of much scrutiny in the physics education community (see, for example, Henderson, 2002) and there were some minor revisions in 1995, but it remains the gold standard for assessing student learning gains in elementary Newtonian mechanics.

Mechanics Baseline Test

The Mechanics Baseline Test (Hestenes & Wells, 1992) is the semi-quantitative counterpart to the FCI. It is a 26-question multiple-choice test, but whereas the FCI requires no formal training in mechanics, success on the MBT can not be achieved without a certain mastery of the terminology and formalisms of elementary Newtonian mechanics. Hestenes & Wells note that though success on the FCI may not be sufficient to predict success on the MBT, it is a necessary precondition. The MBT was administered to all teachers attending the Modeling Workshops to assess their quantitative competency in elementary mechanics. The MBT is not as widely used as the FCI probably because many alternative quantitative assessments of student learning are available, unlike for the FCI.

Views About Science Survey

I have already described the Views About Science Survey (Halloun & Hestenes, 1996 – see Appendix 9) in some detail, above. One of the authors' purposes in designing this instrument, however, was to attempt to assess the impact of classroom pedagogy on students' views about science. In particular, Halloun & Hestenes hoped to "to measure the *effectiveness of instruction* in *changing* student views and profiles" (italics in the original). The survey measures the respondents' beliefs across three "scientific" and three cognitive dimensions. Halloun & Hestenes describe the scientific dimensions as "pertaining to the structure and validity of scientific knowledge, and to scientific methodology," and the cognitive dimensions as pertaining to “the learnability of science, reflective thinking, and personal relevance of science.” According to the authors, their unique “Contrasting Alternatives Design” resolves many of the potential problems associated with other types of instruments used to assess personal beliefs including respondents’ equivocation on Likert scales and researchers’ misinterpretation of essay questions. Halloun & Hestenes were particularly interested in measuring the impact Modeling Instruction might have on students’ views, but the surveys they administered between 1995 and 1998 to Modeling Workshop teachers and their students were inadequate for that purpose because of too much variation in the scores (other data collection problems complicated the analysis, as well). On other the hand, students’ profiles were strongly predictive of their success in introductory-level physics classes. That is, the more “expert” a student’s profile the more likely he or she would do well in physics. Since all my subjects had essentially “expert” profiles, I used responses to individual questions almost exclusively within the “scientific” dimension to compare and contrast teachers’ beliefs and to get more nuanced insight into their perspectives on the nature of science.

The VASS was substantially revised in 2004 and is still in use.

Modeling Instruction Survey

I have described the Modeling Instruction Survey (Halloun, 1998 – see Appendix 7) earlier in this paper. In this section I will list the 60 items from the survey I selected to generate a teacher’s MIS score and the rationale for my selections. The survey uses a traditional 5-point Likert scale spanning a range of choices from 1-“Regularly” to 5-“Never.” The large majority of questions ask teachers how often they engage in classroom behaviors consistent with the Modeling pedagogy (e.g., question 63: “Have students use whiteboards to present their findings in a laboratory experiment”), but a few are clearly antithetical to Modeling (e.g., question 56: “Spend more than a quarter of class period lecturing). (When calculating a teacher’s score, responses to items such as question 56 were reversed to maintain consistency.) The status of some behaviors, however, is not so easily determined. Therefore, I created a 3-tiered categorization scheme to aid my analysis. The scheme is based on data collected by Modeling program staff and my interpretation of Modeling practices. I later refined the scheme based on a statistical analysis of the pooled responses of my subjects.

Category 1 behaviors are “essential” to Modeling, that is, in complete accord with the principles and behaviors described in the section on Modeling Instruction in Physics, above. Category 1 behaviors often are unique to the Modeling pedagogy and are the behaviors one would expect to see in any Modeling classroom. Examples of Category 1 behaviors include (item 10) planning one’s instruction based on the models laid out in the Modeling theory, (item 5) expressing relationships among constructs qualitatively, and, of course, (items 64 – 67) activities associated with whiteboarding.

Category 2 behaviors may or may not be unique to Modeling, but, in any case, they are less critical to the pedagogy. This is not to say they are not important components of good *physics* pedagogy and failing to enact them entirely may diminish the learning experience for students, but they are not the exemplars of the Modeling pedagogy Category 1 behaviors are. Examples of Category 2 behaviors include (item 7) doing a dimensional analysis to set up or verify the units of a concept and (item 68) allowing students to prepare whiteboards according to their own preferences.

Finally, Category 3 behaviors are not at all unique to Modeling and fall into the realm of teachers' personal preferences that may or may not be enacted as the teacher sees fit. Examples of Category 3 behaviors include (item 17) using examples from the history of physics and (item 50) asking students to do error analysis in their lab reports. A teacher could choose *not* to engage in these behaviors and still be considered an expert Modeler (I observed both forms of behavior during my field research).

The table below is a listing of behaviors by category. The 49 items I used to aid my classroom observations were all the Category 1 behaviors plus several Category 2 behaviors I judged unique to Modeling (e.g., item 68 but *not* item 7). Only items from Categories 1 and 2 were used to calculate a teacher's MIS score.

Table 4

Modeling Instruction Survey Taxonomy by Category

Category 1	1,2,5,10,12.13,14,15,19,20,21,22,27,32,33,41,43, 45,56,60,61,62,63,64,65,66,67,69,81,82,86,87,94
Category 2	3,4,6,7,8,9,11,16,23,24,25,26,28,31,38,40,42,44, 47,51,55,57,58,68,84,85,88
Category 3	17,18,26,29,30,34,35,36,37,39,46,48,49,50,52,53, 54,59,70,71,72,73,74,75,76,77,78,79,80,83,89,90, 91,92,93,95,96,97,98,99,100

Participant Experiences Survey

The Survey of Participant Experiences (Halloun et al, 1997 – see Appendix 3) is an instrument designed to satisfy program evaluation requirements set by the Modeling program's funding agency, the National Science Foundation. The survey was administered immediately following a teacher's first year deploying the Modeling pedagogy (i.e., at the start of the second summer's Workshop). It combines multiple-choice and free-response questions covering six domains of teachers' practice: method (pedagogy), (use of) technology, content, assessment, classes (taught), and school environment. Generally speaking, the multiple-choice questions are intended to assess the extent to which a teacher engages in specific behaviors consistent with the Modeling pedagogy, but some questions also gauge participants' reactions to different aspects of the pedagogy. As might be expected, several questions in the method and content sections are similar if not identical to questions on the MIS, but most questions in the other sections have no counterpart on the MIS. The Participant Experiences Survey provides a broad overview of a teacher's practice which makes it a useful yardstick for comparing teachers. Since every teacher attending the second summer's Workshop completed a Participant Experiences Survey, as well as submitted student FCI scores for the previous school year, these were the best tools available to me for identifying potential subjects. I selected questions from every section of the survey except "Classes" that a) had a response from every teacher, b) were most indicative of a teacher's Modeling practices, and c) could be combined into a single composite score without second-level analysis. The included items were numbers 1-8 (items 4 and 6 were reversed), 10-13, 19, 23-25, 27-31, 42, and 43.

Reformed Teaching Observation Protocol

The RTOP (Sawada et al, 2000 – see Appendix 6) evaluates three dimensions of an enacted lesson from a constructivist perspective: its design and implementation; its content, in terms of the propositional and procedural knowledge presented; and the classroom culture it embodies through the communicative interactions that take place during the lesson and the character of the evident student/teacher relationships. The protocol determines the degree to which an observer witnessed constructivist-oriented, student-centered, inquiry-based pedagogy, that is, "reformed teaching" as defined by the Arizona Collaborative for Excellence in Teacher Preparation, for whom it was created. It consists of 25 multiple-choice questions scored along a continuum from 0-"Never Occurred" to 4-"Very Descriptive." Based on 287 classroom observations, Sawada et al (2002) showed that teachers' RTOP scores are highly correlated with the normalized gains on measures of student learning, including the FCI. As a result, many educational entities across the country, including the Modeling Instruction program, continue to use the RTOP to evaluate teaching.

Though the RTOP was not designed for the Modeling program, it is consistent with Modeling precepts in every regard. Thus, a "perfectly" presented Modeling lesson could score at or near 100 points. At least two caveats when using the RTOP to evaluate a Modeling lesson should be taken into consideration, however. First, the RTOP makes no provisions for the occasions when a descriptor is not applicable to a particular lesson. This is probably more an issue in high schools than at the college-level. For example, for students actively engaged in a lab activity the descriptor "student exploration preceded formal presentation" (item 3) may not apply until the next day's lesson. Thus, the perspicacious observer must be sure to enquire as to the progression of instruction so as to justify any alterations to the score. Second, the RTOP is not content specific, so the observer must be competent in the propositional and procedural knowledge intrinsic to the lesson.

Findings

Allan

Teacher	Modeling Instruction Survey		3-day RTOP Avg. %	Baseline Student FCI (spring '98) %	Long-term Student FCI Averages %		
	1999	2007			Pre	Post	Gain
Allan	***185/3.1***	***135/2.3***	***90***	***39.3***	***24.4***	***50.3***	***33.9***
Brian	n/a	148/2.5	80	43.7	35.8	66.4	47.7
Charley	n/a	149/2.5	70	49.7	n/a	n/a	n/a
David	n/a	130/2.2	84	35.0	37.8	65.8	45.0
Edward	145/2.4	96/1.6	71	n/a	30.4	72.0	59.8
Frank	168/2.8	114/1.9	87	41.7	26.0	52.4	35.6

Background

Allan heard about the Modeling Instruction program early in 1998, after about 22 years of teaching, including six years of teaching physics at his current school, and was intrigued by the program. During our extended interview he told me, "I was pretty sure they wouldn't teach me anything at the modeling workshop because I thought I had the physics instruction down pretty good, but I thought it would be fun to be around the other physics teachers so I signed up for it." Allan remarked also that the availability of a grant that would cover most of his expenses and provide a stipend made it especially attractive. He was an active participant at the Workshops and "it turned out that there was much I could learn about teaching physics." In fact, he goes on to say, "If I had been taught this way in high school, I would have probably been a physics major instead of a math major."

As science department chair at the time, Allan experienced no interference as he implemented Modeling in his classes.

> When I started doing Modeling I was department chair, so that really wasn't an issue, and then we kind of rotate the department chair around. As long as my students are learning and they're testing reasonably well people pretty well just leave me alone, they don't have any thoughts on it.

On the other hand, he does report complaints from students:

> During the first year I taught Modeling physics students expressed significant resistance to not receiving direct answers to questions. In the second year of modeling instruction there was still some resistance to Socratic questioning.

With respect to his own initial experiences with Modeling, Allan said,

> …when I came back and tried the Modeling, I thought it was difficult asking the questions, it seemed really to bog down the class, we weren't getting anywhere, but I kept digging in…and probably midway through the first semester I was

> perched right on the verge of saying I'm going to trash this whole thing and we're just going to get our books out and we're going to work out of the books because I know that works. Then, for some reason, I seemed to start getting a little better asking questions. I didn't have to put quite so much effort into figuring out the questions I needed to ask; the classroom seemed to move along a little more efficiently and so I decided to stick with it.

Allan, as did four of my six subjects, also said he most likely would not have adopted the Modeling pedagogy without the completed mechanics curriculum. But, he goes on, “Even with the curriculum, I almost gave up on the pedagogy after trying it for three months. Only faith in the Modeling leadership made me stick with it.” So, it seems both the credibility of the Modeling program staff and their research data as well as a fully developed set of curriculum materials were vital to Allan’s motivation to persevere with his efforts to implement Modeling. But persevere he did and now he “cannot imagine going back to the old learn from the lecture method.”

Allan’s school is a medium-sized (about 1600 students), comprehensive public high school but it has no designated attendance area. This means that students and their families come from across the city and make a conscious choice to attend this school, presumably because they buy into the school’s mission statement of “high expectations, ethics, and academic standards;” what’s more, they must sign a contract to that effect. The school is academically well-regarded and the students are among the top 15% on the state achievement tests. The demographics of the school are 74.9% white, 12.5 % Hispanic, 4.9% Black, and the rest are Asian and Pacific Islanders and Native Americans. These percentages are not far from the demographics for the county in which the school is situated except that Blacks account for 10.5% of the larger population. About 49% of the students are girls and 14.7% of the students qualify for free-or-reduced lunch. With respect to Allan’s classes there were 11 boys and 17 girls, all white, in his AP(B) class; 7 boys and 15 girls, 2 Blacks, in his conceptual physics class, and 47 boys and 32 girls, 4 non-white, in his three regular physics classes. Each regular physics class has between 3 and 6 more boys than girls.

Observations

Allan’s classroom is rather long and narrow with lots of natural light from two banks of windows along the long sides of the room. In the front of the room is a traditional demonstration bench behind which is a large whiteboard. Student benches, unfixed, are in front of the demo bench and 4 large worktables are in the back of the room. Eleven computers of various vintages with PASCO interfaces sit on countertops along the perimeter of three sides of the room. Lab equipment is located in cupboards underneath the counters and demonstration equipment fills glass-fronted cabinets above the countertops. Students are crowded when they are at the computer workstations but there is plenty of room available at the worktables for preparing whiteboards. Allan has a mesmerizing rotating helix mobile hanging from the front ceiling and various science posters on most of the available wall space. Also on the front wall of the classroom is a placard with words like “oomas” and “yorts,” which are student-created units of measure concocted during a lesson early in the year. Each class begins with a “hot sync” (warm-up) problem relevant to today’s or yesterday’s lesson.

My first day's observation in Allan's 4th period regular physics class (and similarly for 5th and 6th periods) opened with a hot sync problem which was to draw a force diagram for a ball undergoing uniform circular motion (corresponding to Phase 2: *Nominal Models* in Unit 8 of the Modeling curriculum). After the students wrote down their answers, which Allan dutifully checked and recorded on the spot, he led a class discussion using a ball-on-a-string prop by asking questions about the forces at various points along the ball's orbit. Allan accepted just about any student response which he then would paraphrase and repeat as a question – "So, you're saying the force is…? So the ball must be behaving in such and such a way, right? Oh wait, it goes this way." This continued until there was a general consensus, supported by Allan's tacit agreement, about the disposition of the relevant forces.

Allan next spelled out the procedure for conducting a virtual lab on uniform circular motion using the "Interactive Physics" software application (corresponding to Phase 5: *Model Formulation*: Investigation and Initial Model Formulation). This was a follow-on activity to a qualitative hands-on paradigm lab that the students had completed previously. The computer program was set up so that students could adjust the variables more or less as they saw fit so as to obtain "data" separately for the centripetal force vs. the speed of revolution, the mass of the object, or the radius of the orbit (length of the string). It seemed to this observer that the level of engagement was inversely proportional to a student's distance from the keyboard. However, most groups in all three periods finished collecting data in anticipation of preparing whiteboards tomorrow.

The day's hot sync problems focused on mathematical manipulations of exponential functions anticipating the relationships to be developed between the variables in the previous day's virtual lab. Immediately following the hot sync activity students proceeded to prepare whiteboards of their lab results. Allan was sitting at the back of the room grading student lab books and responding to questions about the lab and the whiteboards, but in any case it was clear that students were familiar and comfortable with this arrangement and several students seemed appreciative of the quick feedback this system affords. Allan told me later that he had come to this procedure late in his career and has found it to be just as effective as his old style of grading and a lot more efficient.

The whiteboard presentations began about 20 minutes into the period. The students arranged themselves in a rough circle around the room and began the presentations with a simple recitation of the mathematical relationships they had found by graphing and fitting the data for each pair of variables (F vs. v, F vs. r, and F vs. m) using the "Labpro" software. The graphs themselves were crude and qualitative, but each one had a corresponding numerical equation. No questions were asked at this time. Allan then said, "Ask yourselves any questions you want then I'll ask some questions." The students asked a few perfunctory questions (e.g., "What are the units of the slope of your graph" and "Is there a y-intercept?"), as did Allan. Next, he directed students to look at the other boards for agreement about the shape of the graphs: "Hold up one finger if graphs agree, two if not" – most students held up two fingers. He then summarized the degree of agreement graph by graph. There was general consensus on all the graphs except for one group's F vs. r graph, for which they had depicted a negative linear relationship when it should have been an inverse relationship.

Allan next directed students to write on their whiteboards a single equation for the centripetal force that combines the information from the three separate graphs, but he also told them to leave the slope unspecified. Most groups were able to derive the fundamental relationship, $F_C \propto mv^2/r$, after which Allan instructed them to multiply two of the three fit constants they generated in "Labpro" and compare the product to the slope of the third graph. Given that students had "perfect" data they found that the overall constant of proportionality was 1. Allan then summarized these findings on the front whiteboard and made the connection to $F_{NET} = ma$ in order to derive centripetal acceleration, $a_C = v^2/r$ (corresponding to Phase 6: *Model Formulation*: Rational Model Extrapolation). He next defined centripetal force as the net force that makes something move in a circle and thereby specified the essential feature of the central force particle model. Finally, Allan passed out Unit 8: Worksheet 1 (corresponding to Phase 7: *Model Deployment*: Elementary Deployment) and gave a short lecture that addressed the perennial confusion shared by many students: an object undergoing uniform circular motion is accelerating not because of changes in its speed but instead because of changes in its direction of motion. However, Allan was not able to reach this point, concluding the lab and passing out the worksheet, in either 5th or 6th periods in part because there was far less consistency and agreement in the whiteboards for the virtual lab. This necessitated a lot more direct questioning (e.g., about which is the independent variable and which the dependent variable, choice of units and scale for each axis, etc.) on Allan's part to try to resolve students' misconceptions, consequently a final resolution was left for the next day.

The hot sync problem for my last day of observation concerned a uniform circular motion calculation. Allan decided to have his 4th period students whiteboard the worksheet. This is somewhat atypical among Modelers because worksheets, especially early in a unit, generally include the sorts of questions a teacher would ask during a whiteboard session and usually contain only one or two scenarios for consideration. A typical whiteboard problem set has several problems illustrating different aspects of the model under consideration. Allan did something else unusual with the assignment. He informed the class that each student group must whiteboard the problems associated with the first of the two scenarios on the worksheet but that he would pick one board at random (by rolling dice) for which the entire class would receive a grade. Before presenting their board, however, the selected group was free to consult with the rest of class and make any changes to their board until such time as the group indicated they were ready for their presentation. Almost the entire class was enthusiastically engaged in their work and some of the conversations among the students were quite animated. Allan's only role during this period was to mediate the conversation because so many students were trying to speak at once. The final product and presentation were nearly flawless and no one in the class ever asked what grade they had earned.

The situation was quite different in 5th and 6th periods. Fifth period finished up the virtual lab but in this class Allan gave students the choice of individually completing the worksheet or working in groups to prepare a whiteboard. My observation was that the groups seemed somewhat off-task until and unless Allan checked in with them, but by the end of the period most students either completed the assignment or had a completed whiteboard for presentation next class. Sixth period also had to finish the virtual lab but they had somewhat more difficulty than the other periods resolving the coefficient on the final equation. In this class students were not required to whiteboard the worksheet and Allan went carefully over the first problem which was to create a motion map (vector diagram) for a car driving over a hill at constant speed. He told me later that he was reacting to the difficulties 5th period had had with this task.

Assessment

When he applied to the Modeling program Allan evidently was not seeking to significantly change his practice believing that, "I had the physics instruction down pretty good." Furthermore, in his application letter to the Modeling program Allan said that his "personal project this year was to establish a questioning method that would allow me quickly to probe student understanding" and that "the project has been quite successful." On the other hand, in his interviews with me Allan recounted his near-death struggles with managing classroom discourse in his first few years of Modeling. I did not ask Allan about the differences between his previous questioning techniques and Modeling, but despite these initial challenges Allan clearly has developed a comfortable and efficient teaching style. He pointed out to me on more than one occasion that Modeling shifts the burden of work away from the teacher and on to the students where it belongs:

> I find now the students are working really hard and I'm not having to work nearly as hard as I used to and if I had continued teaching physics the way I had before I just think it's a major burnout because the students are coming in, you have to tell them how to do the same thing five times and, you know, when you have 20 or 30 students coming in it just burns you out, it takes, it burns a lot of time, whereas in Modeling all of a sudden it's on the student to learn and so that's much better, they learn and it's easier on the teacher.

It is interesting to note that Allan's views on this issue seem to have evolved. Questions 5 and 6 on the VASS are as follows:

> My score on physics exams is a measure of how well:
> (a) I understand the covered material.
> (b) I can do things the way they are done by the teacher or in some course materials.
>
> For me, doing well in physics courses depends on:
> (a) how much effort I put into studying.
> (b) how well the teacher explains things in class.

In both cases Allan selected choice 4, the "mixed" response, which indicates that he generally would share the responsibility for learning more or less equally between teacher and student. His remarks above, on the other hand, suggest that Allan now believes the Modeling pedagogy correctly shifts the burden of learning more onto the student. Allan was the only subject to hold a mixed view on these questions. Four of the six teachers selected choice 1 or 2 on question 5 and the remaining teacher selected choice 5. On question 6, all the other teachers selected choices 1 through 3. Of course, Allan strongly believes that his students are learning physics better as well:

> I think the students learn a lot. The students come back, that have had me, come back and tell me when they go to college they're telling everybody else how to do physics; they know how to do it, they remember it.

Moreover, about 90% of Allan's students pass the state physics end-of-course exam (taken in the junior year) and his long-term student FCI scores compare favorably with other Modeling teachers, especially when one takes into account their relatively low pre-test scores.

However, it was Allan who I quoted in the introduction:

> Scientists believe that numbers represent the truth. Scientists get their numbers from measuring things and then they try, they use different techniques to evaluate what those numbers mean. We do that because we can make good predictions with numbers that are useful to us, they enhance our health, our welfare, and so this is something important to study and learn about because we're interested in our health and welfare.

This sentiment, expressed during the extended interview, would seem to be antithetical to a constructivist philosophy, as appears to be the case with the following comment Allan made in response to a question about his role as a science teacher:

> The role of the science teacher is to provide students with an opportunity to learn about collecting numbers and data and applying that to a variety of situations, life situations or physical situations, that allow students to understand how science works, and to possibly give the students a career in science if that's something that they elect, but certainly to make them knowledgeable about science and the world around them.

Again, there is nothing here that suggests Allan might see his role as, say, Brian does, who sees his students' pursuit of scientific knowledge as a "journey" and himself as a "guide," or like Frank, who describes his role as one of "helping the students make those same connections, build those same models." A careful review of Allan's observed classroom practice confirms this ambivalence. His questions were more procedural than conceptual (e.g., what is the slope of your graph, what are the units of the horizontal axis, etc.) and he lectured, albeit briefly, more than once. Except for the once instance where, by Allan's own admission, he deviated from his normal practice to let one class collectively prepare a whiteboard, this behavior was consistent across all his classes. My sense is that Allan, despite the fact that he takes nearly three-quarters of the year to complete the "first semester" mechanics curriculum (or maybe precisely because of this), feels pressured to "move on," and will sometimes sacrifice opportunities for deeper student engagement for efficiency's sake. Of course, the mere fact that Allan now uses whiteboards and questioning represents a significant departure from his previous didactic teaching style. Allan made a professional decision to adopt the Modeling pedagogy, in part, because he had made a commitment to the Modeling program as a condition of the acceptance criteria, but also because he perceived it as *potentially* more effective than his traditional teaching style. I conclude that as a result of his participation at the Modeling Workshops and his subsequent implementation of the Modeling pedagogy, Allan has experienced a conceptual restructuring of how students learn physics and thus how to teach physics. He did not experience such a restructuring with respect to his understandings of the nature of physics as a discipline.

Notwithstanding the above, that Allan now is comfortable with the Modeling pedagogy is confirmed by the significant changes he reports in his pedagogy via the two Modeling Instruction Surveys he completed in 1998 and 2007. There are fourteen “essential” Modeling activities for which Allan’s responses shifted from a 5 (“never”) or 4 (“seldom”) to a 1 (“regularly“) or 2 (“often”), several of which he has in common with the other two teachers for whom I have MIS data for both years. The “common” activities include items 63 through 67 which relate to whiteboard presentations, as would be expected for Modelers. Among the other items are: expressing various constructs qualitatively (item 5), using agent-object notion in describing forces (item 15), having students figure out the relevant independent and dependent variables in a scenario (item 43), and *not* assigning typical textbook problems as homework (item 51). Allan’s very high (in retrospect, possibly too high) RTOP scores of 90, 84, and 96 also are indicative of his assimilation of the Modeling pedagogy as is his active presence on the Modeling listserv.

Brian

Teacher	Modeling Instruction Survey		3-day RTOP Avg. %	Baseline Student FCI (spring '98) %	Long-term Student FCI Averages %		
	1999	2007			Pre	Post	Gain
Allan	185/3.1	135/2.3	90	39.3	24.4	50.3	33.9
Brian	***n/a***	***148/2.5***	***80***	***43.7***	***35.8***	***66.4***	***47.7***
Charley	n/a	149/2.5	70	49.7	n/a	n/a	n/a
David	n/a	130/2.2	84	35.0	37.8	65.8	45.0
Edward	145/2.4	96/1.6	71	n/a	30.4	72.0	59.8
Frank	168/2.8	114/1.9	87	41.7	26.0	52.4	35.6

Background

For the first four years of his tenure, Brian's assignment was physics and honors 9th grade physical science. He describes his teaching style during this time as "non-traditional but not very progressive." He had contacts with other teachers in his district who were working with Jim Minstrell, a long-time physics teacher from the Seattle area and a co-developer of the DIAGNOSER physics instructional web-application (see http://www.diagnoser.com), so he "tended to look at things a bit differently," but still relied on the textbook and a lecture format for his pedagogy. Questions to the class were rhetorical and students did not work in groups. He told me that he had had a general dissatisfaction with the way he taught, prompted in part by his discussions with these other physics teachers, but he did not feel "equipped" to make the appropriate changes. In his application letter to the Modeling program, Brian said that "one area that has been the cause of some concern for me has been a feeling that my students don't fully engage the material that we are studying" and "seem to be rather formula centered." Despite his somewhat traditional teaching style, Brian's predisposition with respect to lab activities was clearly constructivist because he goes on to say, "I don't give the students a set procedure or expected results, but rather tell them I would like them to investigate the relationships between several quantities." Brian's desire to see his students actively engaged in learning physics and conducting discovery versus validation lab activities seems to anticipate some aspects of Modeling.

In 1997, Brian entered the MAEd program at the same university where he had earned his bachelor's. The program required that he take a methods course appropriate to his discipline, but because the university did not have anything really suitable during the summer sessions, Brian's graduate advisor recommended he attend the Modeling Workshops for which he would receive full credit towards his degree. Of his workshop experience Brian says:

> You know, it sounds really corny but I've got to say… my workshop was like an old-fashioned tent revival. I went there seeking something – what, I didn't know. When I got there, it's like, oh my gosh, this is it, and if this isn't it, this is as close as I've ever seen to it, whatever it is. I can honestly tell you that I'm not anything like the teacher I was before nor could I ever go back to being that person.

The clincher, Brian says, was the changes he saw in his students.

> …but the thing that sold me and I'll remember, I can actually remember the mo-

> ment, was in studying projectiles. I had taught projectile motion, had spent a couple, several weeks talking about projectile motion, I'd demonstrated projectile motion, I have all this equipment for demonstrating projectile motion, and I would give the most lucid lectures and demonstrations and everything I could about projectile motions and in the end my students didn't really seem to have that much of an understanding about the way projectiles move. So, in Modeling first year, 98-99 school year, we did Unit 6, we'd been, I'd been following through, doing the best I could following the practices, my students, we did the unit, the paradigm lab, the projectile motion and using the video camera, although at that time I didn't have video analysis software so we just used photographs that we'd captured, measured, and kids drew graphs, and this group was presenting and they go, "Hmm, well we got a straight line on the x-t graph, we got a curved line on the y-t graph, so we knew it was accelerating in the y-direction but not in the x-direction; well that makes sense because gravity's only acting in the y-direction and so, yeah, it's moving with a constant velocity in the x-direction and its accelerating downward in the y-direction." I said, "What, really?" They said, "Yeah, we get that." I asked a couple of questions and like they really had it. So what that really meant in the end was my kids got it when I modeled and they didn't get it when I didn't.

Brian has been "a real sort of diehard Modeler ever since." So much so that for the past several years Brian has been very active in developing and sustaining an online Modeling community of practice (separate from the Modeling listserv) and working with his district's science curriculum coordinator to get Modeling adopted as the district's approved physics curriculum.

Brian began using the Modeling pedagogy during his fifth year at his school and it was not well received initially by his students or his colleagues in the science department. Brian said better students felt the pace was too slow and became impatient for Brian to just tell them the answer – a problem he still faces. These are the students he calls "cave kids."

> …you could put this kid in a cave in September with a physics book, you could come back in June and take them out, and give them a test, and they probably could pass any test you gave them because they are already high level thinkers and they have the ability to process information and build models; they don't need my help to do it…

Following the advice of a long-time Modeler from Arizona, Brian now has a "physics open house" early in the year to introduce parents to the Modeling curriculum and pedagogy. The open house seems to have been particularly effective and Brian says the parents are very appreciative.

> In fact, some of the hostility that I was getting from my department stopped after the first time I did that. When my principal, the old principal, came here and saw 60 parents come for a physics night, his attitude towards what I did changed. So it also may have been the first time I had a chance to explain to him what Modeling was about.

Most of his departmental colleagues, then as now, were and are indifferent to whatever pedagogy Brian's employs even though he has taken the time to describe Modeling and his success with it. "Perhaps it's even evolved to the point of we don't care and we don't want to know; so beyond indifference, a little bit to the rejection side." However, both the assistant principal (for instruction) and his department chair were openly hostile to Modeling, though neither individual required that he change his practice. Brian had even heard from a reliable source that the assistant principal wanted to replace him. Most of their misgivings seemed to be of the same type I heard from my other subjects: student complaints that because Brian rarely directly answers questions and doesn't use a textbook, he must not be teaching. "Neither of them had ever asked me about Modeling, I don't believe that either of them had any real notion what I was doing, they just didn't like it, and I don't know why." Brian weathered that storm and, until recently, has experienced the same benign neglect that my other subjects have reported.

But there has been a recent thaw at Brian's school. Brian describes this in a conversation he had with the current (new) assistant principal:

> In one of the four school faculty meetings before we even started for the year (last year), we talked about some of the goals that they wanted for the school and things of that nature and I went up to [the AP] afterwards and said, "OK, I feel like I have a lot to offer here that's not being tapped. I've been to two Modeling workshops for four weeks each at [a west coast university], 120 hours each, I've gone back to ASU," at that point it'd been like three times, I said, "I've done a lot of this work and I have a lot to share, have a lot of ideas and things that I've learned that I think are consistent with your goals for this school, but I'm not being utilized, and I just want to tell you that I want to share, I want to help, please allow me to do that if I can be of any help." So he said, "Yeah, OK, that's fine." But, nearly a semester went by where that never came up again and then in one of those moments that you never can predict, I stopped by his office one day, for what I don't know, and we sat down and chatted, and I started describing to him again that I really did have something I wanted to share and it's based on my Modeling and he asked, "Well, what was that?" Well, that's a big mistake to ask me about that, so I told him, and I started describing to him what Modeling was and how it was used and how it's effective, I started telling him about, you know, things like my FCI scores pre- and post and how they compared with non-Modeling schools and why I thought that they were consistent with the goals of our school and our state and, you know, anybody that's trying to educate kids, and that conversation lasted until nine o'clock at night, we sat in his office until nine o'clock at night. From that [conversation] was born this idea, gee, how can we actually try and promote this then.

The assistant principal now is an enthusiastic supporter of Modeling and aided Brian's efforts to send a departmental colleague to a Modeling Workshop. While the rest of his departmental colleagues still are more or less indifferent to his pedagogy (as, I suspect, he is of theirs except that they are not using Modeling), the support of the assistant principal as well as the district's science curriculum coordinator, after similar prodding from Brian, has given Brian the confidence to push for widespread adoption of Modeling in his district. Modeling is now being used in three of the five high schools in the district and, Brian says, “recently came very, very close to being approved as the district’s physics curriculum.” The struggle continues.

Brian’s high school is in a middle-class part of the city, the major metropolitan area of the region. The school has about 1800 students and is noted for its academics as well as for its very successful athletics and music programs. Brian even complained to me that he often has very small physics classes during the various state athletics championships and holiday musicals because so many of his seniors are either participants or enthusiastic spectators. As reported by the state department of education, the student demographics for the school are 52% male, 48% female; 87.1% are white, 3.8% Black, 2.6% Hispanic, 4.1% Asian, and 1.6% American Indian. These numbers are reflective of the metropolitan area in which the school is situated. About 26% of students are eligible for free-or-reduced lunch and the graduation rate is 81%. The demographics of Brian’s classes are nearly identical to the school’s which means, at most, one or two students of color in any physics class. The ratio of males to females is at least 2:1. For his 10th grade science class, however, the ratio is about 3:2 females to males and more students of color (every student has to take 10th grade science whereas physics is an elective course).

Observations

When I observed Brian his schedule included three periods of regular physics and one period each of “second-year” physics and 10th grade integrated science. Second-year physics is just that, a second year, and Brian, the only physics teacher in the school, does not consider it an honors class though most of the students in the class are concurrently enrolled in pre-calculus or calculus and, therefore, represent a population normally associated with honors or AP-level classes. The school also offers a second-year chemistry class and an AP biology class but neither AP physics nor chemistry. All the students in the second-year courses are seniors. I did not probe the school’s rationale for second-year versus AP courses, but I was told that the decision was deliberate. One consequence of the second-year physics course, however, is that it affords Brian the luxury of time. That is, he does not feel compelled to rush through the curriculum in the first-year course and takes at least three-quarters of the year to complete “first semester” mechanics.

Brian teaches in a very traditional physics classroom with a large demonstration bench across the front of the room and a raised platform behind the bench and in front of sliding blackboards. He has also installed hooks above the blackboards and around the room for hanging student whiteboards. Students sit at fixed benches and little space remains around the perimeter – an arrangement not particularly conducive to group labs. Brian has acquired about 10 Macintosh computers on rolling carts so the students can create group work areas on or around the benches. During one circle whiteboarding session I observed, students perched themselves on the benches or to one side in order that every student could view the whiteboards. Thus, like other teachers in this study, Brian found various ways to accommodate his Modeling pedagogy to a distinctly Modeling-unfriendly physical plant.

My observations began on a Monday morning during mid-third quarter by which time the class was about a third of the way through Unit 7: Energy. Working in groups, students were to prepare a whiteboard for an assigned problem from Unit 7: Worksheet 3a completed over the weekend (corresponding to Phase 5: *Model Formulation*: Initial Model Formulation). This worksheet presents students with a variety of scenarios depicting different systems' initial and final parameters (e.g., height, speed, or, in the case of some elastic component, stretch length). By employing the principle of the conservation of energy, students are to indicate on bar graphs the relative magnitudes of the various forms of energy for the initial and final states shown in the scenario (i.e., gravitational potential, kinetic, and elastic potential energy). Thus, the students' job really is just a bookkeeping task, that is, to balance a system's energy accounts. No formulas are required. Student misconceptions are typically manifested in the failure to ensure that the system's final energy equals its initial energy and in decoding the parameters specified in the scenario so as to properly apportion energy among the various categories.

It took only about 10 minutes for the students to obtain, clean, and prepare their whiteboards. During this time Brian circulated around the class checking student worksheets for completion. He asked one student, "On a scale from 1 to 10, how prepared do you feel?" The student replied, "I'm not sure about one problem, so 8." Brian then advised two groups by asking them probing questions about their whiteboards. He kicked off the whiteboard presentations by announcing to the class, "Let me just express the idea that there can be different ways for these bar graphs to look depending on how you defined your system and initial conditions. Ask them questions about anything you're not sure about."

It was clear to this observer that students were very comfortable with this mode of classroom discourse and had a well-developed sense of the teacher's expectations. After the first group's initial presentation the first few questions to the group were from other students. Brian jumped in with a couple of probing questions which were followed by more questions from the student audience. Brian closed the first presentation by reminding the class that the different representations of the problem must be consistent with the given scenario. There was little student interaction for the next problem. Most of the discussion was dominated by probing questions from Brian who would wait as long as necessary for a response from the presenters, though he sometimes rephrased a question if a response was not forthcoming. There was much more student interaction with the third group, and, at one point, Brian stepped in to moderate the discussion as the student presenters were trying to manage three simultaneous lines of questioning from the audience. Brian's questions then seemed to be directed at the entire class and not just the presenters. The scenario is a car at the bottom of a hill with $v_0 > 0$ that then comes to a stop some distance up the (frictionless) hill:

> S – How does it [the car] stop if there was no friction?
> T – If energy is the ability to cause change, can the car at the bottom of the hill and not moving experience a change in this case?
> S – No.
> T – Can we say that the initial gravitational potential energy is 0?
> S – Yes.
> T – What force is transferring energy from kinetic energy to gravitational potential energy?
> S – Gravity.
> T – What brings the car to a stop?
> S – Gravity.

Six of nine groups had presented by class's end and while there were some insightful questions posed by a few students, Brian continued to dominate the discussion by asking both directed and undirected questions.

The discourse in Brian's other two regular physics classes was much the same, though Brian did take time to revisit the concept of the energy flow diagram that had caused some confusion in the first class. I had the sense that students were more than familiar with Brian's style because it seemed to me that some of the students had settled in for the long haul (which is to say they were reasonably attentive but not actively participating), well aware that Brian would not move on until he was satisfied with the responses from the student presenters. In none of the three classes did whiteboard presentations get past problem 6 out of the total of 10.

I had also observed Brian's second-year physics class, his first class of the day. In this instance, each student group prepared a whiteboard for the same problem (in magnetostatics). Whiteboards were presented in a circle fashion and, initially at least, the discourse was among the students. As in other classes I observed, Brian's interaction with the various groups was strictly through questioning until the relationship between the variables in the problem was (reasonably) well established. Brian similarly used whiteboards and questioning in his 10th grade integrated science class in a lesson on phenotypes and genotypes (Punnit squares).

The next two days' lessons centered on a virtual lab similar to the one in Allan's conceptual physics class using the "Excel" spreadsheet application. Brian's goals for the lesson were: 1) to develop some sort of quantitative relationship between the gravitational potential energy and the consequent kinetic energy of a falling object; and 2) to introduce students to the "Excel" spreadsheet application (continuing Phase 5: *Model Formulation*: Initial Model Formulation). Only five or six students confirmed that they had previous experience with "Excel," but with a few simple oral instructions from Brian and a quick demonstration (via LCD projector), students soon were generating "data." The thrust of the lesson was the previously constructed concept of the conservation of energy. Thus, students had no apparent difficulty accepting the premise that the initial gravitational energy of an object released from some height is equivalent to the final kinetic energy the object develops just prior to hitting the ground (neglecting air resistance and the like). Students entered formulas in the spreadsheet to calculate the energy stored gravitationally as a function of height for 50 different heights, equated these value to the kinetic energy, calculated the final velocity similarly (using kinematics), and then plotted the kinetic energy vs. the final velocity. Of course, the resulting graph is parabolic. The final step was to "linearize" the graph by re-plotting the kinetic energy vs. the *square* of the velocity. If correctly plotted and interpreted, students should have been able to deduce that the slope of this graph is one-half times the value of the (constant) mass they had entered in the spreadsheet.

The following day, students completed their spreadsheets and drew both the kinetic energy vs. velocity and kinetic energy vs. velocity-squared graphs on a whiteboard and wrote an equation for the linear graph. Whiteboards were presented in a circle fashion and most of the discussion initially was among the students but it was confined to simple descriptions of their choices of variables and of their graphs. No group had derived an appropriate equation for the linear graph (nor, for that matter, did every group prepare a properly linearized graph). At this point, Brian prompted the class by asking if everyone agreed that the kinetic energy was proportional to the square of the velocity to which there was general agreement (corresponding to Phase 6: *Model Formulation*: Rational Model Extrapolation). Most groups were consistent in using $J/(m/s)^2$, that is, units of energy vs. velocity squared, for the slope of the linear graph, but Brian had to do the reduction from these units to kilograms (mass). Even though it was now evident that the units of the slope were units of mass, no student group was able to connect this slope with their hypothetical mass. Brian asked in an obviously rhetorical fashion if the slope was equal to one-half the mass. Given this fact, several student groups then were able to generate the final equation ($E_k = 1/2mv^2$).

Brian followed the whiteboard session with a deployment activity (corresponding to Phases 7 & 8: *Model Deployment*: Elementary and Paradigmatic Deployment). He drew a diagram on the board of a problem taken from R. Gibbs' *Qualitative Problems for Introductory Physics* that shows two objects of equal mass at different positions up a frictionless incline. Students were asked to consider the gravitational potential energy and the kinetic energy of the two objects at $t = 0$ ($v_0 = 0$), when the lower object has reached the bottom of the incline, and when both objects have slid down the incline and now are sliding on a frictionless horizontal surface. Brian initiated the discussion by saying, "Let's hear somebody address the initial condition. How many of you agree/disagree/ don't know" (that the objects have different gravitational potential energies, but equal kinetic energies)? One student disagreed, "Don't the objects have the same weight?" Another student pointed out the first student's confusion between force and energy. The rest of the discussion was fruitful and mostly among the students.

Assessment

Brian is an easy-going fellow with a sense of humor and near infinite patience when it comes to learning – but not misbehavior. He enjoys teaching and feels he has found his calling. He thinks about his practice constantly and is a true believer in Modeling. He took an "advanced" Modeling course and has worked with the Modeling Instruction program staff developing Modeling curriculum in chemistry and biology. Brian's Modeling perspective influences his pedagogy in all his classes. He is very aware of and sensitive to student "commonsense" conceptions and is always respectful of such alternative conceptions during class discussions. Brian is quite adept at asking probing questions and knows how to guide the conversation. However, he does tend to dominate class discussions, but, again, only by asking questions, and he waits for responses to the questions. Brian speaks passionately about Modeling and sees it as his mission to convert the "heathens." He is not a fanatic, however, and is well aware of the forces arrayed against his quest. He loves to talk shop and is a mentor teacher for a new teacher at a nearby high school who once was a student in his class. His mentee has had just a week of Modeling instruction and Brian is pushing to get the new teacher to take the full workshop sequence. He also helped another colleague in the school take the workshops.

Brian, like most of my other subjects, can be considered an "early adopter" of Modeling. He was in the third cohort of the Modeling Leadership Workshops, as were my other subjects, but unlike some of them he was actively looking to change his practice. Recall that in his application letter Brian expressed concern about the level of student engagement in his classes and mentioned also that he employed discovery labs. Brian was thus purposefully seeking out a pedagogy that would accommodate his teaching goals and, evidently, found it. His receptiveness and subsequent devotion to Modeling, therefore, come as no surprise.

In terms of his Modeling pedagogy as I observed it and he reported via the Modeling Instruction Survey (MIS), Brian is less likely than my other subjects to show how a construct (model or part of a model) applies in different contexts, which is to say he is somewhat more likely to present the models piecemeal and not emphasize them as part of a larger theory of Newtonian mechanics (MIS). He is at the mid-point of my subjects on nature of science (NOS) questions from the MIS suggesting that his views are also mid-way between empiricist and constructivist perspectives. This was confirmed in the extended interview. For example, in response to the question, “How would you define science and scientific knowledge?” Brian said, “I think that nature is what it is, that is, I think that there is, if you want to go with a truth with a capital “T” or a lowercase “t,” things are the way they are.” But he also said,

> If you're asking me if I'm more of a builder of knowledge through a constructivist approach to scientific knowledge, or am I more of a you should just get this out of the book and learn what it is, (then) there's no question there, I'm not in the middle. I have stacks of brand-new textbooks that have never even been opened. You need to engage and experience it, that's how you uncover it. You uncover science, you don't read about it.

On the other hand, Brian holds only expert views on the NOS portion of the VASS (the only subject to do so), which is consistent with his commitment to a constructivist pedagogy, as is the fact that he is the least likely of the subject teachers to use a textbook. Brian scored in the middle on the Participant Experiences survey (a 2.0 average on a 1 to 5 scale, where the range of scores is from 1.52 to 2.43), which I consider to be an indication of his initial struggle mastering classroom discourse. Brian’s student long-term FCI scores, both in terms of the normalized gain as well as average score, are the second highest among my subjects and compare favorably with scores from across the universe of Modeling teachers.

I gave Brian an RTOP score of 91 on the first day of observation, noting particularly the clear expectation among students that he would wait as long as necessary for answers to his guiding questions, his well-tuned ear for student misconceptions, but also the fact that he tended to dominate classroom discourse, albeit strictly through questioning. The next day’s score was only a 73 because students were involved mostly in generating virtual data via an Excel-based simulation in anticipation of presenting their “findings” during the following class and the only student-directed input in the lesson was a choice of the mass of the object under test. Thus, given the preliminary nature of the lesson, there were few opportunities for student-directed discourse or student generated hypotheses. The third day’s score was still “only” a 77 because the simulation did not allow for much in the way of student exploration of alternative conceptions and problem solving strategies (but surely much more than would a lecture). Moreover, many students got lost in their attempts to generate the quantitative relationship between the variables and never were able to derive it until Brian stepped in with revealing prompts.

Charley

Teacher	Modeling Instruction Survey		3-day RTOP Avg.	Baseline Student FCI (spring ‘98)	Long-term Student FCI Averages %		
	1999	2007	%	%	Pre	Post	Gain
Allan	185/3.1	135/2.3	90	39.3	24.4	50.3	33.9
Brian	n/a	148/2.5	80	43.7	35.8	66.4	47.7
Charley	***n/a***	***149/2.5***	***70***	***49.7***	***n/a***	***n/a***	***n/a***
David	n/a	130/2.2	84	35.0	37.8	65.8	45.0
Edward	145/2.4	96/1.6	71	n/a	30.4	72.0	59.8
Frank	168/2.8	114/1.9	87	41.7	26.0	52.4	35.6

Background

Charley is a member of a local “physics alliance,” that is, a group of physics teachers, university professors, two-year college instructors, and industry professionals that meets several times during the school year to talk about all things physical. Teachers can give and get answers to content questions, share or refine a lesson, get help with or ideas for demonstrations and lab activities, triangulate their curriculum with the two- and four-year college instructors, and even talk about physics education research. It was at one such meeting in the course of his 16th year of teaching that Charley heard a presentation about Modeling from a teacher who had gone through the pilot Workshops. One of Charley’s best friends, another physics teacher from a nearby district (and one of my subjects), was at the same meeting and the two of them were sufficiently impressed that they decided to apply to the program. In his Modeling Workshop application letter, Charley said that despite the positive student comments mentioned above,

> …I am ready to embark upon a different approach to physics instruction. I think it’s time for my students to become more responsible for their instruction and for the physics curriculum to become student-centered. It seems that that the Modeling Theory of Instruction will provide a curriculum that will allow my students to be active learners utilizing new technologies and study physics by doing physics.

In the same letter Charley also said,

> It is my hope that my students gain an understanding about the natural world in terms of the basic laws of physics so that they can “see” physical interactions as part of a whole, cogent set of rules that have been studied and systematized by people.

These responses are particularly intriguing for at least two reasons. First, despite Charley’s statement that he is desirous of a “different approach” to his instruction, his language is suggestive of an empiricist perspective, i.e., physics as a “set of rules” that has been “systematized.” This is not to say that the content of the Modeling curriculum is not systematic, but the emphasis of the pedagogy is guided inquiry and developing students’ meta-cognitive skills and not about mastering a set of rules. Second is the consistency in Charley’s views over time. In response to a question about the nature of science during the extended interview (and fully eight years after the writing of his application letter), Charley said,

> I would define science as an approach to doing things, it's a way of finding out about, really, about anything, and that, it's a process, it's just a way of doing things. Scientific knowledge is something that I think has been pigeonholed and put into categories that are sometimes called chemistry and astronomy and biology and so forth.

I next asked Charley to expand on what he meant by “process.”

> It's a process of doing things, of finding out about nature, and not just how things work, but, at least, coming up with recipes or models or representations that can be used to describe the world and things physical, at least natural things that happen, and basically to codify how the world works.

Recall also that Charley is the teacher I identified earlier as having given apparently conflicting responses on the VASS. He leans towards the view that “physics is inherent in the nature of things and independent of how humans think,” but he also strongly believes that “the laws of physics portray the real world by approximation.” Moreover, Charley’s “mixed view” response to question 11, whether mathematical formulas express meaningful relationships among variables or provide ways to get numerical answers to problems, was unique. Four teachers strongly believe and one teacher leans towards the belief that formulas express meaningful relationships.

Taken together then, Charley’s responses and remarks suggest that his views are not conflicted so much as they indicate a practical point of view. That is, I interpret Charley’s views to mean that he is simply making a statement about the limitations of human knowledge and, at the level he teaches, Charley believes the “laws of physics” are both good enough and eminently useful. One of my teacher colleagues aptly describes this pedagogical approach as “finding the acceptable oversimplification.” Consequently, Charley believes it is interesting and worthwhile for his students to investigate physical phenomena and learn – note I do not say construct – some of these useful laws. However, these views clearly are not consistent with Modeling’s constructivist perspective and they do not represent a “different approach” or the “student-centered” curriculum Charley alluded to in his application letter.

This interpretation is supported by some other comments Charley made during the extended interview and elsewhere that also help explain why he no longer employs Modeling except for just a few weeks at the beginning of the year. Three things seem to have impeded Charley’s implementation of Modeling: pacing and content coverage issues, dissatisfaction with certain pieces of the curriculum, and his students’ mathematics preparation. Charley addressed his concerns in this response to a question about the reasons behind his decision to limit his implementation of Modeling:

> One, I think my students have a really hard time with the mathematics in the physics course, even the mathematics at the level that the Modeling involves. In fact, half of my students, or even possibly fewer than half of my students, are concurrent in trigonometry, so they're unable to do anything involving trigonome-

> try and even some of the algebra students have a hard time with it. The other part is that, unless it's changed, I was never in love with the Modeling approach to energy; I always found the energy unit to be kind of confusing and personally I didn't like it, so originally I would sort of move away from the Modeling around the energy time. But I just found that a lot of the worksheets, particularly the worksheets involving Newton's laws, although they were very, very rich, absolutely wonderful, they took a tremendous amount of time, and I found myself having to sort of trade time for curriculum. In fact, that's another big reason why I've moved away from Modeling, at least for the latter part of the year, is that I find it is so time intensive, and our school's bell schedule is such that we really don't meet a lot – just three times a week [which] is kind of minimal.

Charley reiterated his distress with Modeling’s pacing and curriculum on several additional occasions:

> The very first year I did Modeling, granted it was the first year I was doing it, we did mechanics the entire year and I don't even think I finished mechanics. The second year, being more comfortable with it, I think we finished mechanics and only had time left for one of the units – perhaps I did electricity, I forget. The following year I tried to streamline things even further and that was where I decided I really didn't like the energy unit. I guess since then it's been about a quarter and a half of Modeling curriculum.
>
> My biggest issue is not [Modeling’s] value, but I guess I'm still of the school that wants to "get to rainbows." The school year isn't long enough to do justice to any physics curriculum, at least I can't make it work, and I try to both teach kids how to do science and to also get turned on to the nature of nature.
>
> I was impressed with the depth to which the pedagogy had been developed. It made sense to me, although I sometimes thought the representations for energy (symbols, schema, pie charts) a bit too abstract. I felt a dedication to use the pedagogy as is, but in practice, the students' pace was excruciatingly slow.
>
> Furthermore, the second semester materials seemed less connected than the first semester (mechanics). I didn't think my students would "get it."

Charley’s reference to “getting to rainbows” is from a quote by one of the foremost practitioners of “conceptual” physics, Paul Hewitt. The author of highly regarded high school and introductory-level college physics textbooks, Hewitt decries what he believes to be excessive instructional time spent by some teachers on kinematics (as is most definitely the case with some of the other teachers I observed), which he attributes to “the teachers’ love affair with graphical analysis” (see http://www.conceptualphysics.com/rainbows. html). But even though Charley might not be as enamored with computer technology as much as some teachers, he did express his appreciation to the Modeling Workshops for this very reason: “I found the methodology of instruction more important particularly in terms of using the computers and probes to DO physics.” Starting off the year with Modeling, therefore, serves Charley’s purposes as it introduces students to computer technology with its probes and graphical analysis software, tools that will be valuable later in the year even if the pedagogy is not. Evidently, like Hewitt, Charley believes that "most of the fascination of physics lies beyond [kinematics]" and he is not able to move past this seeming barrier to full-fledged Modeling.

Observations

Charley teaches in a rather cramped lab space in an annex attached to the gym that has not been substantially updated since its construction in 1976. The room is oddly organized with the demo bench and blackboards in one corner. Student desks are crowded in front of the demo bench and flanked on two sides by large work tables behind which is a narrow aisle way and then countertops with computer workstations. Students fill the twenty or so desks and the overflow sits at the work tables. A peculiar alcove with sinks that Charley says was once used for photography cuts off one corner of the room. There are lots of science posters on the walls, various pieces of equipment lying about the room, and a wall clock marking the time in radians – the room has a very lived-in feeling.

The school has a block schedule: all classes meet for 50 minutes on Monday; periods 2, 4, and 6 meet for 97 minutes on Tuesday and Thursday; and periods 1, 3, 5, and 7 meet for 93 minutes on Wednesday and Friday – Charley, therefore, sees each class three times a week (I spent four days in Charley's classroom). Periods 2 and 6 are pre-calculus, period 4 is an AP(B) physics class, and periods 3 and 5 are Charley's regular physics classes. The AP class has 23 students (seven girls, two non-white students). One physics class has 25 students (nine girls, two non-white students) and the other has 29 students (11 girls, 3 non-white students). One pre-calculus class has 35 students (22 girls, 4 non-white students) and I have no data for the other pre-calculus class (6th period) as I did not observe it, but Charley mentioned that it also has more girls than boys. Charley lamented the small number of girls in the physics classes ascribing it to the recent addition of a second-year advanced biology class that, together with the AP biology class, is attracting girls away from physics.

Since my observations began on a Tuesday, I observed Charley's 2nd period pre-calculus class and his 4th period AP physics class. Charley's classes get off to a slow start – five to ten minutes may elapse before class really gets underway. In part, this is due to the school's peculiar schedule for announcements and such, but there also seems to be an expectation that an extended "settling time" will be tolerated, especially on the days with longer periods. Charley has an easy rapport with his students and he allowed plenty of time for questions, but his delivery in both classes was very traditional. In the pre-calculus class, he did some standard trigonometric derivations on the front blackboard which took about 50 minutes, including a few student questions. He then assigned some problems from the textbook for students to work on in class during which time he circulated around the room to help and coach students as necessary. With five minutes remaining in the period, Charley asked how many students had successfully completed the problems and assigned some homework. AP physics was similar: Charley went over the previous day's homework by asking students for their answers and affirming or correcting the answers and presented a formal lecture on electrostatic work for which students were expected to take notes.

Wednesday's 3rd period physics class opened with Charley instructing students to turn in a homework assignment. He then said to the class, "Let me ask you this: when you stand in front of an ordinary bathroom mirror where does your reflection seem to be?" There were a few single-word responses from the class ("in the mirror," "closer," "same," etc.) after which followed a terse mini-lecture about reflection and images. Charley compared a reflection in a mirror to a sound echo. He next handed out a "Law of Reflection Activity" worksheet that states that the purpose of the activity is to "demonstrate the law of reflection." The activity is a standard one seen in many physics classes employing small mirrors and pins so as to line up a pin with its reflection to establish the angles of incidence and reflection. The worksheet does not explicitly state the law of reflection, but it does have a data table in which students are to enter the "angle of incidence" and the "angle of reflection" and it directs students to discuss their results on the back of the paper. Charley circulated around the room directing and assisting student groups as necessary.

In an aside, Charley said to me that this was an appropriate activity for his students because they "can't handle the math for geometric optics." When I queried him about this later he said he meant that his students are unprepared for trigonometry. He also expressed a concern about not making physics too difficult so that kids keep signing up for the course.

Most groups finished the activity within 35 minutes or so after which Charley called the class back to order and asked if anyone could "articulate the results of this activity." A student said, "The angles are the same" and Charley then wrote out a formal statement of the law of reflection on the board. He next directed the students to summarize their results in their lab books in a short paragraph and then passed out another activity worksheet. This activity involved the use of two plane (flat) mirrors hinged together like a door so that the mirrors could be opened to different angles. The worksheet includes diagrams of the mirrors set at 90, 60, 45, and 30 degrees apart and asks students first to predict how many images they will see in each configuration and then, after they have collected data on the several configurations, to derive a mathematical relationship between the angle separating the mirrors and the number of images. Charley explained how to complete the diagram for the 90-degree mirrors and then circulated around the room while students worked on the activity.

There was a great deal of confusion and frustration expressed by the students and Charley was kept busy answering questions. Things calmed down once students were actually allowed to use the mirrors to check their predictions, but confusion about the questions on the worksheet and how to answer them persisted. Most groups had not finished the activity by the time Charley recalled the class to order and passed out a homework assignment, but there seemed to be a clear expectation that time would be allotted next class to complete the activity.

Fifth-period physics opened similarly with the discussion about images in a single plane mirror and the associated activity. However, before Charley had students begin the paired-mirrors activity, he displayed a slide depicting a young woman wearing a hat with a flower in it holding up a small mirror behind the flower while she looks at her reflection and the reflection of the small mirror in another, larger mirror. The question he posed was that if the young woman in the hat is two feet from the large mirror and holds up the small mirror one foot behind her hat, at what distance from the young woman does the image of the flower as reflected in the small mirror appear to be in the large mirror? This prompted an interesting discussion and students proposed several answers, but the issue was left unresolved at this time.

Friday's classes both began in the same fashion: Charley demonstrated a situation similar to the girl in the mirror problem using a full-length mirror and a small, hand-held mirror. Cast as a homework assignment, the objective for students was to diagram the setup to determine where various reflected images appear to be. As Charley discussed his expectations for the assignment he posed the following question, "If mirror images switch left and right, how come top and bottom don't also switch?" Students offered no particularly coherent answers in either class. Charley next redisplayed the slide of the girl and the mirror and again asked students for their solutions. As was the case the previous day, students still offered a range of answers (including a correct solution, which Charley did not acknowledge). There was no further discussion and Charley moved directly to the next challenge: how tall must a mirror be for you to see your full length reflected in the mirror? Again, students proposed a wide range of solutions (including a correct answer which, as before, Charley did not acknowledge). Charley demonstrated this scenario with the aid of a student helper and a piece of cardboard to cover up various portions of the bottom half of a full-length mirror. The student was still able to see his entire image with as much as half the mirror covered by the cardboard. When Charley displayed the ray diagram solution for this problem he asked if anyone could recall the law of reflection, but no one was able to do so without consulting his or her notes.

Immediately following the resolution of the full-length mirror problem, Charley announced, "I'm just going to put some notes on the board." He proceeded to list definitions and descriptions of various aspects of reflection (e.g., diffuse vs. specular, etc.). Most students copied the notes, but one student in 3rd period seemed to be asleep during this phase of the lesson. Next, Charley directed students to complete the multiple-mirror activity begun on Wednesday, but first he said, "Let me give you a little more guidance." Charley then drew a diagram for a mirror configuration (different than the one he diagrammed on Wednesday) on the blackboard. Students worked on the activity individually or in pairs with as much socializing as there was talk about the investigation (which I found to be typical in all my subjects classes and undoubtedly is just a natural consequence of the student collaboration process). Charley circulated among the student groups providing guidance as requested or he deemed necessary. With about five minutes left in class Charley warned the students, "I'm going to want you folks to turn this in today," obviously trying to coax the students into completing the activity. After another minute or so, Charley wrote a homework assignment on the board. Finally, just before the bell rang, Charley said, "Bell's going to ring in a minute or so – you don't have to turn this in today."

There were a few differences in the conduct of class between 3rd and 5th periods. Charley did not provide a second diagram for the multiple mirror activity as he had done in 3rd period, but most groups in 5th period completed the activity with time to spare. At the close of the period, Charley asked, "How many of you folks feel like you got it, less so, or not at all?" Most students indicated they "got it." Charley then asked, "What do you think the point of this activity was?" Student replies included "to play with mirrors," "something about images," "trying to see patterns," etc. The question evidently was posed rhetorically as Charley did not acknowledge these responses in any way. I suspect his intention was to prompt a little reflection on the day's activity as students walked out the door.

Assessment

In his application letter, Charley seemed to be quite unequivocal in his desire to find a “different approach” to his physics instruction. When I asked Charley about his participation at the Modeling Workshops he said,

> My experience at the Modeling Workshops was enjoyable, rejuvenating, and empowering. It especially gave me the backbone to introduce computers and computer-based lab experiments into my instruction. It also helped me to recognize the strength of my students "preconceptions" about the natural world and how difficult in can be to replace such with better models. I was actively engaged in the workshops. I performed the labs, did worksheets and “whiteboarded” similar to what I was to expect from my students. It was very valuable that I actually did their work.

These comments suggest that with his positive experience at the Workshops, Charley should have been both motivated and well-prepared to begin to implement Modeling in his physics classes. Moreover, as Charley implies in his responses to questions about his Modeling practice, he was faithful to the methodology of the pedagogy, taking as long as an entire school year just to get through the mechanics curriculum. However, when I asked Charley how he would describe the theory of learning behind the Modeling pedagogy he said,

> Honestly? I think I'm not as knowledgeable, comfortable understanding what the theory behind it is. I like the notion of trying to reduce as many natural processes to as few models as possible and I think that's one of the things that the Modeling theory is about; I like that a lot. So it's really hard for me to answer.

Thus, in spite of Charley’s dedication to using the pedagogy “as is,” it seems that mastering just the “technical” aspects is insufficient. Without a deep appreciation of the epistemological foundations of Modeling, Charley simply could not see any merit in attempting to sustain the levels of discourse and student engagement inherent in this pedagogy. Despite Charley’s stated intentions that his instruction become more “student-centered” and his students “active learners,” he did not assimilate the constructivist underpinnings of the Modeling pedagogy. At the close of the extended interview I asked Charley if there was anything he wanted to add:

> I think just a few comments about the Modeling curriculum. I think the Modeling curriculum is absolutely wonderful. I feel, and again this is mostly anecdotally, I feel like my students who learn using the Modeling curriculum, they learned the subject matter deeper, they learned it better, and it will probably stay with them longer than those students who get the more traditional instruction. But personally I feel so thoroughly torn in a lot of ways. I get torn because, as I've mentioned before, I want my students to learn about rainbows, I really do, [and] I think they want to learn about rainbows. I'd like to get to that and the Modeling curriculum is, at least, the amount of time I have with my students, my school year, is just too short, we just don't get to that. I also feel torn because sometimes I feel like the Modeling curriculum, although better prepares them or they learn it better, and may better prepare them for a career in science, and sometimes I think

> that some of the students are not oriented or not desirous of that approach and would much rather experience something that is just more experiential and definitely, I hate to admit it, fluffy, and so I kind of get torn having to try to teach all the different approaches. You know, if we had 12 different sections of physics and I had to choose what I wanted to teach and if we could break it up into fluffy, experiential physics and Modeling physics, maybe a college prep or a college-level physics, you know I'd want to do it all but, of course, I can't be in all of those places all at once, and maybe that's why I do it little bit of everything in terms of what I do here.

I interpret Charley's use of "experiential" to refer to the sorts of informal hands-on encounters one might have at a science center or museum, that is, experiences intended to amaze, awe, or otherwise pique one's interest in the natural world and with no more intellectual responsibilities than appreciating the experiences for themselves – hence "fluffy." Charley also seems to be making a distinction between Modeling Instruction and "college prep" and "college-level" physics, referring to AP-type, that is, test-driven, courses, in which content coverage is paramount. The clear implication is that the pace of Modeling Instruction as typically presented precludes meeting the demands of such classes. I reject the implication on intellectual grounds – Modeling covers the material to a much greater depth than a typical AP class possibly can. But Charley is quite correct in terms of coverage unless special provisions are made such as class meetings outside the regular school day.

Successful Modeling initially can be demanding on the teacher. It usually means letting go of a significant percentage of one's "traditional" curriculum, letting go of complete control over classroom discourse, letting your students flounder about as they struggle with their own thinking and learning, and, especially hard for many teachers, learning how to facilitate rather than direct student learning. Modeling simply is not as "efficient" as more traditional pedagogies in terms of pacing, coverage, and delivery; it is slower and often proceeds in an uneven fashion – much more like real science than a nice, neat lecture or a cookbook lab. Despite his initial willingness after 16 years of teaching to explore a new pedagogy, absent a constructivist perspective Charley can not quite "let go." His convictions about what he should teach and the demands he is willing to place on himself and his students preclude him from fully implementing Modeling.

Charley has a relaxed and comfortable relationship with his students, he is patient and allows for considerable wait time when he asks questions, he is sympathetic and responsive to students as they wrestle with the material, and he has created an environment where, at least some of the time, students work collaboratively to explore fundamental principles of physics. For these reasons Charley achieved an average score of 70 on the RTOP during my observations, above the so-called "reform threshold" of 60, but well below the scores of most of the other subjects of this study. I note also that Charley had the highest baseline student FCI scores (administered after nearly a full year's instruction) of any of my subjects, almost as high as Allan's long-term average posttest scores, so his students obviously are learning some physics. Nevertheless, I must conclude that Charley has experienced no significant transformations in his conceptions of physics or physics instruction as a result of attending the Modeling Workshops.

David

Teacher	Modeling Instruction Survey		3-day RTOP Avg.	Baseline Student FCI (spring '98)	Long-term Student FCI Averages %		
	1999	2007	%	%	Pre	Post	Gain
Allan	185/3.1	135/2.3	90	39.3	24.4	50.3	33.9
Brian	n/a	148/2.5	80	43.7	35.8	66.4	47.7
Charley	n/a	149/2.5	70	49.7	n/a	n/a	n/a
David	***n/a***	***130/2.2***	***84***	***35.0***	***37.8***	***65.8***	***45.0***
Edward	145/2.4	96/1.6	71	n/a	30.4	72.0	59.8
Frank	168/2.8	114/1.9	87	41.7	26.0	52.4	35.6

Background

In 1998, David earned his MS in Science Education through a distance-learning program. One of the program requirements was that David complete a science practicum in his classroom. David told me that as he pondered his options for meeting this requirement he knew at least that he was dissatisfied with certain aspects of his teaching and thus wanted to use the practicum to address some of these issues.

> I got a little tired of it myself; listening to myself drone on all day. Have three sections of one class and doing the same thing over and over and over, and the kids sitting there trying to understand it and trying to regurgitate what I said, not having to do any thinking on their own, figuring out if they just follow the same algorithm I wrote on the board and repeated the same thing I said about the subject during the lecture that somehow they would learn physics, and they never understood it. It was shocking to see how little they understood just in regular conversation.

Then he just happened to discover the Modeling program.

> I was looking for a better way of teaching the students, and I ran across the ad for Modeling, I think it was in *The Physics Teacher* or NSTA *Reports*, that there was a new program that looked interesting. When I did the research on it I found that their data supported that the results were due to the [teachers] implementing the information, not on their degrees, [and] that it was backed up by a test called the FCI that actually gave data on how significant the learning was. I had already read many other articles [about] inquiry as part of my master's program, and was actually implementing them the spring of that year. [That] summer I went to [the] Modeling [Workshop] – I had already started changing [to] inquiry – and Modeling just fit it. So, I signed up for the two summers of that, and it's been well worth it.

When I later asked about his experience at the Workshops, David said it was "more important to my students understanding physics than my undergraduate education courses and tied with my physics courses."

When David was hired to teach at his current school, his principal gave him free rein to design all his curricula and even his classroom. The principal continued to support David as he began implementing the Modeling curriculum but not so the assistant principal. As has been reported by many Modeling teachers, students initially are very uncomfortable when the teacher refuses to answer questions directly and, instead, is more likely to respond to a question with still another question. In addition to this practice, to which David is relentlessly faithful, it is also David's custom not to directly affirm students' experimental findings or solutions to problems during whiteboard presentations. These practices became a bone of contention between David and the assistant principal:

> The assistant principal always bothered me about why am I not giving answers: these kids are not comfortable, it's too hard on them not to know for sure if they're right when you let them sit down. Well, if they got to sit down they can be pretty sure that they're right. But [the AP] still hounded on me to give them answers, give them answers. Even though I explained to [the AP] that they're like alcoholics, you can't just give them one little answer, you can't give an alcoholic one little drink, they will just clamor for more and more and more, they have to realize they have to do it themselves, they have to think, they can't just take the easy way out, and I outlasted [the AP].

David had similar problems with the assistant principal's successor.

> Then we got an assistant principal that was a shop teacher and totally linear, just could not understand the broader picture of it, and [tried] to get me to put objectives on the board, a daily objective, what the student will be doing that day. And again, toe-to-toe, spent many an hour in [the AP's] room explaining to [the AP] you can't do that to these kids, they shut down. There's too many of these kids that think science is nothing but a bunch of definitions. If you put a word up on the board that they think that they know they are done, they think I don't have to worry about that, I already know what energy is or I already know that. Even though they may know what the term is they have no clue what it means and how to use it. So I wore [the AP] out.

David said he also has had problems with parents over the years and some have even threatened him with lawsuits "for not teaching." But he said that he has received many positive comments as well:

> I've had many parents tell me about how much their kids learned, how easy college was for them, and they've been happy that the kids have gone through the classes with me, and I've had parents say that [mine] was the only class their kid was ever challenged in and for kids who want to go back East to a big college they need that. That part of it, you know, you get one or two a year that really appreciate what you're doing, forcing their kids, and especially the professional/science parents. When they see what inquiry is and how their kids are doing stuff and actually doing real science I get a lot of response from those parents in a positive way.

David said things at school have calmed down in large part due to positive comments from his students and the high scores his AP students earn on the AP test. He even persuaded his department chair, who also teaches physics, to attend the Workshops.

As evidenced by his comments above and the classroom practices I observed, David's commitment to the Modeling pedagogy is steadfast and unshakeable. Moreover, he uses the pedagogy in all his physics classes, from applied through AP(C). But he has made significant modifications to the curriculum over time. Like my other subjects, David said that having a complete curriculum to take back to school "was very important the first year," but he also said, "If the first exposure [to Modeling] was one-half time using the materials and then using the rest of the time developing variables for inquiry labs, the results would probably have been the same for me." Thus, David's practice has been to "develop my own labs working backwards from what equation I want and figure out how to craft my variables." These changes have been in response to David's perceptions of student difficulties with labs, especially due to students' inadequate preparation in mathematics. For similar reasons, but also because state law requires that every student has a textbook for each class and David wanted that text to be Modeling-friendly, he replaces or supplements Modeling curricula with materials from the *Minds on Physics* series:

> *Minds on Physics* [spends a lot] of time on concept development [but] there seems to be a little bit of a gap in between its conceptual development and the jump right to hard math problems. The students seem to have a little bit of a problem making that jump. I use the Modeling physics worksheets to bridge that gap and that makes the kids seem a little bit more successful.

David heard about the series via the Modeling listserv (to which he is a regular contributor), reviewed the books himself, and then cajoled the powers that be to purchase the texts for him even though they have not been officially approved by the district's textbook committee.

Observations

As I indicated above, David designed his own classroom as part of the addition of a new wing to the school building. The room is large, perhaps 40' x 40', and is well appointed with plenty of storage cupboards, student worktables, and lots of free space. Student workstations are located along three walls of the room and each workstation comes equipped with an extensive inventory of probes and other experimental hardware. Each student has his or her own laptop computer that has been configured to handle all data collection and analysis tasks. Printing and internet access are managed via a wireless router located in the room. Students sit at three rows of unfixed benches facing four full-sized sliding whiteboards which front even more storage cupboards. Samples of student work and a few posters are on the walls, but what catches the eye are the flotsam and jetsam of past and present student projects littering nearly every free surface that is not a workstation. On the other hand, lab equipment is neatly stored in numbered boxes in the cupboards under the workstations and, during my observations at least, students were pretty good at putting their equipment away at the end of class. The students in all of David's classes appeared always to know where to go to get what they needed for whatever they might be working on. Everyone seemed very comfortable in this space.

The school has a rotating block schedule: all eight periods meet for 43 minutes Monday, Tuesday, and Friday, and then the schedule cycles through four periods each on Wednesday and Thursday for 85 minutes each period. School is from 7:05 am until 2:00 pm, except on Wednesday. David arrives at 6:15 each morning. A "teacher assistance" period is offered every day except Wednesday from 1:30 to 2:00 so school gets out at 1:30 on Wednesday. I found the bell schedule to be convoluted and confusing – classes seem to begin and end at random times – but I suppose the residents are accustomed to it. Teachers teach six of the eight periods: David's schedule was AP(C) 1st period, honors physics 3rd, 5th, and 7th periods, and applied physics 4th and 6th periods. The school also offers a class designated simply as "physics," but David's "honors" physics course aligns better with the physics courses of my other subjects in terms of prerequisites and content. The demographics of David's classes are: 1st period AP(C) – 13 students, all male, three or four Caucasians, one African American, at least one Hispanic, the rest Asian/Pacific Islander; 3rd period honors physics – 17 students, two girls, a diverse mixture of ethnicities; 5th period honors physics – 16 students, six girls, about nine Caucasians; 7th period honors physics – 11 students, one girl and one Asian male; 4th period applied physics – 23 students, four girls, about ten Caucasians; and 6th period applied physics – 18 students, four girls, about six Caucasians. I have to admit I had trouble identifying the ethnicity of quite a few students – perhaps a consequence of the locale?

My observations began on a Wednesday morning with David's 7th period honors physics class (an 85-minute period). The class was very small: eight students, only one girl (David said three students were absent). The students were beginning a lab activity in Unit 7 – Energy. They had previously completed a simple Hooke's Law paradigm lab activity (various known masses hanging from a spring-scale), including whiteboard presentations. They also had prepared "pre-lab" write-ups that describe the experimental setup and procedure to be used for the lab as well as specifying the relevant independent and dependent variables. The lab is intended to connect the physical work done in stretching a spring (i.e., the elastic potential energy stored in the spring) and the kinetic energy imparted to a connected cart rolling on a low-friction track after the spring is released (corresponding to Phase 5: *Model Formulation*: Investigation and Initial Model Formulation).

As the students arrived, they went immediately to their workstations and started setting up the lab with no direction from David. (I commented on their apparent efficiency and David said that it had taken them quite some time to achieve this level of proficiency.) The experimental setups were essentially identical among the student groups – a very typical situation in high schools due to the limited availability of lab equipment. As students worked on the lab, David circulated among the groups asking guiding questions and providing some assistance with the physical setup. The lab procedures were such that students measured the force on the spring as a function of the distance stretched with a force sensor and the subsequent speed of the cart with an ultrasonic motion detector, the data for which were recorded on students' laptop computers. Using the graphing functions of the software, students simultaneously generated graphs for F vs. Δx and v vs. Δt. The class had previously constructed models for work and kinetic energy so most of the groups were attempting to find a quantitative relationship between the work done on the spring (as the area under the F vs. Δx graph) and the maximum velocity of the cart. One group was struggling with some confusion between the general formula for work, $W = \vec{F} \cdot \Delta\vec{x}$, which apparently they had read about somewhere (*not* in this class according to David), and the work done on a spring, $W_S = 1/2\vec{F} \cdot \Delta\vec{x}$, but they finally agreed that the relevant parameter was simply the area under the F vs. Δx graph. I also observed intra-group conversations, most of which were focused on the lab – more so than I had observed in my other subjects' classes. In addition, I noted that the lone girl in the class seemed merely to follow the lead of her male partner. He handled the equipment and told her which data to record. To be fair, however, other students sought out his "advice," as well. These behaviors may have stood out more in this class simply because of its small size. On the other hand, despite their relatively low numbers, most of the girls in David's classes held their own during labs and whiteboard presentations and seemed as comfortable in class as their male colleagues.

Students worked on the lab activity for about an hour and started to clean up on their own. They then moved to the student benches to generate fitted v_{MAX} vs. W graphs on their laptops and, shortly after the students began this work, David announced, "OK, you have 20 minutes to get your data for whiteboarding tomorrow." As they worked, there was considerable discussion among and within the groups as to the various quantitative relationships. Most students' v_{MAX} vs. W graphs indicated that v_{MAX} increased as the square root of the work done on the spring. Standard practice in the Modeling pedagogy is to have students create linear graphs to test for the appropriate power fit. That is, if students' data are correct, the graph of the *square* of v_{MAX} vs. W should be linear (i.e., $v_{MAX}{}^2 = mW + b$). The students struggled with a couple of conceptual challenges with their graphs. First, there was some confusion between the work done *on* a spring and the work done *by* a spring. By convention the first is a positive quantity and the second is negative (because the force exerted by a spring is opposite to the direction of stretch). Plotting $v_{MAX}{}^2$ vs. W in the second instance gives a graph in the second quadrant with a negative slope and is much harder for the students to interpret. The second problem was resolving the units of the slope of the graph ($(m/s)^2 / kg(m/s)^2 = 1/kg$) and then connecting the slope to the mass of the cart. I saw most of the possible iterations on students' whiteboards.

David's 3rd period honors physics class got off to a slower start, perhaps because it is a larger class – 17 students (but only 2 girls). David did not interact as much with the class because he was busy grading students' pre-lab write-ups. He returned them to students because he includes guiding feedback on the lab itself that they might need during class. As time wound down, it seemed to me that this class had not progressed quite as far as the earlier class.

The 5th period honors physics class (Thursday morning) proceeded similarly to the other two classes, but in this class I observed a 10-minute conversation between David and a student who had misidentified the independent and dependent variables on his pre-lab write up. David was very patient with this student, only asking questions, but I got the impression that the student's confusion was unresolved. I suspect that David was satisfied that he had asked sufficiently pointed questions that the student should have been able to properly identify the variables on his own, but I did not ask him about it.

Friday's 3rd period physics class opened with David passing back a quiz on momentum that the students had completed a few days before. This means that David's curriculum has the unit on momentum immediately preceding the unit on energy, which is the order in the *Minds on*

Physics text. This is not an atypical sequence in high school physics, but the Modeling curriculum sequence is energy (Unit 7), followed by uniform circular motion (Unit 8), and lastly momentum (Unit 9). I have heard that other Modeling teachers make similar adjustments to the sequence for various reasons, so I am merely taking note of the difference. In any case, about 10 minutes into the period David announced, "Whiteboards need to be ready to go." Shortly thereafter the first group trooped to the front of the class.

The first group was unprepared both in terms of their whiteboard and their ability to explain the lab. These facts were made apparent with the first student question about the units of the slope of the graph; the indicated units were incorrect. David followed up with three questions about the units of the variables and finally asked the group, "What's the model behavior?" (An acceptable response would have been something to the effect that the square of the cart's maximum velocity increases with the work done on the spring). The group was not able to articulate the model and David asked them to take their seats.

I should mention here that after just a couple of presentations it was clear to me that David had trained his students in asking the structural sorts of questions associated with whiteboard presentations in the Modeling pedagogy, e.g., about the slope of the graph, the significance of the *y*-intercept, the choice of units, connecting the shape of the graph to the observed behavior, the mathematical relationship (equation) between the variables, etc. When I queried him about this during the extended interview, he said,

> Well, it's the old Skinnerian thing where you reward the behavior you want, so 15% of their quarter grade is for asking these questions. At the beginning of the year they're just pointed towards trying to get points, but after they realize for a while that they are learning stuff it just becomes part of their nature to ask those questions and learn from them.

David also said that students learn to ask appropriate questions mostly by listening to the questions he asks and that he does make allowances for those few students who are just too shy or unsure of themselves to ask questions.

The second group moved forward and, just as I have indicated, the first question was from a student about the units and meaning of the slope. A member of the group responded, correctly, that the units of the slope were 1/*kg*. David then asked, "What is the significance of the size of the slope versus the mass of the cart?" (The coefficient of the slope must be some function of one-half the mass, i.e., $(m/2)^{-1}$). This group, as did others, confused the variables with the units, that is, the slope was depicted as 1/2 *kg* rather than 1/(*m*/2), substituting the units of the variable for the variable itself. The group was not able to answer David's question so he said, "Let's try another group. Thank you." There was polite applause from the audience and the group sat down.

Groups 3 and 4 also had problems resolving this issue with the slope. Finally, David asked group 4, "What would be the general equation with just variables?" With a bit of coaching from David and the class, a group member wrote $(m/2)^{-1}\mathrm{PE} = v^2$, (where PE is the elastic potential energy stored in the spring and is equivalent to the work done on the spring – concepts developed in a previous class). David told the group to solve for PE and they wrote 1/2 $mv^2 = PE$. David then asked the group, "What do we call 1/2 mv^2?" A student responded, "Kinetic energy." The fifth and final group then presented and all the questions were from students. The questions more or less reinforced what had just been established with group 4.

The discourse in David's 5th period honors physics classes evolved quite differently. The first group to present was immediately challenged by the student audience to reconcile the evident confusion between units and variables in the equation for their $v_{MAX}{}^2$ vs. W graphs. The ensuing discussion continued for some 24 minutes with no intervention from David. Eventually the students managed to resolve the issues. Since the relationship between the variables had been properly established, the questioning was more probative than in 3rd period. The questions focused more on how the shape of the graph reflected the physical behavior of the system and on the influence of the various parameters. One particularly insightful student asked a group how the slope of the graph might change if the spring's stiffness were to change (it would not). This prompted another series of interesting exchanges. In the end, three groups were able to present their whiteboards. David asked only one question (addressed to the second group) and students asked a minimum of twenty questions.

Seventh period faced the same issues as 3rd and classroom discourse mostly remained focused on the units vs. variables problem. Four groups managed to present their work and students asked a few more questions than David. In this period, however, the formal relationship between the elastic potential energy in the spring and the kinetic energy of the cart was never fully developed. This apparent lack of closure did not appear to discomfit anyone and there seemed to be an expectation that the issue would be dealt with appropriately in a subsequent class.

As a matter of course, I also observed David's AP(C) and applied physics classes. The AP class (13 boys; all seniors who have taken at least one year of physics, but for some this is their third year of physics with David) had just finished a lab in rotational mechanics for which they now were presenting whiteboards. The applied physics class was finishing up a mousetrap car competition and moving on to some activities demonstrating the interference of sound waves for which they also had to present whiteboards.

Two things stood out in the AP class. First was the poor quality of the students' whiteboards; they were nearly impossible to read unless you knew precisely what to look for. Second was the intellectually sophisticated classroom discourse and that almost all of it was just among the students. The give and take was similar to what I experienced in my graduate courses in philosophy and education (note I do *not* say physics!). It was obvious that this was expected behavior, but most of the students seemed genuinely to enjoy it. It was quite exciting.

The applied physics classes (18 and 20 students, respectively, 4 girls in either class, mostly sophomores) struggled valiantly to get mousetrap-powered cars to roll a set distance – the closer to the mark, the higher the score. Students were permitted as many practice trials as they wished and after each one they were free to modify their cars as they deemed necessary. However, once a student announced that the next run was for a score, no subsequent runs could be scored. Most of the students were actively engaged, but a few of them seemed to have lost the will to compete, possibly because their cars did not roll accurately or reliably.

On the next day of my observations in applied physics, David set up two speakers at the front of the classroom to demonstrate sound wave interference. That is, the sound waves from the two speakers will interact in such as way as to create loud zones (“antinodes”) and quiet zones (“nodes” – but these are harder to perceive), similar to the interaction of the crests and troughs of waves in a pond. He played a 200Hz tone and instructed the students to “Grab a meterstick and move around till you find a loud spot. We’ll see what it looks like when everybody finds a spot.” After they had done so he directed students to move to another loud spot and measure the distance between the two spots. He then repeated the procedure with a 400Hz tone and told students to make other relevant observations about the distribution of student-observers around the room. Finally, he instructed the students to get back into their groups (which must have been assigned in a previous class), talk about their observations, and prepare whiteboards. While students were working on their whiteboards, David circulated around the room checking off a mechanical-waves vocabulary assignment students were to have completed prior to class (the mousetrap cars must have been an insertion activity and some discussion of the characteristics of mechanical waves must have occurred in a previous class).

The most interesting thing about the whiteboard presentations was the sophistication of students’ questions and the complete inability of the student-presenters to answer them. Students asked about the importance of the relative positions of the speakers, the number of speakers, the distribution of student-observers during the experiment, and others. This phenomenon did not seem to upset anyone and the presentations proceeded with just a few questions from David. One student-presenter, however, was able to correctly specify the relationship between the distance between loud spots and the frequency of the sound. That is, the wavelength of a sound wave is inversely proportional to its frequency, so as the frequency of a wave increases the distance between zones of interference decreases.

T – So, what are you assuming when you say higher frequency means shorter wavelength?
S – Wave speed is the same.
T – What in your experience suggests this is true?
S – Concerts.

If the speed of a sound wave were dependent on its frequency, i.e., its “pitch,” then the sounds from the instruments in an orchestra, all plucked, struck, bowed, or blown at the same instant, would reach an observer at different times and sound out of synch. That they do not is evidence that sound waves travel at the same speed in a given medium regardless of frequency, a fact this student seems to have learned.

The biggest conceptual obstacles seemed to be a persistent confusion between transverse and longitudinal waves and about which type are sound waves. Imagine a quick push (or a series of pushes) is applied to one end of long spring such as a *Slinky*® lying stretched out on the floor and held in place at the opposite end. Such “pulses” will compress and decompress the spring coils as they travel down the length of the spring. This is an example of a longitudinal wave, as is sound. In air, sound waves manifest as a series of alternating high pressure regions, as air molecules are forced closer together by collisions with other air molecules, and low pressure regions, created by the lower density of air molecules in the regions vacated by the molecules that had been forced closer together. For a transverse wave, on the other hand, imagine moving one end of the *Slinky®* in a side-to-side motion *perpendicular* to the length of the spring. Students seem able to envision longitudinal waves only with difficulty because most "everyday" examples of wave phenomena are transverse waves such as a flag flapping the breeze or the crests and troughs of water waves.

One student question about the speed of sound in media other than air prompted David to adjourn the class outside next to a long metal stair rail. David directed the students to compare the timing of the sound of a (distant) student's tap on the rail to a second tap while they listen instead with their ears on the rail itself. The rail was long enough that students were able (so they said) to perceive such a difference. Class reconvened and David closed the lesson with a brief discussion of constructive versus destructive interference using two pieces of corrugated plastic roofing material as a visual aid.

Assessment

David has a dry, generally unflappable demeanor and a wickedly droll sense of humor. He never once raised his voice or, for that matter, changed his delivery at all, but from time to time he would drop a subtly sarcastic remark that would take students a few minutes to absorb and react to – which they did with uproarious laughter. David is also deeply committed to inquiry-based teaching. He demonstrates this quite clearly in his classroom practice, as I have shown.

What is the genesis of this commitment? Recall that David was twenty years in construction before getting his undergraduate degree and seven years teaching AP physics, a decidedly inquiry-unfriendly curriculum at the time, before entering his graduate program and attending the Modeling Workshops. I maintain that David arrived at this position, in part, as a result of his experiences teaching physics to struggling students, but more directly from the reading and research he conducted during his graduate studies. Evidently, his undergraduate education program did not promote inquiry-based science teaching. David mentioned to me that he read many articles about inquiry-based teaching for his graduate program, including various journal articles about Modeling, an assertion he includes in his application letter to the program. He writes further that he had already "(since fall '97)" instituted some of the techniques encompassed by the Modeling pedagogy such as whiteboards and "peer review of labs" – activities also probably inspired by his graduate work. As a consequence he has become a believer: Students learn science by doing science.

> The role of a science teacher is to help their students learn how to behave like scientists, to be critical of information. Just because one of your peers put something up on whiteboard to explain to the rest of the class doesn't make it correct, doesn't make it wrong either. They have to be able to decide amongst themselves with a critical eye about what is real and what isn't and how it fit their own data and work it in. Teacher' s got to stop being the sage that everybody turns to and looks for the answer; the kids have to be able to think for themselves and, not only in science, all the way through their life: politics, everything down the line they have

> to be able to analyze information critically and come up with a valid conclusion. Without being given the opportunity in science there's not very many other opportunities for a student to learn that critical thinking.

David's decision to learn and implement the Modeling pedagogy, therefore, was influenced by his graduate work, but most strongly by the Modeling program's published research.

> So many things in education are just sound-good, feel-good fixes, there is no data, and if there is any data it was that one person that developed it and it never transfers across. The Modeling data shows that it transfers to whoever uses it; it's the method. The teacher's part of the loop and the teacher does get better over time, but the method of inquiry, of putting the load on the students to where they learn for themselves and become complete humans that way is the most impressive thing about it.

David was not the only subject to mention FCI data as a factor in his decision to implement Modeling, but he was the most forceful about it in that it provided him justification for his continuing efforts with the pedagogy even though his students' first post-Work-shop scores were the same as the baseline scores.

> With this experience and my novice approach to Modeling, my first year Modeling FCI score was the same as my previous year. [But] because of this experience I was not shocked by the curriculum and looked forward to using it the next year.

His years of practice since attending the Workshops have served to reinforce his constructivist perspectives.

A focus on student learning data continues to inform David's teaching as evidenced by his constant refining of his curricula to make the material as accessible as possible, as well as his analysis of students' FCI scores to identify their conceptual difficulties.

> I do a quick look at them [FCI scores] and most of the time it's the [Newton's] third law stuff that's always driving them crazy; it's so hard to get them past that third law. They do revert and you always have to loop back to that third law all year long, even when we get into electric forces and stuff about which one's pulling and which one's pushing. You still revert back to that third law and it takes a long time to cure that.

As I reflect on watching David in his classroom and conversing with him, I am reminded of a manufacturing management technique I practiced as a quality assurance engineer, "continuous quality improvement." As the term implies, the object is to use real-time manufacturing process data to identify and target problem areas and to make incremental changes in the process with the ultimate goal of producing defect-free product. This is distinctly different than the (at the time) more traditional warranty-returns analysis (product returned by customers for repair or replacement) and is not dissimilar from the equally traditional waiting for end-of-unit test results to assess one's teaching. Perhaps David is incorporating some "quality conscious" management strategies from his past life as a construction manager. Of course, it may just be that he did a little reading about formative assessments.

David said, both in his application letter and eight years later to me, that he would have pursued some sort of inquiry-based pedagogy whether or not he had been able to attend the Modeling Workshops. Of course, Modeling now "just fits," as David put it, and he finds the pedagogy "invigorating" and "well worth it." But besides such subjective measures, as heartfelt as they may be, David finds more potent validation in actual student achievement:

> One really reassuring thing is because I have three different levels I give the posttest, the FCI, at the end of the year. When the kids come back to the next level they take that [pretest] FCI again, and on average, over the summer, the kids that come back to me their score goes up one full point, which to me means that once you teach them how to think they don't stop thinking, they keep working it, everything they see reminds them of the physics. Because they're used to thinking about the physics for themselves it's an added benefit that they keep learning it, once they learn how, and that's fun.

Despite the 84 I report as David's three-day average RTOP score, he actually scored much higher on an item-by-item basis. That is, there were some items for which I was not able to give David a score because they simply did not apply to the day's lesson and the RTOP does not provide for "not applicable." In fact, on my last day's observation, I scored David at 92 – he achieved the top measure of 4 on all but four items. On that day for example, his lesson did not "make connections with other disciplines" neither were "real world phenomena explored and valued," and David reports on the (2007) MIS that he generally does not make much of an effort to do so. On the other hand, we do see him make just such a connection in the applied physics class in the whiteboard discussion about sound waves and concerts. David also reports that he seldom expresses to students the qualitative relationship between variables in a model or expects them to interpret a mathematical model qualitatively. This behavior is consistent with his response to question 21 on the VASS in which he indicates his belief that the laws of physics are independent of how humans think. But these self-reports of his practice appear to contradict the classroom behavior I observed. Consider his question to one group in 3rd period honors physics, "What is the model behavior?" or his use of the conceptually-oriented *Minds on Physics* and Modeling textual materials. I suspect that David is telling us merely that he *emphasizes* the quantitative aspects of the subject. This may well be a consequence of his years of teaching AP physics where the focus of the curriculum is precisely that, but it may also be inhibiting his students' complete assimilation of the material as is suggested by the essentially flat trend in his students' FCI scores.

Edward

Teacher	Modeling Instruction Survey		3-day RTOP Avg. %	Baseline Student FCI (spring '98) %	Long-term Student FCI Averages %		
	1999	2007			Pre	Post	Gain
Allan	185/3.1	135/2.3	90	39.3	24.4	50.3	33.9
Brian	n/a	148/2.5	80	43.7	35.8	66.4	47.7
Charley	n/a	149/2.5	70	49.7	n/a	n/a	n/a
David	n/a	130/2.2	84	35.0	37.8	65.8	45.0
Edward	***145/2.4***	***96/1.6***	***71***	***n/a***	***30.4***	***72.0***	***59.8***
Frank	168/2.8	114/1.9	87	41.7	26.0	52.4	35.6

Background

Edward stumbled into Modeling while surfing the Internet sometime in 1997, looking for project-based lab activities. It so happened that he was doing a unit on uniform circular motion at the time and took the opportunity to "try out" the Modeling curriculum by downloading materials from the Modeling website.

> I tried it and I liked it and I started trying to adapt it. The thing that I really liked was just before I started looking at Modeling I had started doing a lot of project-based labs and open-ended labs and making my students come up with their own procedures and writing them up. I was fascinated by the fact that unlike labs that I had given them, cookbook labs, which they just turned in, "Like, well, okay, that's what the numbers were," I noticed when they designed their own labs, if something went wrong that they would work and work and work at it to try and make it better. I think that's one of the reasons, somewhere in there, Modeling popped up and I saw that as a way of doing more of an open- ended inquiry-based labs.

Recall also that Edward is a member of the same physics alliance as Charley and that the two of them heard a presentation about Modeling at one of the meetings. It was then they decided to apply to the program and go together if accepted, which, of course, they were. In his letter of application to the Modeling program, Edward summarizes some of the major reasons many physics teachers have sought out this pedagogy:

> My first seven years, I taught as I was taught. My science education consisted mainly of traditional lecture and weekly labs. While the method was successful with me, I have found it less than desirable with the majority of my students. First, I do more work than they do. Second, students become very algorithm bound and do not understand the underlying principles. Third, students quickly forget recent material; they do not internalize their understanding of the physics taught to them. Fourth, traditional cookbook labs make little connection between the material being studied and the design of these labs frequently allows little cognitive thought on the part of the student. When the data doesn't correspond or varies greatly from accepted values, students forge ahead and blame the lab de-

> sign or the teacher without thinking of the underlying systematic or experimenter errors that caused the deviation.

With this eloquent indictment of his own practice, as well as his anticipatory foray into Modeling, Edward was obviously announcing his intention to find a new pedagogy. Of his experience at the Workshops, Edward said that he was an "enthusiastic participant" and that "Modeling methods have added to my teaching in a positive way and make the daily grind of teaching much more enjoyable for me (and I hope my students as well)."

Edward was the science department chair when he completed the Modeling Workshops so he faced no obstacles to implementation in that regard. Edward says also that his administration has always been very supportive, since, as he put it, "I just did it, I didn't ask for permission, and I never had to ask for forgiveness, so it's worked out okay." On the other hand, like most of my other subjects, Edward did experience some disgruntlement from students early on.

> It was brutal at the beginning. Students went one way or the other and either they really liked it or they didn't like it. The most interesting thing to me was the students who were the most successful in school were the ones who liked it the least – tell me the answer, tell me the answer. I think students expect it now, I think the reputation is there; they talk to each other.

However, Edward also described for me a fairly recent occasion where he ran afoul of certain students and their parents:

> I had quite a blow out a few years ago with some young ladies that always got A's and B's in their classes – "But they're getting a D in your class, what's wrong with you?" That's the only time the Modeling method has been challenged, but at that point I'd been doing it long enough that nobody said, "You really can't do that anymore." So they dropped the class. The most amazing thing to me was the question of "What's wrong with you?" Why does it always have to be the teacher? It was actually one of the worst professional experiences of my life; these are real powerful people, they were talking to the board, they were talking to the administration.

Edward said that other than this one unfortunate incident he has not had any problem with parents. As do many teachers, Edward describes his Modeling curriculum and pedagogy at a "back to school night" event for parents held early in the school year. He reports that most parents have been very accepting of Modeling – especially the parents with scientific careers.

Over the few days of my observations, Edward several times expressed his concerns about the relatively slow pace of the Modeling pedagogy and the limited content coverage it allows. In particular, for the last two or three years (it's unclear) the state of California has decreed that in whichever science class a student might be enrolled during their freshman, sophomore, and junior years, he or she must sit for a performance assessment in that subject. Thus, Edward frets about the juniors in his regular physics class who must take the physics examination because he is not able to cover much electricity and magnetism, optics, or thermodynamics –

typical second semester content. Consequently, Edward worries that he sometimes rushes the Modeling process, to the detriment of student learning, so that he might have more time for content beyond mechanics. Despite this fact, however, Edward's regular physics students do fairly well on the examination, though a few students score "below basic" each year (I found no scores for physics before 2006 on the state test website). Edward's Juniors in AP do even better, as one would expect. Edward also said that the state test requirement was the reason his school dropped his 9th grade "physics first" class since the test does not distinguish between developmental levels of a subject – if "physics" is in the course title, students must take the physics test regardless of their level of preparation.

Another issue of some concern to Edward is that he feels somewhat isolated as a Modeler. He is the only physics teacher in the school and his good friend and Modeling Workshop classmate, Charley, does not really Model much any more.

> Because I'm in a vacuum here, I don't have any feedback. But I miss that interaction, and that's why I like the Modeling Workshops themselves. It was difficult to learn how to question and I think I've tried to do a good job, but I don't know, sometimes I just want to get through stuff, so I feel like sometimes I give it short shrift on that.

This situation is one of the reasons Modeling program staff set up the Modeling listserv. The listserv is a venue where Modeling teachers can communicate with one another, albeit virtually, to give one another the kind of feedback and support Edward seems to be craving. Of course, these virtual interactions typically lack the immediacy and the intimacy of face-to-face meetings such as at workshops.

Observations

Edward's classroom is not unlike Allan's in that it is rather long and narrow, but it is perhaps only half the size and feels quite cramped. Three-quarters of one long wall is floor-to-ceiling windows, though the windows face north and trees and bushes are close to the windows. Student desks are close-packed in the front, opposite a small demo bench behind which are two whiteboards. Eight well-equipped chemistry lab benches set back-to-back in two rows completely fill the rear of the room. Power Macintosh computers and probe interface boxes perch precariously on a high shelf at each bench. Obviously, both physics and chemistry labs are performed at the lab benches. Little wall space exists because of windows on the one side and storage cabinets on the other, but Edward does have a few posters up as well as some humorous flyers intended to recruit new physics students from among his chemistry classes. The room is well kept and neat except in front at the demo bench and near the teacher's desk – that is where Edward "lives," after all.

Edward's schedule is three periods of chemistry (mostly sophomores and a few juniors) and one period each of regular and AP(B) physics (juniors and seniors). I recorded the demographics for only one chemistry class (3rd period): 21 students: ten girls, and five Hispanic students. Edward's regular physics class (4th period) also has 21 students, but only eight girls, one African-American student, and two Hispanic students. The AP class (2nd period) has 19 students including seven girls and two Hispanic students. The school runs on a block schedule: all classes meet Monday, Tuesday, and Friday for 51 minutes; periods 1, 3, and 5 meet on Wednesday and periods 2, 4, 6 on Thursday for 111 minutes each. I visited Edward's classes near the end of third quarter on a Thursday, Friday, and Monday so I was able to observe each of his physics classes three times.

Thursday's AP class opened with a 45 or 50-minute PowerPoint lecture on electric forces and electric fields that was tightly scripted to match the textbook and AP test conventions. The format of this presentation was nearly identical to what I had observed in Charley's AP class, so I suspect the two friends must be sharing teaching tips (this is just Edward's second year of teaching AP). Edward addressed several questions to the class and waited for a response to each question, but any subsequent discussion was limited. Edward next reviewed the results of a "sticky tape" electrostatics activity students had completed previously. By investigating the behavior of pieces of cellophane tape that had first been adhered to one another and then quickly pulled apart, thereby becoming respectively attractive and repulsive to a third piece of tape, students verified the bipolar-charge model for electricity. A more comprehensive version of this activity is an integral part of the Modeling unit on electrostatics, but since it can be performed quickly Edward uses it in his AP class as a paradigm exercise. Edward then conducted a "personal response" activity. He passed out sets of four cards, each labeled "A" through "D," and displayed several PowerPoint slides with multiple-choice questions in electrostatics such as might appear on the AP exam. As each slide was displayed, students held up cards corresponding to their responses to each question. Edward then asked for volunteers to explain their selections. There were few disagreements among the students, but other students were quick to point out obvious conceptual errors or otherwise correct their classmates. Students seemed to enjoy the exchanges as they exhibited no hesitation in responding to a question or defending their selections. (I observed no such interactions in Charley's AP class). This activity lasted about 25 minutes. The remainder of the period, about 15 minutes, was reserved for working on homework, including online assignments.

Edward's regular physics class started off with a review of the classic "exploding carts" momentum lab (Unit 9: Momentum) students had completed in a previous class. In this paradigm lab, a compressed spring is placed between two carts on a low-friction track. When the spring is released, the carts "explode" apart moving in opposite directions. Students measured the carts' velocities and, using the previously measured masses of the carts, calculated and compared their resulting momentums. Several trials were performed by changing the mass of the carts. Since the carts initially were stationary, the initial momentum is zero and, thus, so should be the final momentum (after taking experimental error into account, of course). Edward's review consisted of reminding students about their findings and the formula for momentum, $p = mv$.

The focus of the day's lesson was to establish the impulse-momentum theorem, which Edward did via what I would describe as a highly interactive lecture. That is, Edward set up a demonstration, complete with data probes and software, and guided a step-by-step investigation to identify the salient relationships in the system under consideration. In fact, a demonstration of this sort rather than a student lab activity is recommended by the Modeling curriculum guidelines for this unit probably because the conceptual leap from Newton's second law to the impulse-momentum theorem is difficult to bridge and hard to motivate without the mathematical formulation already in place. Edward did say later, however, that he would rather the students had performed the lab themselves, but the unit paradigm lab had taken four class periods to complete, including the whiteboard presentations, and he felt pressed for time. Inasmuch as students are not asked to develop their own models and given that this activity comes after the paradigm lab, this demonstration corresponds best to Phase 7: *Model Deployment*: Elementary Deployment.

The system in this case consists of a cart on a low-friction track. Aboard the cart is a force probe with a spring attached to the probe's sensor hook. A string is tied to the other end of the spring and then to one end of the track. The cart is given a push and after it is released it moves at a constant speed until it has traveled the length of the string. At this point the string becomes taut and the spring begins to stretch, first slowing the cart to a stop and then pulling it in the reverse direction until the spring returns to its relaxed length. The cart will once again roll at a constant speed approximately equal to its initial speed until it is recaptured. An ultrasonic motion detector is used to collect position and velocity vs. time data for the cart. (Recall that David's students used a nearly identical setup to conduct their investigations of energy: ${v_{MAX}}^2$ vs. W).

Edward began the interactive lecture/demonstration by incorrectly deriving the impulse-momentum equation from Newton's second law. That is, Edward wrote $F = ma$ and $a = \Delta v/\Delta t$, so $F = \Delta mv/\Delta t$, and consequently $F\Delta t = \Delta mv$. Edward "justified" the Δmv by saying that mass changes at very high velocities (a fact Newton was certainly not aware of, neither was he familiar with the changing mass of rockets). However, in the Newtonian formulation mass is always treated as a constant, so the formula is properly $F = m\Delta v/\Delta t$ and thus $F\Delta t = m\Delta v$, which is the form Edward used during later phases of the demonstration. In any case, Edward proceeded to run the demonstration a few times, all the while asking students to describe and explain the behavior of the cart (e.g., when does the cart move with constant speed, why does the cart slow down, why does the cart speed up in the opposite direction, what is the momentum of the cart, what happens when the spring goes slack, etc.). Several students, mostly boys, were actively engaged during this discussion and exhibited no difficulties in properly explaining the cart's motion.

Edward next summarized the cart's behavior by stating, "So, the cart changes momentum as the spring brings it to a stop and pulls it back. We'll use this to explore the impulse-momentum relationship," which he specified thusly: $F\Delta t = Impulse = m(v_1 - v_0)$. Edward directed the students to draw predictive v vs. t graphs over the range of the cart's motion. He then redrew students' graphs on the front whiteboard while asking for critiques of each graph from the audience. Students were happy to offer suggestions and corrections until a consensus was reached about the most likely shape of the graph.

The next step was to collect actual data from which to make calculations so as to compare the magnitude of the impulse provided by the spring to the change in momentum experienced by the cart. To this end, Edward displayed simultaneous computer-generated F vs. t, x vs. t, and v vs. t graphs. The impulse was determined by using the computer software to find the area under the $F\Delta t$ graph. Similarly, the change in momentum was calculated automatically by the software using the formula, $m(v_1 - v_0)$, that Edward had set up previously in the application. The results appeared to be sufficiently close ($F\Delta t =$ –.5380 kgm/s vs. $m(v_1 - v_0)$ = –.5488 kgm/s) to persuade students of the validity of the relationship.

Edward revised the situation by adding mass to the cart and asked the students how this change should affect the critical variables. The gist of students' comments was that the fundamental relationship $F\Delta t = m(v_1 - v_0)$ would remain unchanged, but the magnitudes of the impulse and change in momentum would be greater according to the increase in mass – as indeed they were. Then Edward changed the spring to one with a stiffer spring constant and again asked students about the effect this should have on the critical variables. The students quickly agreed that a stiffer spring must make Δt shorter and, consequently, F larger. As before, their prediction was rewarded by a successful outcome. Edward closed the demonstration by reviewing the several $F\Delta t$ graphs and pointing out, "So we're going to talk about average forces, not necessarily the maximum forces." I also noted that most of the student discourse during the demonstration was dominated by three or four male students and, judging by the apparent passivity of most of the other students, this was not atypical – an observation Edward later corroborated. This activity consumed about 25 minutes of the period.

Edward moved on to a second deployment activity (also corresponding to Phase 7: *Model Deployment*: Elementary Deployment) utilizing a series of short video excerpts from popular "action" movies. His purpose was to show students how to use "data" extracted from a video clip and the impulse-momentum formula to explicitly calculate the requisite forces to produce the action depicted in the scene and thereby judge its credibility (which students must do themselves during the next class). The first clip was a scene from *Superman* in which the "man of steel" flies to the rescue of a falling Lois Lane. Using the video software's frame counter function as a timer, Edward was able to estimate the duration of Lois' fall, from which he calculated her initial velocity, and the duration of Superman's catch – from initial contact to a final stop – which gives Δt. Edward exercised the impulse-momentum formula to show that Superman exerted a force of about 2200 N (494 lbs) over a period of 2 seconds to stop Lois' fall. This is a "reasonable" result in that a "real life" person could have survived it, unlike in the clip Edward ran next. In a similar scene from *The Matrix*, the hero plucks his beloved out of midair, but in the merest fraction of a second – too fast even to estimate the timing. The unfortunate conclusion is that the heroine would have been obliterated had the situation occurred in a Newtonian universe. The students obviously enjoyed this activity because they asked many questions about the specific details of these "rescues" (e.g., will it break her back, would her arms be ripped off, etc.). Edward told me later that students often will prod him to show a video clip or "bring out the toys."

Edward returned to his review of the exploding-carts lab the students had previously completed to formalize the relevant mathematical relationships. For this lab, Edward had had his students create a graph of the ratio of the carts' speeds versus the ratio of their masses (i.e., v_A/v_B vs. m_B/m_A) – an intriguing variation I had not seen or heard of before. The graph is linear and the slope of the best-fit line is essentially 1, from which students (apparently) concluded that $v_A/v_B = m_B/m_A$ and thus, $m_A v_A = -m_B v_B$, ($\vec{v}_A$ and $\vec{v}_B$ are in opposite directions and so have opposite signs) or, equivalently, $m_A v_A + m_B v_B = 0$. Edward explained that this shows that the total momentum of the carts after the "explosion" is the same as the total momentum before the "explosion," namely, zero, and thus, we have demonstrated the principle of the conservation of momentum, $p_1 = p_0$ (read "p-final equals p-initial"). Edward then wrote out a standard mathematical expression for the conservation of momentum of two bodies interacting in one dimension (such as in this activity): $m_A v_{1A} + m_B v_{1B} = m_A v_{0A} + m_B v_{0B}$. Students seemed comfortable with this formulation; at least there were no questions about it. Edward asked the class how this concept applies to the proverbial "bug hitting the windshield" and several students were quick to reply that the bug and windshield both experience the same impulse and consequently the same change in their momentums. Edward then rederived the conservation of momentum expression starting from the equivalence of coincident impulses, i.e., $I_A = -I_B$, and thus, $m_A(v_{1A} - v_{0A}) = -m_B(v_{1B} - v_{0B})$, etc. About forty minutes remained in the period at this point.

Edward passed out Unit 9: Worksheet 1 (continuing Phase 7: *Model Deployment*: Elementary Deployment) and instructed students to start working on the problem associated with their (previously assigned) group number. The worksheet requires that students utilize the impulse and momentum formulas Edward had just developed but not the conservation of momentum. Edward circulated among the student groups mostly asking guiding questions, but he did provide a few direct answers to students' questions about which formula was appropriate to the group's problem. Edward commented to me later that because this content is somewhat more abstract than in previous units, students often get stuck on the worksheets because they attempt to apply formulas indiscriminately:

> One of the things that's happening in my classroom is that the students are taking the equations that they've used in other solutions and plugging them in as if they were going to work every time. So we talk a lot about first principles and going back to what I'm now going to call the "gateway" equations.

Most students appeared to be working collaboratively on their assigned problems; however, some groups finished quickly and started to socialize. Edward reminded the class that each student must individually submit a completed worksheet and students returned to work. About 10 minutes before the end of the period Edward instructed students to prepare whiteboards of their assigned problems for presentation during the next class.

The next day I observed Edward's 2nd period AP physics class, his 3rd period chemistry class, and his 4th period physics class. The day's classes were 5 minutes shorter (46 minutes) than normal because of a school-wide assembly. The AP class took a period-long test. Prior to the test, however, students placed 2' x 2' pressboard partitions between each occupied desk, essentially creating little study carrels (I had never seen such a thing before).

Edward's 3rd period chemistry class opened with a quick review of a worksheet problem in stoichiometry and then adjourned to prepare whiteboards for the rest of the problems on the worksheet. (Edward has adopted the Modeling pedagogy in chemistry to a limited extent and uses some of the curriculum but he has not yet taken a Modeling chemistry workshop – although he mentioned he might next summer.) It took little time for students to get their whiteboards ready since they had completed the worksheet problems in advance of the class and seemed to know exactly what was expected for a properly prepared whiteboard. The chemistry Modeling curriculum uses a “bookkeeping” technique for chemical reactions they call Before-Change-After (BCA). The emphasis of BCA is to track the number of moles of reactants and products before, during, and after a reaction has occurred. It is then an easy matter to calculate masses or volumes afterwards. That is, the focus of BCA is “how many” rather than “how much.” What stood out for me in this class, however, was that Edward did all the questioning, both procedural and conceptual, leaving no opening for student questions. The student-presenters, nevertheless, appeared to have no difficulty answering Edward’s questions. It may be the case that since Edward had not fully implemented Modeling in chemistry, he had not yet cultivated a discourse environment entirely suited for Modeling.

After just a few minutes of “touching up” their boards, the students in Edward‘s 4th period physics class quickly proceeded to the whiteboard presentations of Unit 9: Worksheet 1. Unlike in the chemistry class, the first question for the first group of presenters was asked by a student. The question seemed to me to be purposefully trivial (“Is momentum proportional to mass?”). The worksheet problem asks students to compare the momentums of two objects with identical velocities but different masses, so the student’s question merely recapitulated the worksheet. The remainder of the questions for the first group, perhaps two or three, were from Edward. This same student asked the first question for the second group and, again, the question was a paraphrase of the worksheet problem, but the group struggled with the phrasing of the question. The worksheet problem asks students to compare the momentums of two objects that have identical masses but different velocities; specifically, one object has twice the velocity of the other (and, therefore, twice the momentum). The student’s question was whether the product $2mv$ is identical to $m(2v)$. As the group pondered a response, another member of the student audience attempted to rephrase the first student’s question, but as this did not seem to prompt a meaningful reply from the group, Edward rephrased the question yet again. This time the group was able to provide a correct response. When I queried Edward about these exchanges later he told me that this student is “very exuberant and likes to interact” and often asks good questions, but sometimes does so to the point of distraction.

Edward did all the questioning of the 3rd and 4th groups and, given that the problems were simple calculations, Edward’s questions were similarly simple. I did find it interesting, however, that the three members of group 4 had arranged to alternately recite the various steps of their solution. I also observed members of the audience copying these solutions onto their worksheets, a practice I have witnessed in my own classes with some disapproval. Edward did not seem to notice it.

Group 5’s problem concerned the impulse delivered to a baseball struck by a bat. The “exuberant” student described above jumped in first again with a question about whether the angle at which the ball is struck could affect the answer (not directly). A second student asked the group to clarify their numerical solution (it was a little hard to read). For the sixth group the challenge was to extend the work of group 5 by solving for the force of the *ball* on the bat, which they did correctly, i.e., the force of the ball on the bat must be equal in magnitude but opposite in sign to the force of the bat on the ball. Edward then posed a more conceptually-oriented question than he had done for any of the previous groups, undoubtedly anticipating the upcoming lesson on collisions. He asked, “Since we now know that the magnitudes of the forces are equal, what is the effect of the mass of the ball and bat on their acceleration during the impact?” The group handled the question well; correctly pointing out that the much smaller ball must experience a far greater acceleration than the bat. A student in the audience asked about the sign of the force of the ball on the bat and a group member responded that the sign must be opposite the force of the bat on the ball in accordance with Newton's third law.

The seventh and final group of the day was tasked with calculating the length of time a rocket's engine must fire for the rocket (constant mass) to attain a particular speed. The problem requires that students first draw a force diagram for the rocket. This step helps students realize that they must find the *net* force on the rocket (the rocket's thrust minus the force of gravity on the rocket) to find the correct solution to the problem. I was a little surprised that Edward did not take this opportunity to revisit his original formulation of the impulse-momentum theorem, $F\Delta t = \Delta mv$. This would have been a good time to discuss the constant mass constraint on the elementary form of the theorem and, at least, introduce the "rocket equation" which incorporates the time rate of change of the rocket's mass as it burns up its fuel. As it was, the group properly included the relevant forces acting on the rocket to solve the problem. At this point, about nineteen minutes remained in the period.

Edward next showed another video clip, this time from a James Bond movie, for which he provided students with a worksheet. In this scene, our hero, suspended by a bungee cord, jumps from the top of a dam to fall some 722 feet. At the bottom of his fall, just before the cord begins to retract, he shoots a roped piton into a building located beneath him and pulls himself down. Obviously, the students' task was to calculate the impulse acting on Bond that makes a soft landing possible. There was a brief exchange between a couple of students and Edward regarding the effect of air resistance and whether Bond ever reaches terminal velocity (he does and this must be taken into account). Solving the problem also requires that students dredge up previously learned kinematics and conservation of energy models, so it is more sophisticated than simply entering numbers into the impulse-momentum equation. Students worked in pairs for the remainder of the period.

Monday's AP class was much like the previous class with the same interactive lecture/demonstration format. Edward started off with a PowerPoint presentation on electrostatics, punctuated with many challenges to the student audience to explain aspects of electrostatic behavior depicted in the slides or demonstrated with various props. After the lecture Edward showed a short video clip, circa 1959, on electric lines of force from "Physics Video Classics."

The students in Edward's 3rd period chemistry class moved immediately to the lab benches in order to complete an activity they had begun a few days earlier. They had been waiting for the filtered precipitate from a double-displacement reaction to dry out so they could weigh it and add this datum to their data tables. This datum also provided them with the last bit of information they needed to complete whiteboards for the lab. This process took about 20 minutes after which the whiteboards were set aside.

Edward then proceeded to work through the combustion of octane (gasoline): $C_8H_{18} + O_2 \rightarrow CO_2 + H_2O$. As seems to be his practice, Edward constantly sought input from the students to motivate and justify each step of the derivation. Edward uses this particular reaction for a few reasons. First, it is a little more difficult to balance this reaction than the simpler single- and double-displacement reactions with which students are familiar. Second, it is personally relevant to students since this is the basic reaction that powers their cars. Third, the balanced equation, $2C_8H_{18} + 25O_2 \rightarrow 16CO_2 + 18H_2O$, reveals the large amounts of greenhouse gases produced in the burning of fossil fuels.

For the final 20 minutes of class, students were split into groups to work on a “March Madness” chemistry challenge. This was a worksheet setup like the annual NCAA basketball tournament brackets. Different chemical compounds (reactants) sit on “opposing” brackets and the “winner” is the product of the reactants. This product then becomes a reactant in a new reaction and so on until the final product is revealed. Some students instead worked on the lab or the worksheet from the previous class.

Edward opened his 4th period physics class with another review demonstration of the exploding-carts paradigm lab (this was a Monday, after all). The difference in this review, however, was that Edward acknowledged that there was, in fact, an impulse delivered by the spring to the two carts which was not directly investigated in the lab. (My data do not indicate that Edward said anything about internal versus external forces in such cases but he should have. An important constraint on the principle of the conservation of momentum is that it holds only in “closed” systems, i.e., systems to which no external forces are applied. Since the spring is internal to the system, the conservation of momentum is perfectly applicable.) Edward continued his practice of asking students to name, describe, and explain each aspect of the carts’ behavior as he performed the demonstration. He also paraphrased students’ comments using more appropriate vocabulary so as to reinforce proper use of the new terminology (e.g., “impulse,” “initial momentum,” “final momentum,” etc.). I noticed that a few students did not appear engaged in this lesson as they had been during the two previous reviews.

After the review, Edward moved on to a series of “pre-lab” demonstrations involving collisions (students will perform this lab during the next class). The apparatus was essentially the same one as described above but with two simple modifications. Edward alternately installed Velcro strips on each cart to demonstrate inelastic collisions (the carts stuck together) and then similarly polarized magnets to demonstrate elastic collisions (the carts “bounced” off one another). As before, Edward asked for student input during the demonstrations, but he expanded his focus to include energy considerations (recall that in the “standard” Modeling curriculum energy, Unit 7, precedes momentum, Unit 9). When Edward asked about the system’s total energy, students were quick to respond that total energy is always conserved. “What about kinetic energy,” Edward asked, “is kinetic energy always conserved?” Students’ responses now were not so quick and Edward had to provide prompts such as asking students to consider what happens when the pieces of Velcro stick together. However, Edward did not directly answer the question about kinetic energy, leaving it unresolved for now.

I was particularly struck by the near constant dialog between Edward and his students but also by the fact that there were no side discussions among students, though this format perhaps made it difficult for attentive students to do so. Edward closed this phase of the lesson with a demonstration using “happy” and “sad” rubber balls – one has an excellent bounce (happy), the other just thuds on the table (sad). Edward asked students to ponder this result. About fifteen minutes remained in the period.

Edward, obviously reacting to what he had observed of students' work on Worksheet 1, said, "I noticed you guys were using old equations that worked under other conditions. I want you to start from first principles – the conservation of momentum will always work." He then passed out Worksheet 2 and directed students to get together in their groups and get to work; he said, "As always, work wisely." Worksheet 2 presents students with a series of problems that invoke the principle of the conservation of momentum, so I was somewhat surprised that he assigned it in advance of the lab, that is, prior to students' own experimental investigations intended to develop the principle. When I queried him about this later, Edward said,

> Since the computers are going to measure the velocities, they're going to have all those quantities; they're going to measure the mass, they're going to measure the velocities. However, I do see the conservation of momentum, the use of that equation, as a segue into collisions and what's going on with collisions.

Edward circulated around the room as students worked and responded to students' questions with guiding questions of his own, though he did sometimes confirm or rephrase students' solutions. Most students seemed to be on task.

Assessment

Edward is something of an enigma. During my three days in Edward's classroom, I did not observe what I would call ideal Modeling. There was lots of talk, but it was almost exclusively between Edward and his students. What little talk there was among students was confined to a few brief exchanges as students worked together on whiteboards or worksheets – the same sort of talk one might hear in any busy classroom. This may be due to several factors. As I mentioned above, the Modeling curriculum guidelines suggest an interactive lecture/demonstration for developing the impulse-momentum relationship because of its comparatively abstract nature. The underlying conceptual challenge for students, of course, is Newton's third law, which students investigated somewhat back in Unit 4: Free Particle Model. Unfortunately, several student misconceptions are associated with this law that are resilient to instruction, sometimes even Modeling instruction, and make the law easy to misconstrue. The most familiar of these misconceptions, for example, is the belief that objects with larger mass exert more force than objects with smaller mass. My point is that the impulse-momentum relationship is distinctly counterintuitive for many students and thus it can be difficult to devise a paradigm lab in which students could identify the relevant variables themselves. Therefore, "giving" the students the impulse-momentum equation, as Edward did (but, again, not without their active participation), may have been appropriate. Edward's obligation then was to ensure that students had ample opportunity to engage in meaningful discourse about this new idea, but this he did not fully accomplish, as described above. Moreover, the algorithmic nature of the worksheet/whiteboard problems makes their usefulness in this regard somewhat problematic. In any case, student learning would have been better served if more of the questioning had been student initiated.

Edward, like Allan, also mentioned several times feeling pressed for time:

> Time, time, I don't have enough. I'm constantly pulling things together at the last minute. I saw this interesting video on teachers; it was a parody, satire of teachers, and they were asking different teachers what they do, and this one person said

> that when I become a teacher I'm going to teach one year 25 times. I see people around me do that. I've never been able to do that. I've had a lot of jobs, as I mentioned, I never had a job that wears on me like this one does because I'm always thinking about what I could do differently, I always know I could do something better, and as a result I'm constantly redoing things. In some ways that keeps me sane because I'd go crazy if I had to do the same thing, but I think the biggest limitation on me is just the time I have to teach.

Now it is late in the third quarter and if his juniors are to get any exposure to physics beyond mechanics before the state test, time is of the essence. Given this pressure, Edward's desire to move things along clearly helped write the script for these last few days. Notwithstanding this last comment, the conduct of class was a carefully orchestrated sequence designed to maximize student engagement under the circumstances and I was impressed with the scope and pacing of the activities.

The other half of the enigma is that Edward's students exhibited few procedural or conceptual difficulties with the material during lecture/demonstrations or whiteboard presentations. With very few exceptions, every student whiteboard in both his physics class and in the one chemistry class I observed displayed a proper solution to the assigned problem and every group successfully explained their solution. It is true, as I point out, that Edward did some coaching while students prepared their whiteboards, but so does every Modeler I have observed. It may also be the case that each group had at least one able student and it was he or she upon whom the other students relied – also not atypical for a high school physics class. The situation may have been similar with respect to student participation during Edward's lecture/demonstrations as well – the most capable students may have monopolized the student half of the dialog. On the other hand, Edward may have sufficiently prepared his students, via Modeling, that they were now able to assimilate the information as presented. However, without more robust evidence of classroom discourse, I find it difficult to judge the full extent to which Edward has implemented the Modeling pedagogy.

To be fair to Edward, I only observed a brief moment of his curriculum, but I did have the opportunity to speak with him about his teaching. Among other things, I asked Edward what he thought was the philosophy behind the Modeling pedagogy:

> I think one of the things that it really establishes in a Modeling classroom is discourse, that it really is the conversations that the students have with themselves, [that] the students have with me, and that I have with them. I think that's really an inherent aspect of Modeling. It's not something that's in the traditional class. You know, you certainly get the give-and-take with a class or with a student but, nevertheless, I think in those situations, and I'm as guilty as anyone when I was a student, I knew what the right thing to say was, but I didn't necessarily know why it was right. But I could tolerate that sort of conflict. I don't think that's a sign of a good student. In fact, I think a good student is one of those folks who come at you and at you and at you because they don't understand something. But I think that the philosophy of Modeling is to get students to use the vocabulary, talk about what they are doing, what they think is happening, what they think should

> happen. Out of that either they encounter problems with that and fix it on their own or, with careful listening, which is part of being a good Modeling teacher, you can draw those things out and let them see them [the problems] themselves rather than tell them how this is wrong, this is what you should think. I think you really let them work a lot of things out on their own. It's one of the reasons I'm sort of hands off in the beginning and get more hands on towards the end of a unit.

This response suggests that Edward has assimilated the theory of learning that undergirds Modeling, that the purpose of Modeling is to create just such an environment as Edward describes to facilitate students' self-construction of scientifically-aligned conceptions of physical phenomena. Edward also mentioned that he had attended other programs of professional development for physics teachers (Amusement Park Physics and Comprehensive Conceptual Curriculum for Physics) before going to the first Workshop. Considering that he does not use much of the curricula he acquired from these programs, I asked him why, after eight years, he still keeps Modeling:

> I like it, I like it a lot. It's a much more interesting way to teach, I find that student interest is much higher; they're up there out of their seats, they're moving around. I don't think you've seen that as much as it actually happens in here just because of the timing of all this, but they like it. I mean they love to get up and whiteboard – they're all hams and they want to get up on stage. But I guess the real reason I like it is that it allows me to engage the kids in a different way. That is, they are curious [and] they do want to know how to do it right, so we have conversations about what that process is all the time without me being, well, I suppose I am the expert in the room, but I feel like I'm just another resource in the room rather than the sage that's up there to tell them what's going on. I find the interaction with the groups to be the most powerful. You know, it's almost like being able to tutor these guys in class because you can go around from board to board and look at what they're doing, I can ask questions and you can deal with that in a much more informal setting and I find that really powerful.

This language also is consistent with the Modeling philosophy, but I decided to probe a little deeper. I asked Edward how he knows his pedagogy is effective:

> There we get some Modeling. I know because they remember it. I know because they've come back to me and told me that. I had a kid who's an aeronautical engineer now tell me, "Thanks for the force diagrams, I'm still using them, you know." I thought that was real interesting, and I made him come in, he was out in the hall, and tell my physics class just to stop them complaining about doing force diagrams. But I find that they seem to internalize it more, they do remember what it is that they've discovered in the lab better or the discussions we've had here than they did when I just told them the way it was. And I when I gave the FCI to my AP class last year, the Modeling kids smoked them, and yet in terms of who is in those classes, you know, they shouldn't be scoring higher. I thought that was interesting.

Edward’s last comment about the FCI, in particular, would seem to indicate that he has indeed been successful with Modeling. But in order to ascertain the extent to which Modeling has transcended mere technique, as it is for Charley, to become a teaching philosophy, I asked Edward how the Modeling pedagogy is important to his teaching:

> I think it fits my style better. I mean even though I thought I was a very good lecturer, I'm fairly low-key in my classroom, I try not to be a real dominant force, I try not to be a real dominant person, and be approachable. So it allows me to be part of a seminar in here rather than a real traditional sort of class. And I like experimenting, I like to play, that's why I'm a scientist, you know, I mean that's what I did. So I feel like although I don't know all the answers, I know the answers that they are trying to derive here, it's still kind of fun to work out problems and figure out ways to do it. I still try to come up with new ways to do some of the labs and so in that respect the pedagogy really suits me.

I am convinced that the sentiments expressed above can best be attributed to a teacher who has experienced a genuine reconceptualization of his role as a physics teacher.

Significantly, Edward did not complete extensive course work in physics. Most of his background was the work he did preparing to teach and in teaching physics the six years prior to attending the Modeling Workshops (plus the enrichment activities described above). This limited background might have made Edward susceptible to the empiricist perspective and such a view is suggested by his responses on the VASS. He was the only subject to present the folk view on questions 21 and 22, that is, that the laws of physics are independent of how humans think and portray the real world exactly the way it is. However, Edward also indicated a certain ambivalence on the other nature of science questions on the VASS that suggest his beliefs were not so hard and fast. For example, he positioned himself equally between the statements that Newton’s laws of motion “will always be used as they are” vs. “could eventually be replaced by other ideas” (question 24). In contrast to these scores is Edward’s statement that he “was always interested in alternative methods of teaching” and the fact that he had already experimented with Modeling curriculum before attending the first Workshop. Thus, I believe that with respect to the VASS, Edward was revealing his inexperience with physics rather than any particular epistemology. Now that he has had the benefit of the Workshops and eight years practice as a Modeling teacher, I think Edward’s scores would be very different today.

Edward’s 3-day RTOP average was a relatively low 71, mostly because of the lack of hands-on activities and student-to-student discourse I have described. As Edward points out, however, this may have been more a timing issue than a true reflection of his pedagogy. Edward’s score is still well above the “reform threshold” of 60 and is due primarily to his relentless questioning during interactive lecture/demonstrations and the variety of activities in which students were engaged. Furthermore, unlike David, for example, Edward made a point of having students apply their new knowledge to situations outside the classroom that they might see its ramifications in the real world (video clips). Finally, the few physics foibles that Edward committed, though mistakes no physics major would have made, are not directly addressed in the Modeling curriculum notes or student materials and, hence, are forgivable. Given all this plus his comments during the post observation and extended interviews, his lowest score on the Modeling Instruction Survey (a 1.6 average on a 1 to 5 scale, where the range of scores extends up to 2.5), and his students' highest average gains on the FCI, I conclude that Edward did experience a significant transformation in his conceptions of physics learning and teaching at the Modeling Workshops.

Frank

Teacher	Modeling Instruction Survey		3-day RTOP Avg.	Baseline Student FCI (spring '98)	Long-term Student FCI Averages %		
	1999	2007	%	%	Pre	Post	Gain
Allan	185/3.1	135/2.3	90	39.3	24.4	50.3	33.9
Brian	n/a	148/2.5	80	43.7	35.8	66.4	47.7
Charley	n/a	149/2.5	70	49.7	n/a	n/a	n/a
David	n/a	130/2.2	84	35.0	37.8	65.8	45.0
Edward	145/2.4	96/1.6	71	n/a	30.4	72.0	59.8
Frank	***168/2.8***	***114/1.9***	***87***	***41.7***	***26.0***	***52.4***	***35.6***

Background

At the end of Frank's first year at the school, he was asked if would teach a physiology class for next year's seniors. Instead, he persuaded the administration to let him create a physics class as physics was not offered at that time. Frank designed the class himself and, the following year, was able to expand enrollment to include juniors because, as he said, "I really prefer them to have physics before chemistry." However, the administration decided not to continue this sequence for the upcoming school year preferring to reserve chemistry for juniors and physics for seniors since that was the conventional progression. This meant Frank would not be teaching physics the next year, all the juniors having already taken his class, and he decided to seek employment elsewhere. Now that he had his credential, Frank hoped to find a position at a public school since the pay would be better. Frank's tenure at this school had lasted four years.

Frank next moved not too far away to a large public high school that had a highly regarded science program. His daily schedule was three 90-minute periods of senior physics. Frank said this school was a wonderful place to teach; the students were all college-bound and the curriculum was the renowned "Project Physics" with its unique emphasis on the history of physics. Moreover, with 90-minute periods, Frank was able to get through almost the whole text over the course of the year. Frank said the entire school was very proud of the reputation of the science program and he would be there still except a family crisis compelled him to move to New England. Frank was at this school for three years.

After his relocation to New England, Frank spent one year at one school and two years at another. Frank said he was very unhappy at the second school because the administration made programmatic changes that swelled the enrollment of special education students in the 9th grade physical science classes he was teaching, but they stopped providing instructional assistants to help with the students. He left that school and moved to a third school where his assignment was "all physics, all the time." He was very happy at this school and remained there 12 years until he decided to remove his family to the desert Southwest so his child could attend a public high school for the performing arts – where Frank also now teaches. It was Frank's first year at this school when I observed him.

In 1996, Frank's roommate from his graduate school days, whom he had first met as an undergraduate and by this time was a physicist at Los Alamos, sent him the first pages of several articles from the *American Journal of Physics,* including "A Modeling Method for High School

Physics Instruction" (Wells, Hestenes & Swackhamer, 1995). Intrigued, Frank asked his friend for the rest of the paper. After reading the article, Frank applied to the program but had to postpone his participation for a year because of the birth of his child. Thus, Frank attended his first Workshop in 1998 following his 14th year as a teacher.

Frank was by no means new to inquiry-based physics instruction, however. Frank told me that during his time at the girls' school he had been actively involved with a local "teachers' institute" that promoted a very hands-on approach to science teaching. Furthermore, in his letter of application to the Modeling program, he wrote that this experience had been "an invaluable resource in developing my abilities to teach the concepts of physics in a way which was accessible to most students, *but their misconceptions persisted throughout the course and seemed to change only minimally by the end of the academic year*" (italics added). Frank goes on to say that he had become aware of physics education research in 1990 when he read *A Guide to Introductory Physics Teaching* by Arnold Arons. In reading this book, Frank says he found "that many of the issues I was confronting were the subject of current research and debate." In the same letter, Frank wrote that a few years later he had the opportunity to "conduct hands-on experiments using computer-based motion detectors" and that "the experience convinced me that this was one of the most effective teaching tools I'd ever seen and that, properly used, it could help students to confront their misconceptions about the differences between velocity and acceleration." Finally, Frank says that after reading "A Modeling Method for High School Physics Instruction" he "recognized that Malcolm Wells and David Hestenes had developed a program that addressed virtually all of the shortcomings I had perceived in my own methodology." Thus, in the space of a paragraph or two, Frank had laid out the evolution of his conceptions of teaching that eventually led him to the Modeling Workshops.

> When I asked Frank about his experience at the Modeling Workshops he had this to say,
> It was, without a doubt, the best professional development experience of my career. Our entire group of 24 participants took to behaving like students so well that we had to institute a 25-cent fine system to penalize those who said something so outrageous that even our most clueless student would have been embarrassed. It paid for a really nice party at the end of the workshop, too! [But] the pedagogy was really the hook for me. I knew the content already but was looking for a method of teaching that would work better for my students.

I asked Frank what it was about the Workshop that made such an impression on him:

> The Workshop was different than any other workshop I'd ever been to. For one thing was a lot longer. But the difference was that it wasn't a workshop where somebody just told you how to do stuff; it was a workshop where you did the whole mechanics curriculum in four weeks. Usually when you go to a workshop you get a sample of something, a little bit of this and little bit of that, but you don't do the whole thing. And you also don't get a chance to practice it. We did everything. The nice thing about it was you could just sit there and over the course of the four weeks it was like, "Yeah, this will work a lot better than what I'm doing"; you could really see the value of what was happening.

I was intrigued by his last comment, so I asked him what it was that he saw there that he thought was of such great value compared to what he had been doing prior to attending his first Workshop:

> A lot of it was the whiteboarding. It's like I get a chance to see inside my kids' heads, my students' heads, which I don't get any other way. I think the other piece was the way it's organized, the way the curriculum, the way the method’s organized makes sense to me. You start with the experiment because, I forget who said it, but physics at its heart is an experimental science. Without the experiment then you have all these great theories, but if you never test them. It goes back to what science is and what scientific knowledge is. You start with the experiment and then you try to explain it and then maybe that explanation generates a new experiment.

With respect to implementing Modeling in his classroom, which, of course, he did first at his previous position in New England, Frank said he has faced no obstacles at either school from any constituency – not even from students:

> I'm very up front with them. When they walked in at the start of year, I was very up front. I said, “I'm going to do something different from what you're used to but it works and I've got the proof that it works. So you're going to be asked, you're going to be doing these things differently, you're going to be up here, you're going to be talking. The only way it's going to work is if you share with me what you're thinking because that's the key piece. If I know what you're thinking I can help you get to where I want, what I want you to be thinking. But if you don't share it with me don't complain to me later when you don't get it because if you're not letting me know what you're thinking I can’t help you.” My administration was very supportive, they provided computers and money for sensors.
>
> I have always considered myself extraordinarily lucky. The principal at [the school in New England] said, I had both of his kids in class, you know, he said, “You do it, you do what you think's best, just tell me how I can support you.” One of the things I think that really helped was on open house night to have different experiments set up and whiteboards, different experiments set up for the parents to see what the kids were doing. A lot of the kids would come with their parents on that night and they would come in and they would say, “This is what we're doing and it's really cool, we get to do this stuff and we’re playing with the computers.” The parents that were professional engineers and scientists came in and said, “You know, this is the way it should have been like when I was in high school.”

I also asked Frank about his initial experiences with the new pedagogy:

> It was a huge change when I went from 75-80% lecture presentation of material to 95% not lecturing and it still remains that way. The first couple of years were really slow, but I worked through that. I still go through the first units on motion pretty slowly because I think they're really important and basic; if the kid doesn't

> get acceleration, the rest of year is pretty much not going to work for them.

Like David, Frank has made substantial revisions to the Modeling curriculum materials, including, he said, completely rewriting Unit 4: Free Particle Motion. His motivations, however, are different. Frank has been a Modeling Workshop instructor since the first summer after completing the Workshops himself (2000). In addition, he is an assiduous reader of physics education research. These two unique sources of information have proven invaluable to Frank in terms of provoking new ways of thinking about his curriculum, such as the lesson I observed, but always within the context of the Modeling pedagogy.

> A lot of it is learning from people that already know the physics, but, they're learning to teach this new way, too, and they have ideas. They say, “Oh, what about this, this might work better for my students,” things like that, and so there's going to be new ideas. The other thing is, I think it was back in 2002, somebody at the ___ University started a physics alliance up there but that was too far for me to travel, an hour and a half each way, and I thought why can't we have one in near where I live? So I got some money from ___ College, which is in the city right across the river from where I taught, to actually pay teachers to come to a monthly meeting and talk about physics. We got dinner and 50 bucks for showing up, that kind of stuff, and actually everybody had a copy of Arons, and so that started in January, 2003 and I don't think I ever missed a meeting; it was a good opportunity.

Observations

The main facility of Frank’s school is a converted single-story Spanish-style office building located just outside the downtown area of the city. The school faces onto grassy lot and has a pleasant courtyard between its two parallel wings. Additional classrooms are leased from a church across the street. Frank’s classroom occupies the space vacated by an ambulance service. The space is comprised of three or four small offices and rooms that Frank uses for a personal office, equipment and chemical storage, and a quiet study area for students; a larger room, perhaps 25’ x 35’, that serves as his classroom; and a restroom. Student tables fill two-thirds of the larger room, surrounded on two sides by counters with storage space below and work space on top, including a couple of sinks. Six or seven computers of various vintages sit on the countertops and Frank has a full compliment of PASCO interface boxes and probes. The room is small enough that the student tables must be moved to allow easy access to the computers and the tables themselves are often used during labs. A screen, a large whiteboard, bookcases, bits of equipment and assorted paraphernalia, plus Frank’s teacher desk and computer fill the remaining third of the room. A bank of windows along Frank’s third of the room and a glass door provide some natural light. However, the room has only 7-foot ceilings and it seemed somewhat dark. Walkie-talkies comprise the intra-school communication system.

Core classes are conducted only in the morning, four periods per day, from 7:45 until 12:15. Classes are usually 60-minutes long, but the schedule rotates to provide for two 90-minute periods plus one 60-minute period on Wednesday and Friday. The rest of Frank’s day is spent meeting with his grade-level team and, during third quarter, working with students preparing for their senior project presentations. I observed Frank’s classes over a four-day period, Monday through Thursday, near the end of third quarter. Frank teaches two periods of physics, 1st and 3rd periods, and two periods of chemistry, 2nd and 4th periods. Due to scheduling requirements Frank's physics classes are tracked according to students' math level placements. First-period physics has 20 students, including six boys and one non-Caucasian; 3rd period physics has 18 students, including six boys; 2nd period chemistry has 16 students, including three boys; and 4th period chemistry has 20 students, including seven boys. Except for the single non-Caucasian student in 1st period, all Frank's students are white.

When I observed Frank's physics classes he was just starting on Unit 5: Constant Force Particle Model, though he had already done projectile motion which is normally part of Unit 6: 2-Dimensional Particle Models. Frank said he is "way behind" in his curriculum compared to previous years, in part because this is his first year at the school, but also because the non-academic demands on students' time are so extensive that he has had to slow down to give students more time to stay caught up on homework. I arrived in Frank's classroom in time to watch his physics classes begin an investigation of Newton's third law (corresponding to Phase 5: *Model Formulation*: Investigation and initial model formulation). As the attentive reader should have surmised by now, Newton's third law is a particularly difficult concept for students to assimilate and a source of frustration for conscientious physics teachers, myself included. It was with more than usual interest, therefore, that I observed the proceedings. We begin at 7:45 on a Monday morning in Frank's 1st period physics class, which he described as his "higher math-level class."

Frank passed out a very detailed worksheet he had prepared outlining six activities exploring Newton's third law in different situations. Frank told me later that he designed the activities based on work of Bao, Hogg & Zollman (2002) that identifies the contextual nature of students' misconceptions about Newton's third law. The authors isolated four themes in their analysis of student reasoning in problem-solving situations involving Newton's third law: velocity, mass, "pushing," and acceleration. For example, some students believe that in a collision of two objects with the same mass, the object with the greater initial velocity will exert the greater force. Similarly, students believe that in a collision of two objects with different masses, the object with greater mass will exert the greater force or if one object is pushing another object, the object doing the pushing exerts the greater force. And, finally, if one object has an initial acceleration, the accelerating object will exert the greater force. In these last two cases, the objects' masses are assumed to be equal. Thus, the activities on the worksheet give students the opportunity to investigate the interaction between two objects in each context. A critical feature of each activity is a force sensor of some type constantly measured the forces exerted by each object during their interaction, which was displayed on a computer-generated F vs. Δt graph. In most cases the sensors are force-probes mounted on dynamics carts or battery-powered toy vehicles, but one exploration has students pushing off one another with force plates (bathroom scale-sized force sensors with handles).

To start the activity, students first must have answered a "focus" question on the worksheet that asks them to predict which object in the given scenario will exert the greater force and to provide an explanation for their predictions. The worksheet includes space for students' predictions, observations and data, force diagrams, and conclusions (as well as a photo of the setup for each activity – it was clearly the product of several hour's work). For this class period, students were required to record their predictions, data, and observations, and to start answering the five questions in the conclusion.

Students worked in groups of three or four and progressed sequentially through the stations, each group starting at a different station. Frank was constantly circulating around the class and kept students on a schedule of six or seven minutes for each activity, which seemed to be adequate, though Frank did have to attend to a couple of computer glitches along the way. I overheard some wonderful exchanges among the students as they argued about their predictions, voicing every misconception Bao, Hogg & Zollman (2002) had described; the negotiating and bantering; and registering shock when the F vs. Δt graphs were *always* nearly identical. I observed very little off-task behavior. Frank closed the class by telling students, “Think about what forces are acting, starting with your first activity.”

Events in 3rd period physics proceeded similarly except Frank spent more time on his introductory remarks (this is his “lower-level” class). He went over the worksheet and procedures and emphasized that students should carefully read the focus questions as well as the questions in the conclusion before starting an activity. He also told students there was no need to do force diagrams at this time. After the last rotation through the activities, Frank settled the class and responded to some students’ concerns about the small disparities in the F vs. Δt graphs for any given activity, ascribing them to subtle differences in the sensors’ calibrations and sensitivities. As any science teacher will attest, if the teacher proposes that two quantities are the same based on measurements, some students will insist that the quantities be absolutely identical and look askance at arguments about the inherent uncertainties in any measurement. However, students seemed to accept Frank’s explanation. Frank closed the class by exhorting students to, “Think about what forces were acting on the objects and what their motions were like. What were the other forces (e.g., gravity, friction, and normal force) that were acting? Also think about a force diagram for this situation.”

Frank’s 2nd and 4th period chemistry classes were kept busy doing a lab demonstrating the conservation of matter.

Frank opened Tuesday’s 1st period physics class by immediately setting the tone: “I want to start on the force diagrams today, but first what did you find out in the activities? Speak, call on one another. [Student] you go first.” The conversation proceeded as follows:

S – The forces were equal.
T –Let’s talk about which forces we’re talking about.
S – Gravity and support forces canceled so the rest must be the forces between objects which also were equal.
T – What do the rest of you think? I’m not calling on people, just speak if you have something to say.
A – A few murmurs of agreement from student audience (A).
T – [to S] Draw a picture, include the forces.
S – [Went up to whiteboard and drew a picture of the setup – a man, “Bob,” pushing a car]
T – Can you draw some of the forces?

S – [Force diagram mostly correct, except did not show equality of action/reaction forces]
T – Which two forces did we measure?
A – The action/reaction forces.
S – [Adjusted diagram to show action/reaction forces equal]
T – So these forces (pointing to the action/reaction pair) are equal and opposite. But what about the motion of the objects? Do they always have to be the same?
A –No.

Frank continued asking undirected questions specifically trying to get students to say that the action and reaction forces act on different objects. That is, forces do not exist except as coincident pairs – if an object experiences a force of any kind then it must be exerting an equal and opposite force on the agent. Students seemed to be struggling with the terminology. I noted also that boys monopolized most of the discussion.

Frank next directed students to talk in their groups and come to a consensus on the answers to the worksheet questions. After about 10 minutes, Frank said, “Let’s summarize what you’ve concluded. I’ll write it down, but you do the talking.” One student offered his conclusion which Frank paraphrased: “The forces are equal in size and they act in opposite directions.” To this he added a comment from a second student: “They do not ‘balance’ because they don’t act on the same object.” Frank reiterated this last point saying that the term “balanced” is used when then the sum of forces on a *single* object is zero. Frank then summarized the relationship between action/reaction forces yet again, but this time he made a distinction between internal forces, which act on a single object, and forces acting on separate objects. Frank closed the class with a brief demonstration on drawing force diagrams for interacting objects. He instructed students to complete a diagram for each of the activities and prepare a whiteboard diagram for one of the activities to present during the next class.

As in the previous day’s 3rd period class, Frank did a lot more talking than in 1st period: “What we’re going to do today is talk about the results you found yesterday, what was confusing about it, and how to resolve that confusion.” He then summarized the six cases with respect to the relative motion of the objects: stationary, constant velocity, accelerating, pushing, or pulling. Frank next solicited students’ observations about the activities and directly questioned individual students so as to elicit a more precise description (e.g., which forces were equal, how do you know the forces were equal, how did the objects behave, etc.). After one such exchange Frank asked, “Are these activities examples of the same situation as, say, a book resting on a table? At this point this should be something of a mystery to you, that the forces are the same independent of the motion of the objects.” The conversations between Frank and each of the groups continued for a few more minutes. Frank waited patiently for responses to his questions.

In the next phase of the lesson, Frank asked students to summarize their conclusions for the activities:

T – Let’s go through the questions. What did you find out? Let’s write those things down.

S1 – Isn't this Newton's third law?
T – Hey, somebody's been reading, doing research for their….
T – [Listing student comments on whiteboard] Forces always come in pairs, equal in size, in opposite directions
S1 – Why are the forces equal when the masses aren't?
T – We don't know why, but we know that they are. This is not a cause and effect relationship. We have both forces or none – immediately.
Who will draw a force diagram for their activity?
S2 – [Same example as 1st period. Initial force diagram syntactically correct, but force vector magnitudes incorrect]
T – Anybody have questions about the size of the forces?
S1 – Shouldn't there be the force of Bob on the car [on Bob's diagram]?
S2 – No. The force of Bob is on the car's diagram.
S2 – [Coached by another student, S2 has amended the drawing to indicate congruence of the action/reaction forces, but did not change lengths of force vectors]
T – [Corrected S2's drawing]
S3 – Since the objects are connected, couldn't we treat them as one object?
T – Ooh! Good question! Sure, but how would we change the force diagram for the combined object? [Brief discussion about internal forces followed]
T – This is known as Newton's third law, as [S1] said, but since I never named the other two…

I noted that a few students were not fully engaged during much of the discussion. Moreover, as the text above indicates as well as other student comments I do not include, some students appeared to have a tenuous grasp of these concepts.

Frank closed this class as he had 1st period by demonstrating the steps for drawing a force diagram, but solicited student input at each step (e.g., "What forces are acting on Object A, etc.). His final words were, "What I want you to do for next time is draw [force] diagrams for each situation. Use the grid (on the worksheet)."

Frank's chemistry classes presented whiteboards for the lab they had completed during the previous class. Like Edward, Frank uses some of the Modeling chemistry curricula, but he has not yet taken the Workshop, and student whiteboards were prepared in the Before-Change-After (BCA) format I had seen in Edward's chemistry classes. Also like Edward, Frank conducted all the questioning himself. Unlike Edward, however, Frank asked few procedural questions but instead asked conceptually-oriented questions clearly intended to reinforce the principle of the conservation of matter (e.g., what was the limiting reactant, what if there had been more/less of this or that reactant, what quantities are/are not conserved during the reaction, etc.).

On Wednesday, Frank's first two periods were his chemistry classes. Frank had previously assigned readings from *The Making of the Atomic Bomb* by Richard Rhodes to give students an historical perspective on models of the atom. (Perhaps the "Project Physics" approach still influence's Frank's teaching?) Frank proceeded to present a lecture, without electronic visual aids, about the evolution of scientific models of the atom (e.g., J. J. Thompson's "plum pudding" model, Ernst Rutherford's nuclear model, Niels Bohr's "solar system" model, etc.), punctuated with questions to the student audience about the evidence for and against the different models. The students did not appear to be well engaged and were somewhat unresponsive to Frank's questions in both classes.

Wednesday's third period was Frank's 1st period physics class. Students' first task was to prepare whiteboard force diagrams for the Newton's third law activities completed in the previous class. Frank told students, "Concentrate on the following: Label all forces agent/object, label each object separately, and force arrows should be proportional, that is, forces of the same magnitude in different directions should be more or less the same." As students got to work, Frank reminded them, "Remember, force diagrams should correspond to the motion of the objects." About five minutes later, Frank, clearly reacting to what he had seen on one group's whiteboard, announced, "Be sure you indicate which is which. Draw a little picture [of the scenario]." Twenty-three minutes into the period, by which time a few groups had been ready for some time and were starting to socialize, Frank said, "Let's get started. Let's experiment – put the tables in a circle." This statement suggests that Frank had not previously asked students to arrange the tables this way, so I suspect my presence may have had some influence. However this may be, this format proved to be effective for both physics classes in terms of student participation. When I queried Frank about this later he said that he had just wanted to try something different, but he, too, was impressed by the level of student engagement.

The first group to present had the case of a person pushing against a wall (actually, pushing on a force sensor attached to the wall with another force sensor). Their force diagram included the force of the agent (person) on the wall in the person's own force diagram (a force or "free body" diagram properly includes only the forces *acting on* the object and none of the forces the object may be exerting). A student in the audience immediately challenged the group on this point. The conversation proceeded as follows:

T – Let's pick one diagram [each whiteboard has two diagrams, one for each object] and look at those forces. Are there any forces that trouble anyone?
S1 – The person's diagram has the force of the person on the wall.
S2 – What force opposes that force? [i.e., the force of the person on the wall – this student has not yet realized that this force is shown incorrectly]
T – You guys need to resolve this for yourselves. [More discussion among students focusing on the (improperly shown) action/reaction forces and that the force of friction on the person and the wall must be the same since neither object is accelerating]
T – Every force that acts on an object should end with the label for the object [e.g., the force of friction on the person is written $F_{F/P}$]. Are all four horizontal forces the same?
A – Yes.
T – Why?
A – Because the acceleration is zero.
T – We measured it, they're always equal!

The second group had no problems with their whiteboard, but Frank asked the group if their "force of road on car" was meant to indicate the force of friction (as opposed to the normal force – it was). The third group had a minor problem not indicating the equality of forces (with congruency marks drawn on the force vectors), which they corrected after Frank asked them, "So, what's equal in your diagram?" The fourth group's force diagrams were correct, but a student in the audience asked them, "Are the friction forces equal?" The answer is not immediately obvious in this case (a powered vehicle pushing an un-powered vehicle), because the force of (rolling) friction depends on the mass of the vehicle as well as the coefficient of friction between the tires and the ground. The conversation proceeded as follows:

G – [Frank] said we'll get to it later.
T – Does it matter?
G – [Shrugs and mumbling]
T – Can you explain how this corresponds to the motion?
G – [Adequate response]
T – Who's accelerating? How does the force diagram show this?
G – They both are during the push; the force of the push is larger than the force of friction.
T – What happens after they stop pushing?
G – Friction will slow them down.

The fifth and last group of the day had a similar series of exchanges.

Thursday's schedule also began with the two chemistry classes, but this day they were only 60 minutes long. Students finished their whiteboard presentations and Frank wrapped up this phase of the unit by listing the results (the ratio of products to reactants, plus error) the various groups had gotten for the lab. The ratios ranged from .974 to 1.138 and everyone seemed satisfied that matter was, in fact, conserved during the reaction.

Third-period physics was Frank's first physics class of the day. Since this class had not met the previous day, the students' task was to prepare whiteboard force diagrams for the worksheet activities. Frank had assigned the force diagrams as homework, but it was apparent very few students had completed them in advance of class. As students worked on their whiteboards, Frank did a lot more coaching and asking guiding questions in this class than he had in 1st period. He reminded the class that their force diagrams depict a "snap shot" of the forces acting on the objects at the instant of their interaction (i.e., a collision or push). The whiteboard presentations proceeded more or less as they had in 1st period, but I noted that Frank did most, but not all, of the questioning. I also had the sense that Frank's coaching was more overt than in 1st period because the students seemed better prepared than I expected based on my two day's observations. In any case, what stood out during this class was Frank's reemphasis of the principle that, "We know the action/reaction forces are equal because we measured them so." This was the first time I had heard Newton's third law so emphatically expressed as a purely empirical relationship rather than simply as an "axiom" inherent in the Newtonian world view. Recall that Frank had told his students, referring to the equality of action/reaction forces, "We don't know why, but we know that they are." He is absolutely correct. I sometimes ask my own students, however, to consider how things might be different if action/reaction forces were not equal, but this approach may presume they already have an intuitive grasp of the relationship they often do not.

First-period physics, Frank's fourth period of the day, finished up with the last whiteboard presentation (colliding vehicles). Frank used the occasion to lead a discussion carefully comparing the behavior of the vehicles to the force diagram and the F vs. Δt graph. Frank then directed students to work on a set of review questions in anticipation of whiteboarding one problem for presentation next week and a unit test the following day. The review questions were highly quantitative and require that students decompose force vectors in two dimensions (e.g., a mass sitting on a frictionless wedge connected by a rope that passes through a pulley secured to the top of the wedge to a second, hanging mass). The questions were very different from anything I had seen in class. I did not ask Frank how he had prepared his students to solve these problems.

Assessment

Frank utilized alternative, hands-on teaching techniques early in his career. Though these techniques helped make physics more "accessible" to his students, they often were not able to overcome the resilient nature of his students' misconceptions. A few years later, Frank became aware of the relatively new field of physics education research and saw discussed and dissected in print many of the frustrations he faced daily in his classes. But the true epiphany came when he had the occasion to read the full text of "A Modeling Method of High School Physics Instruction" and attended the Modeling Workshops. In a scholarly work such as this dissertation, it is sometimes difficult to put into words the true depth of feeling with which a subject may express himself or herself. As you read the following passage from my extended interview with Frank, please understand that at times he struggled with his emotions. I had asked him why he decided to apply to the Modeling program:

> I'd been unhappy for a little while about what I thought students were learning. I was looking for something that would work better than what I was doing. I don't know if I knew what I was looking for, but I think I knew when I found it or at least it was worth looking into something that seemed to make sense to me after reading the article about Malcolm Wells and how he taught. That was really kind of the inspiration for that. I think probably when I was getting ready to move, when I was cleaning out my classroom back in [New England] at the end of last year, oddly enough I came across that first page of the article that my friend, literally the page that he sent me, it was in something. I know I still have it because I put it aside. [Long pause] I remember pulling it out and saying this changed my life because now I'm taking my family, moving across the country, and the reason I'm doing it is because of what I learned, you know, from learning this method. If that hadn't happened I never would've heard about this school, I never would have had that opportunity for my son when he comes here, and literally a life-changing experience for me and for my family. It was such a moving experience to find that in my papers, just that, you know, that that was it, you know, it was like one sheet of paper can change so much...

Frank's response is very similar to Brian's, but the sentiment is probably shared by most of my subjects (and many other teachers, as well, as reported by Modeling program staff). Frank was casting about for a better way of teaching physics, but he did not quite know what it should look like. After reading the article about Malcolm Wells, he was primed for his experience at the first Modeling Workshop and has since become a Workshop leader. That Frank has now fully embraced Modeling is indisputable. What can we say about his practice?

Frank is conscientious is in his implementation of the Modeling pedagogy and adheres to the Modeling Cycle with great fidelity, as I have shown. For the lesson I observed, he closely followed the sequence in the Modeling curriculum guidelines but he also enhanced and enriched the experience for his students by extending the lesson to include other activities meant specifically to address persistent misconceptions identified in the physics education research literature. This is not to say that my other subjects ignore this important source of information, rather Frank is more deliberate in accessing and applying it and has even contributed to the literature himself.

> I think one of the things that had the most impact on me was getting to know the research that was out there, the physics education research; that's really been a big piece. Every month when the Physics Teacher comes or the AJP comes my wife knows that I'll be gone reading somewhere for the next hour or so to see what's in there. It's really influenced my teaching because I think, I mean right away I started using the FCI, things like that, but more recently using the Lawson test [Classroom Test of Scientific Reasoning] to try to find some connections between the student's skill set when they come into the class and how they're going to do; can I find some connections or something I can do to help the students along while they're in my classes or something I can maybe do to help them before they get here. One of the reasons I'm here is that they were open to the idea of trying some of the work of Philip Adey and Michael Shayer in the sixth, seventh, eighth grade here using the "Thinking Science" [curriculum].

Frank is also similar to Brian in his delivery. He rarely does other than ask questions and his questions emphasize the conceptual over the technical or procedural aspects of an activity or whiteboard presentation. His questioning style is very patient and non-judgmental, but I noticed that boys tended to monopolize student discourse even in a classroom full of girls. Whether this says more about girls, boys, or physics instruction is unclear to me. Frank, however, is the only one of my subjects to have taught in an all girls' school, though it was several years in the past. Frank is also new to the school this year and this may have had some affect as he has not had the time to establish his reputation with the students and staff. Nevertheless, from what I observed, Frank is well-regarded by his students and they were comfortable in his classroom. Recall that this is a performing arts school with twice as many girls as boys, so perhaps the reader can imagine the occasional singing, posing, and drama that occurred and must occur regularly even in science classes.

Frank had been teaching physics for about 12 years before he attended the first Modeling Workshop and took the VASS, so one should expect him to have a reasonably "expert" perspective, which he did. Only on questions 18 and 21 does he present a "mixed" view. Question 18 reads, "How well I do on physics exams depends on how well I can: (a) recall material in the way it was presented in class vs. (b) solve problems that are somewhat different from ones I have seen before." Frank's response to this question surely has evolved since attending the Modeling Workshops:

> What I'd like for them to bring away from [my class] is just a way of thinking, you know, maybe nothing particularly about physics, but a way of evaluating whether something makes sense – does that pass the straight face test.

Question 21 asks the respondent whether he or she believes the laws of physics are "inherent in the nature of things and independent of how humans think" or "invented by physicists to organize their knowledge about the natural world." Frank was my only subject to select the "mixed" option, but I maintain that his choice is a truer reflection of what all my subjects actually believe about the character of physical laws. It would be interesting to see if Frank's views on this issue have changed.

Frank's 3-day RTOP average was 87, second highest among my subjects. Frank was especially well-attuned to students' misconceptions however presented, effective at asking questions that "triggered divergent modes of thinking," and provided a variety of means for students to explore phenomena illustrative of Newton's third law. The post-activity questions and whiteboards were crucial in promoting students' self-reflection about their own learning and student questions and comments often determined the focus and direction of classroom discourse. These observations are entirely consistent with Frank's self-reports of Modeling practice on the MIS. The 54-point change in scores between the 1999 and 2007 surveys are primarily due to his fully exploiting whiteboard sessions, following the Modeling curriculum, and emphasizing conceptual understanding of models.

What is difficult to reconcile with this glowing recitation of Frank's Modeling pedigree are the relatively low average FCI gains of his regular physics students (second lowest among my subjects). Moreover, the contrast with his honors students is striking; about a 15% difference on average but as high as 30% in 2006 at his school in New England. The consensus opinion in the Modeling community is that students' preparation in mathematics and the corresponding development of their cognitive reasoning skills accounts for a significant percentage of the variance in students' scores (an opinion with which Frank concurs), but I have not tested this hypothesis. I am happy to report, however, that Frank's newest students realized a substantial improvement in average gain compared to all previous years, a result Frank is tentatively attributing to their music training (the 8% difference in average gain between his 1st period, "higher level" class, and his 3rd period class is not statistically significant). The fact that many of Frank's students are comfortable in front of an audience may be a contributing factor, as well.

Conclusions

By the time they attended their first Modeling Workshop, the teachers in this study, all within the 45 to 64 age bracket, had been teaching for 22, 4, 16, 7, 9, and 13 years, respectively, and came to their profession via distinctly different routes. None of these teachers has a degree in physics, though three of them have degrees with a physics emphasis, and only two of them have been teachers their entire professional careers. Thus, among physics teachers they represent a fairly broad cross-section of background and experience (except for race, gender, and age!). But how they became physics teachers is peripheral to this study. I wanted to understand how they became *Modeling* physics teachers and why, after eight years of practice, five of the six are still devoted to this pedagogy and why the sixth is not. I also wanted to understand and account for the differences in their practice; why, despite the same training, the students of some of these teachers realize significantly higher learning gains than others.

The three questions that guided this inquiry were:

1. How and to what extent does the design of the Modeling pedagogy induce conceptual change in teachers' conceptions of physics content and pedagogy?
2. What factors, including teachers' beliefs and background as well as their participation in the community of discourse embodied by the workshops and the Modeling program generally, influence their implementation of the Modeling pedagogy in their classrooms?
3. How might the program be redesigned to increase the number of high performing teachers and, similarly, how might teachers be supported after completing a workshop so as to reach high levels of implementation?

1. How and to what extent does the design of the Modeling pedagogy induce conceptual change in teachers' conceptions of physics content and pedagogy?

Conceptual Change and Modeling Theory

The central proposition of the conceptual change theory of learning is that before a new conception can be accommodated there first must be dissatisfaction with a current conception. Consequently, a major premise of this project has been that some physics teachers' dissatisfaction with the persistent ineffectiveness of their traditional, didactic style of teaching in promoting student learning of elementary physics concepts should induce in them a cognitive dissonance between how they teach and what students learn. Typically, this dissonance has been mitigated by laying the failure to learn at the feet of the students and not on the pedagogy. I hypothesized, on the other hand, that for many teachers attending the Modeling Workshops this teacher-as-transmitter/student-as-receptacle conception of teaching and learning was overturned. As teachers were exposed to and practiced an alternative pedagogy they began to realize that *what* students learn depends most on *how* they learn.

In particular, the Modeling pedagogy is built on a constructivist theory of learning most closely associated with the work of Bruner (1960) in which learners "construct" new ideas and concepts based on current and prior knowledge. A key element of constructivist theory is that the cognitive structure of human knowledge is in the form of *mental models*. A contribution of physics education research to this theory of learning has been that one consequence of human cognition is that many of students' mental models about physical phenomena are invariably mis-aligned with the scientific world view. Moreover, these “misconceptions” interfere with student learning and often are resilient to instruction, especially didactic instruction.

I hypothesized, therefore, that by attending Modeling Workshops teachers experienced, first and foremost, a change in their conception of *how students learn physics* towards a more constructivist perspective. The inevitable corollary to this hypothesis is that teachers also experienced a concurrent change in their conceptions of *how to teach physics*. Thus, I proposed that the immediate cause of this conceptual change was teachers’ apprehension that *learning and teaching in physics are fundamentally concerned with constructing scientifically aligned conceptual models of physical phenomena*. This realization comes to many Workshop teachers almost as a revelation handed down from on high. It restructures the way they think about their students, their practice, and physics itself. I review the evidence supporting these propositions below after I describe the context in which this alleged conceptual change takes place.

Modeling Workshops Scaffold and Reinforce Teachers’ Conceptual Change

If we concede that teachers have assimilated the core Modeling principle, it is a relatively straightforward process for them to accept, as an effective strategy for promoting this sort of learning, a student-centered, discourse-oriented pedagogy in which students are actively and collaboratively engaged in their own learning. Much of the impetus for this pedagogy comes from the practice of science itself, but even more is from empirical research conducted by Malcolm Wells for his Ph.D. dissertation and later by others as they worked to refine the pedagogy (Wells, Hestenes & Swackhamer, 1995). Thus, the Workshops were designed intentionally to incorporate the very principles as well as the pedagogy it was hoped teachers would emulate in their own classrooms. Wells, Hestenes, Swackhamer, and others who contributed to the format of the Workshops were convinced that teachers could not be expected to passively absorb a pedagogy diametrically opposed to traditional physics instruction via the same didactic teaching style the Modeling Method was meant to replace. Teachers must be “immersed” in the same environment intended for their students, collaboratively constructing the same models utilizing the same discourse as they collaboratively construct new conceptions of teaching and learning for themselves. They must have a visceral experience with the same sort of active learning they hope to promote when they get back to school.

I have proposed that teachers attending Modeling Workshops experience conceptual change that transformed their conceptions of teaching and learning in physics. I have also described how the pedagogy of the Modeling Workshops scaffolded and reinforced this conceptual change by engaging teachers in the same process of collaborative model building as is intended for their students. I now review the evidence for these propositions.

Teachers’ Experiences at Modeling Workshops

When I asked my subjects what about their experiences at the Workshops prompted them to drastically reform their teaching, their responses were varied but consistent. Allan said most valuable to him was “participating as a student.” For Brian, the Workshops “changed the way he thought about teaching and learning” so as to change his focus from teacher-centered to student-centered instruction. Charley said, “It helped me to recognize the strength of my students ‘preconceptions’ about the natural world and how difficult it can be to replace such with better models.” David’s response was similar to Allan’s: “We jumped at the opportunities to experience what our students would from inquiry labs to whiteboarding homework.” Edward’s reply was particularly thoughtful: “I [was] very impressed with the storyline and simple models developed. I think most teachers have the long view that Modeling offers. The difference is that students [will] also get explicit exposure to ideas that took those of us taught in a more traditional style years to ‘see.’” Frank had a different take: “A lot of it was the whiteboarding. I get a chance to see inside my students' heads which I don't get any other way. I think the other piece was the way it's organized; the way the method’s organized makes sense to me.”

The Modeling pedagogy has three essential components: the models, the Modeling cycle, and classroom discourse. Undergirding these three is the foundational principle that students must be actively engaged in their own learning. Each of the teachers’ comments above suggests which of these facets was most resonant for them at the Workshop (though these recollections are eight- or nine-years old). Allan, Brian, and David responded to active student learning; Charley and Edward to the models; and Frank to the Modeling cycle and classroom discourse. For myself, it was the Modeling cycle (like Frank) and the overarching storyline connecting the models (like Edward). I have a Master’s degree in physics, but the Workshop was the first time I saw Newtonian mechanics presented in a single, coherent framework rather than as a series of disjointed factoids and formulas. Of course, it is difficult to untangle any one component from the others as they are really a connected whole. Because any successful theory of learning must presuppose a correct theory of knowing, the essential power and appeal of the Modeling pedagogy lie in Wells and Hestenes’ insight that since humans make sense of the physical world via models so should teaching about the physical world. I have explained how teachers’ participation in the Modeling Workshops initiated the conceptual change process but what sustained it?

Modeling Workshops Promote Professional Community

Besides the content, two characteristics distinguish the Modeling Workshops from many other, more typical programs of professional development. The first is the aforementioned “immersion” format. The second is the duration: four-week, fulltime sessions over two consecutive summers. Moreover, since many, if not most, of the participants came to the Workshops from distant locales, they required housing, typically in college dorms vacated for the summer. In addition, the Workshop leaders ensured that teachers engaged in various team-building and extracurricular group activities such as outings to local recreational venues, museums, restaurants, and the like. In these respects, as well as in others, the Workshops were not unlike “summer camp.” The picture should be clear: about twenty veteran physics teachers, each of whom has chosen to attend the Workshop with at least some intention of improving his or her craft, working collaboratively and interacting socially several hours a day to learn an entirely new pedagogy. The inescapable conclusion is that the Workshops are, indeed, examples of “professional community” (e.g., Lieberman, 1990; Westheimer, 1998; and Wenger, McDermott & Snyder, 2002) – that is, a collaborative group of teachers intentionally created with an overarching mission to support increased student learning.

The community thus created performed two vital functions with respect to the Modeling program’s mission. First, it supported and reinforced teacher learning by providing opportunities to collaboratively practice the new pedagogy and thereby expanded teachers’ “enactment zones” (Spillane, 1999) so as to “enable teachers to adopt perspectives outside their own bounded practice” (Gallucci, 2003). Such communities “promote shared ways of doing things, allow for the rapid flow of information, create mutually defining identities, and provide a venue for local lore and shared stories" (Gallucci, 2003). Second, membership in the community encouraged "internal accountability," that is, "the set of processes whereby teachers apply shared expectations to their own work and to that of their colleagues" (Newmann, King & Rigdon, 1997). This internal accountability undoubtedly was evident during the Workshops. Peer pressure alone saw to that. But I believe it extended further still, to teachers' own classrooms, especially during the induction period when the novice Modelers struggled most with the pedagogy. Despite various obstacles, not the least of which was adopting a radically different pedagogy, these teachers soldiered on even though no external mandate for reform had been imposed. Teachers' personal integrity, their abiding faith in the ultimate effectiveness of the pedagogy, and the sense of allegiance to the community of Modelers instilled at the Workshops all sustained them through the induction period.

The Role of the Virtual Community

The internal accountability within the community of Modelers diminishes with time, distance, and experience. The bond between teachers, though still collegial, inevitably weakens without continuous reinforcement. Also, as teachers become more experienced and, presumably, expert with the pedagogy, they will naturally tend to rely more on their own judgment and refer less often to the curriculum manual, the Modeling website, or other external sources of support. Nevertheless, both the Modeling website and the Modeling listserv play critical roles in maintaining the community across time and space. The Modeling website serves as an information clearinghouse, but the listserv is an example of what Rheingold (cited in Ellis, Oldridge & Vasconcelos, 2004) calls a "gift culture where information is the gift." That is to say, subscribers to the listserv are "members of a virtual community [who] provide information freely to the community, not in the expectation of immediate reward but in the expectation of diffuse reciprocation." Subscribers know that if they post a question about Modeling, a lab activity, a worksheet, or what have you to the listserv someone will respond. In turn, he or she may eventually return the favor. All manner of queries and bits of information are posted to the listserv from employment opportunities to threaded discussions about physics education research. Thus, active participation in the virtual community can reinforce teachers' self-identities as Modelers. Four of my six subjects report that they are "active members" of the Modeling community. They consult the website regularly for updated curriculum materials and to stay current with the "state of the art." They are subscribers to the listserv as well and read the postings on a daily basis. All four have posted to the listserv in recent months, though some more often than others.

Modeling Curriculum Materials

It is also crucial not to underestimate the importance of the well-developed and complete first-semester Modeling curriculum manual each teacher received at the Workshop. Other factors notwithstanding, all my subjects said that it would have been difficult to impossible to implement the Modeling pedagogy without these materials. Some of my subjects have made substantial revisions to the materials since the Workshops, but, as Brian puts it, "the chances of slipping back into old, familiar ways would have been much greater" without them.

Charley: The Exception

None of this, however, was quite enough for Charley and he has mostly, but not entirely, forsaken Modeling. In the end, it is how Charley perceives his role as a physics teacher that, despite a good-faith effort on his part, finally convinced him to "slip back into old, familiar ways:"

> My biggest issue is not [Modeling's] value, but I guess I'm still of the school that wants to "get to rainbows." The school year isn't long enough to do justice to any physics curriculum, at least I can't make it work, and I try to both teach kids how to do science and to also get turned on to the nature of nature.

So much of physics, even elementary physics, lies "beyond mechanics" and Charley wants his students to see as much of it as he can show them. There may be other issues at play here, however. For example, why did it take Charley an entire year to get through mechanics his first year Modeling? Or, if he found the mathematics of the unit on projectiles (Unit 6: 2-D Particle Models) too difficult for his students, why did he not ameliorate it? After all, one can solve some projectile motion problems without the use of trigonometry. Finally, if he did not like the way energy is presented in the Modeling curriculum, why did he not revise it to his liking?

There are always alternatives to specific elements of the Modeling curriculum and many teachers have made such refinements. What must not change, of course, is the pedagogy. I sense an inflexibility in Charley's approach to Modeling which I suspect rendered it awkward and difficult for him. Much of Modeling is about adapting – adapting to what students reveal about their learning, to the ebb and flow of classroom discourse, and oneself to become a facilitator of student learning. Perhaps, after 16 years of teaching, Charley could not adapt.

2. What factors, including teachers' beliefs and background as well as their participation in the community of discourse embodied by the workshops and the Modeling program generally, influence their implementation of the Modeling pedagogy in their classrooms?

Unpacking the Pedagogical Content Knowledge Construct

I have demonstrated that five of my six subjects experienced profound changes in their conceptions of teaching and learning in physics as a direct result of attending the Modeling Workshops. Consequently, their physics pedagogical content knowledge (PCK) was dramatically transformed as evidenced by the complete overthrow of their previous practice in favor of the radically different Modeling pedagogy. How, then, do we account for differences in their practice? Can they be reduced to mere differences of personal style or are there deeper sources?

The answer to these questions lies in discerning the ways in which teachers' PCK has metamorphosed. To conduct this analysis, let us reconsider Carlsen's (1999) four components of PCK in science: knowledge of students' common misconceptions, knowledge of specific science curricula, knowledge of topic-specific instructional strategies, and knowledge of the purposes for teaching science, and ask how and to what extent each of these components has been modified.

Students' Common Misconceptions in Physics

Enhancing teachers' knowledge of students' common misconceptions in physics is an integral part of the Modeling Workshop pedagogy. Lists of students' misconceptions compiled by Halloun, Hestenes, and Wells as well as by other physics education researchers (e.g., McDermott & Redish, 1999), and even by Workshop attendees, are examined and discussed. More importantly, misconceptions specific to each instructional unit and how they are manifested in student discourse and other student work are thoroughly elaborated. In fact, one of the more dubious pleasures of participating in Modeling Workshops is the opportunity for teachers to behave like their students and “model” student misconceptions so that other teachers might practice their Socratic questioning.

In any case, teachers’ knowledge of students’ common misconceptions is vastly improved, if initially only on a theoretical level. My subjects all report that it took and still takes time to learn to recognize and appropriately respond to students’ misconceptions, but they all agree that their knowledge of students’ misconceptions was greatly enlarged at the Workshops. Furthermore, the Modeling program staff reports, anecdotally, that some of the most effective Modeling teachers seem to have a profound awareness of *individual* student’s misconceptions.

Brian, David, and Frank demonstrated a sound grasp of students’ misconceptions based on the kinds and frequency of questions they asked during student whiteboard presentations. David had trained his students to ask many procedural questions, which allowed him to concentrate on the more conceptually-oriented questions and Frank had completely revamped a lab activity specifically incorporating physics education research on student misconceptions. Both Allan’s and Edward’s questioning tended to be more focused on students’ procedural rather than propositional knowledge. Consequently, I am less sure about the depth of their knowledge of students’ misconceptions.

Teachers’ Knowledge of Science Curricula

Teachers’ knowledge of specific science curricula – in this case, coherent, comprehensive, and scientifically-aligned models of physical phenomena embedded in a well-defined theoretical framework – is at the core of the Workshop pedagogy. It is all about the models. I need not recapitulate the details about the models in the Modeling curriculum or how Workshop teachers acquire this knowledge base, but we can ask whether teachers are explicit in their development of the models in their own pedagogy.

Unfortunately, I do not feel I observed teachers long enough to form a complete judgment on this issue. I did, however, observe each Modeling teacher progress instruction at least through Phases 5 and 6 (Model Formulation) of a Modeling cycle (David and Frank), and three teachers (Allan, Brian, and Edward) got to Phase 7 (Initial Model Deployment). Each teacher did indeed have students employ the multiple representations (graphs, vector diagrams, mathematical formulas, and verbal descriptions) that constitute the conceptual model, but I have no data (or recollection) indicating that any teacher, with the lone exception of David, ever even used the word “model” in class. I suspect also that few teachers have time to explicitly validate the models developed in class (i.e., to specify the domain and range over which a model is applicable – corresponding to Phase 9: Paradigmatic Synthesis). Therefore, I tentatively conclude that although the teachers are reasonably conscientious about having students develop a complete model specification, they are less careful about labeling the construct so developed *a model* and delineating its operational limitations. This practice may leave students in much the same situation they were prior to instruction with a “naive physical causality consist[ing] of a rich system of elements that are organized only in a limited degree” (diSessa & Sherin, 1998). Reaching the validation stage was not stressed in the early Workshops (1995 – 1999), but I am told that this deficiency in the Workshop pedagogy has since been addressed by the Modeling Instruction program staff. However, my subjects may need additional professional development in this aspect of the pedagogy.

Teachers' Knowledge of Topic-Specific Instructional Strategies – Modeling Discourse

Here, I restrict my discussion of teachers' knowledge of topic-specific instructional strategies to the issue of classroom discourse management as most other strategies will be common to any physics classroom. We are now at the very heart of Modeling and I have described this defining attribute of the pedagogy as well as the classroom discourse practices of my subjects in detail. Classroom discourse management is the skill most critical to student learning in a Modeling classroom (Wells, Hestenes & Swackhamer, 1995; Desbien, 2002) and the one in which the most conspicuous differences appeared among my subjects. Since each teacher was similarly instructed in classroom discourse management at the Workshops, the differences in their practice must come in large part from the depth of teachers' apprehension of the essential purposes of classroom discourse in the Modeling theory of learning. Classroom dynamics play a role as well, of course, but this is controlled for to some extent by the similar demographics of the subjects' classes. Wells, Hestenes & Swackhamer (1995) explain the purpose of classroom discourse thusly:

> As students are led to articulate their reasoning in the course of solving a problem or analyzing an experiment, their naive beliefs about the physical world surface naturally. Rather than dismiss these beliefs as incorrect, Malcolm learned to encourage students to elaborate them and evaluate their relevance to the issue at hand in collaborative discourse with other students. *In the context of modeling activities students have a framework for testing and correcting their own ideas*, especially in regard to relevance and coherence with other ideas. [Emphasis in the original.]

Students need the immediacy of conversation; it provides vital, real-time feedback for students as they construct their understanding. This goes beyond simply evoking students' prior conceptions; it allows them to pose questions from their unique, evolving perspectives and challenge others' assertions as they struggle to make sense of the concept under consideration.

Two key features must be present to support this sort of intellectual engagement in the classroom. First, the teacher must create a learning community that promotes scientific inquiry and the public sharing of ideas. There is an anticipatory excitement to authentic inquiry that can stoke the interest of almost any student. As David said, "It's as much a real science as anybody else does and it as new to them as any other new science is to a professional." Of course, emulating a scientist also means presenting one's ideas in a public forum. It is during this teacher-mediated discourse, via Socratic questioning, that students' misconceptions are elicited, confronted, and, hopefully, resolved. However, many high school students are uncomfortable performing in front of their peers. The very idea of appearing wrong or foolish can silence them as can few other forces. Thus, they need "a climate of respect for what others [have] to say" (RTOP item 20). Several of my subjects report difficulties with shy or reticent students, but they also report that their more able students have no qualms with intellectual risk-taking and look forward to whiteboard sessions.

The second key feature is ensuring a high proportion of student-to-student discourse. On one level, this is a built-in characteristic of the Modeling pedagogy. As students work collaboratively on lab activities and whiteboard preparation, much of their discourse will be directed at jointly constructing the model under consideration. They need this "safe place" because many students are much more likely to take intellectual risks with their peers in small groups than in front of the class. More difficult is engaging students in the public debate, but it is just as crucial. Indeed, the teacher may mediate the discussion and conduct some questioning, but ideally students should be active interrogators for it is in such discourse that learning becomes "an inter-individually triggered process of convergent conceptual change" (Duit, 1988). In the end, however, the teacher *is* the final arbiter of the "truth" because the conversation concludes only when the teacher is satisfied that student representations have been reconciled with the model specification.

To be fair to all my subjects and to mitigate somewhat the comments that follow, there *was* considerable between-student discourse during lab activities and whiteboard preparation in all the Modeling classes I observed. These are important venues for student discourse that I did not always get to observe closely. Therefore, the following observations and conclusions apply only to whole-class discussions.

Allan reported that his teaching has radically changed since attending the Workshops and that he adheres faithfully to the Modeling methodology. However, his Socratic questioning focused more on the procedural and he has not created a genuine learning community that supports public student discourse. That the potential for such a community is there was aptly demonstrated on the occasion when one entire class was to receive a grade based on a single, randomly selected whiteboard. Brian's questioning is much more conceptually oriented that Allan's, but he, too, does not seem to have created a learning community. I heard very little public student discourse in his class as almost all the dialog was between Brian and student-presenters. The situation was similar with respect to student discourse in Edward's class, but the lesson format did not allow for many opportunities. All of David's classes and Frank's two physics classes had active public discourse. It was particularly interesting that the whole-class discussions in Brian's second-year physics class as well as in David's AP *and* conceptual physics classes (all Modeling classes) were much more animated and enthusiastic than in any of the regular physics classes (except for the single instance in one of Allan's classes, as described above). As I noted above, David has gone to some lengths to train his students in Socratic questioning and participation is part of their grade. As members of a performing arts community, many of Frank's students are perfectly comfortable in front of an audience, but I observed also that in Frank's two physics classes boys tended to dominate the discussion despite being a small minority in either class. David's deep-seated constructivist convictions and Frank's familiarity with physics education research (and the fact that he is a Modeling Workshop leader!) may well account for their appreciation of the role of discourse in a Modeling physics class.

The problem of overbearing boys and reticent girls has been a long-standing concern in the physics education community and the subject of considerable research (for an overview see McCullough, 2002). Though the Modeling pedagogy makes no attempt to address this issue directly, the mandate of the learning community surely must extend to ensuring an equal opportunity for participation in every phase of a Modeling cycle. Simple strategies, such as the circle whiteboard sessions that so impressed Frank, may do much to alleviate students' anxiety during whole-class discussion and encourage engage-ment. Some Modeling teachers form students in single-sex and even same-language groups for similar reasons. Other teachers spend time early in the year developing the learning community with various team-building activities. In each case the goal is the same: increasing students' comfort level to foster full participation in the learning process.

There is another message here, as well. At best, creating a learning community is a difficult undertaking for most teachers. Moreover, allowing students the full measure of time they need to digest and discuss every fine point may be asking the impossible given the typical constraints on a high school physics class. Under these conditions, getting "beyond mechanics" in a single year might be as elusive as finding the proverbial pot of gold at the end of the rainbow. This is the essential "less is more" tension Modeling teachers face: is it better that students have a deep understanding of relatively few concepts or should students at least be exposed to the broad array of topics they will see in a typical college survey course? Modeling teachers' emphasis on mechanics seems to stem mostly from their belief in the primacy of mechanics as the foundation for student learning in physics, but they also report that the Modeling curriculum in this area is better developed than for "second" semester topics. Coincidentally, some support for this emphasis can be found in the work of Sadler & Tai (2001). In a study of 1,933 randomly selected introductory- level college physics students, they found that in terms of preparing high school students for success in college physics "covering a limited set of topics, dealing primarily with issues in mechanics, appears to be beneficial."

The Purposes for Teaching Science

The last of Carlsen's (1999) components is knowledge of the purposes for teaching science, which in this case means physics. Most physics teachers teach physics presumably because they believe that physics provides a fascinating and fertile perspective on the natural world. However, Sadler & Tai (2001) cite a finding from a 1996 National Center for Education Statistics report that indicates 89% of high school physics teachers also "feel 'preparing students for further study in science' is a moderate to major emphasis in their courses." Allan, Brian, and Frank each mentioned this during our extended interviews, as did Charley, but more important to them and to the other two teachers was teaching students to think critically. Of course, it is also true that many physics teachers think "physics is phun" and the fact that physics has social value is just a happy coincidence. However this may be, let us assume that physics teachers find their profession worthwhile and want to be effective. The issue for them then becomes one of determining the best physics pedagogy and that judgment, in turn, depends on the teachers' views on science education and their conceptions of teaching and learning and their roles as science teachers. As mentioned earlier, some science education researchers (e.g., Tsai, 2006) believe these views are strongly influenced by the teachers' views on the nature of science, but I have shown that this is not necessarily the case. For example, Allan believes that "numbers represent the truth" and that his role as a science teacher is "to provide students with an opportunity to learn about collecting numbers and data." Despite this evidently empiricist perspective, Allan is a committed Modeler. Ultimately, most teachers are practical creatures and want to do what "works best." This sometimes allows them to follow the prescriptions of a pedagogy without completely embracing the underlying theory of learning. Without that underlying perspective, however, their effectiveness must be limited.

Table 5, below, is a very informal assessment of teachers' observed Modeling behavior in the context of the four-component pedagogical content knowledge construct: Student misconceptions: the relative frequency of conceptual vs. procedural questions; Explicit models: the extent to which a teacher was deliberate in the development of a conceptual model *as a model*; Discourse management: a learning community was present that supported a high proportion of public between-student discourse as well as small group discourse; Role of teacher: extent to which the teacher demonstrated an integrated understanding of the Modeling theory of learning via classroom practice.

Table 5
Indications of Modeling Behavior

Teacher	Student Misconceptions	Explicit Models	Discourse Management	Role of Teacher
Allan	+/–	–	+/–	+/–
Brian	+	–	+/–	+
David	+	+	+	+
Edward	+/–	–	+/–	+/–
Frank	+	–	+	+

\+ Strong indication   +/– Some indication   – Weak indication

3. How might the program be redesigned to increase the number of high performing teachers and, similarly, how might teachers be supported after completing a workshop so as to reach high levels of implementation?

I have identified a few areas in which the subjects of this study could have benefited from more robust instruction and/or practice at the Workshops: model validation, creating learning communities that promote public student discourse, and a deeper understanding of the theory of learning behind the Modeling pedagogy. Most of these issues have been addressed by Dwain Desbien (2002) in research he conducted for his own Modeling-based Ph.D. dissertation entitled "Modeling Discourse Management Compared to Other Classroom Management Styles in University Physics." Though Desbien conducted his research at a two-year college, I believe his findings are generally applicable to the high school environment with little modification. Desbien identifies seven essential components to Modeling Discourse Management: deliberate creation of a cooperative learning community, explicit need for the creation of models, creation of shared inter-individual meaning, "seeding," intentional lack of closure, inter-student discussion, and formative evaluation. The reader should be sufficiently versed in the Modeling theory of learning to have a good sense of what is implied for teachers' practice by most of these components, but a few of them merit further explication.

Seeding occurs when "the instructor seeds a small collaborative group with a question or a hint" during whiteboard preparation that then arises naturally during whole-class discussion. For Desbien, seeding is a very deliberate act that requires the instructor have an "agenda" for the whole-class discussion in terms of his or her instructional goals for the lesson. By intentional lack of closure, Desbien means issues and questions raised during whole-class discussion may be left unresolved at the end of class so that "students continue to wrestle with the issues outside class and return with new ideas to share." Finally, formative assessment does not refer directly to student learning but rather to the teachers' practice. Desbien recommends teachers take "copious" notes during class and use them to reflect on the evolution of the lesson. He suggests teachers ask themselves questions such as "Did I intervene too much during discussion?" and "What ideas surfaced that I was not prepared for?"

With the exception of an intentional lack of closure, formative evaluation, as he defines it, and the possible exception of seeding, Desbien's components are explicit in the Modeling pedagogy and the others are, at least, implicit. I observed each of these behaviors to one or extent or another during my field research for this study. David's practice, perhaps, came closest to Desbien's conception of Modeling Discourse Management. The operative word for Desbien is "deliberate" and it is this deliberateness that is missing from the classroom discourse practices of most of my subjects. I am not sure of the degree to which Desbien's recommendations have been incorporated into the Modeling Workshop pedagogy, but the findings of this study clearly support their inclusion.

What about teachers, such as the subjects of this study, who will not have received the benefit of Desbien's research? Students' FCI scores rise for the first two or three years after my subjects completed the Workshops and the trend then plateaus. Perhaps their practice can be re-invigorated by some professional development focused specifically on Modeling Discourse Management. Though Desbien's dissertation has been posted on the Modeling website, the information has yet to be formatted so as to be easily accessible to teachers. I recommend creating an online professional development course in Modeling Discourse Management for graduate Modelers. Since they have had training in and practice with the Modeling pedagogy, they have the conceptual tools that will enable them to assimilate the information and incorporate it into their own practice. The Modeling listserv can continue to perform its role as a venue for question and feedback in support of the professional development course.

Implications

In many respects this project has been a confirmatory study. It confirms the utility of Carlsen (1999) and others' schemes for categorizing teachers' knowledge domains as a means of understanding teachers and teaching. Especially useful has been the construct of pedagogical content knowledge. Parsing teacher knowledge in this way enabled me to consider the impact of different aspects of the pedagogy of the Modeling Workshops and the Modeling pedagogy itself on teachers' conceptions of teaching and learning.

This study confirms the applicability of the conceptual change theory of learning towards understanding the motive forces that provoke and promote changes in teachers' conceptions of their profession and in their core practices. For most of the teachers that were the subjects of this study and for many other teachers as well, attending the Modeling Workshops induced a transformation that was sudden, profound, and permanent. They did not just learn a new pedagogy; they re-conceptualized their self-identities as teachers. This does not mean that every program of professional development must or even should seek to induce this sort of conceptual change. I would argue, however, that if the goal of a program of professional development is to promote lasting changes in teachers' core practice, whether as part of a systemic reform initiative or just for a relative handful of teachers, the program designers would be well advised to consider the results of this study.

Conceptual change theory also helped shed light on what might inhibit such transformations. Charley actively participated in both Workshops and practiced Modeling for almost three years before “slipping back into old, familiar ways.” Modeling did not become the self-defining professional characteristic for Charley as it has for my other subjects because his experiences with the pedagogy could not overcome his long-standing and deeply-held beliefs in his role as a physics teacher.

This study confirms the empirical and theoretical work of teacher educators who research and design programs of professional development for math and science teachers such as Loucks-Horsley et al (2003). Their advocacy especially of “immersion experiences” and building “professional culture” (professional community) are completely validated in this project and should be taken to heart by other designers. Of course, in the same non-mandated context in which Modeling Instruction is offered, neither immersion nor building professional culture can succeed if teachers do not accept the fundamental premise of the program.

Finally, this study confirms much about Modeling and Modeling teachers with which the Modeling program staff is already familiar. They have, of course, observed Modelers in their classrooms over the years and many teachers are not the least bit shy about sharing their trials and travails via the Modeling listserv and at other venues where Modelers might congregate. I hope, however, that I was able to bring new insight via my application of the pedagogical content knowledge model and the conceptual change theory of learning that they might better target their efforts to further enhance teachers’ learning experiences at future Workshops.

Future Research

This project was just one of spate of recent Ph.D.'s written about Modeling by current and former Modeling teachers (see http://modeling.asu.edu for a complete listing). Most of the other dissertations have quite logically focused on the effects of Modeling on student learning, but one investigates the effect of Modeling's constructivist perspective on teachers, and another promotes reform in Modeling teachers' classroom discourse management. Though none of us have reached the bar set over twenty years ago by Malcolm Wells, who, after all, developed the pedagogy, the impact of Modeling on us, our practice, and our careers has been…transformational. What does this say about physics teachers that their perceptions of teaching and themselves as teachers could be so overturned by a couple of four-week workshops? Perhaps the reader now begins to understand why some Modeling teachers so aggressively proselytize the pedagogy when given the chance; they are "born again" converts. Modeling has spread to chemistry, physical science, and even biology – no science class has been spared. What this all suggests is the need for a deeper investigation into the cognitive science aspects of science and science education just as has been proposed by David Hestenes (2006) in his paper "Notes for a Modeling Theory of Science, Cognition and Instruction." I would also be interested in replicating the cognitive and motivational research of Kang, Scharmann, Noh & Koh (2005) with Modeling teachers to possibly develop a predictive model of a teachers' potential for effectively managing classroom discourse. Lastly, I would like to observe those few teachers who the Modeling program staff have identified as able to complete the full year's Modeling curriculum. How do they do it and how do their students do on the FCI?

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Appendix 1
Modeling Method in Physics Instruction Curriculum

1st semester curriculum – Mechanics

Scientific thinking in experimental settings

Constant velocity particle model

Uniform acceleration particle model

Free particle (FP) model

Constant force particle (CFP) model

Particle models in 2 dimensions

Energy

Central force particle model

Impulsive force particle model

2nd semester curriculum – Waves, Sound, Light, Electricity & Magnetism

Mechanical waves:
- Oscillating particle model
- Mechanical waves in 1 dimension
- Longitudinal waves and sound
- Mechanical waves in 2 dimensions

Particle, wave, and photon models of light

Microscopic (charge) model of electricity and magnetism

Modeling-modified CASTLE (Capacitor Aided System for Teaching Electricity) curriculum

Appendix 2

Sample Syllabus for 4 Week Immersion Course - Mechanics

Prepared by Jane Jackson, Modeling Workshop Group, Arizona State University

Syllabus/Agenda

Week 1

Tue Day 1	**(am)** Welcome, Introduction of participants, Schedules, Workshop description, goals, ASU grading parameters, FCI overview, Pre-testing: FCI **(pm) Unit I: Scientific Thinking in Experimental Settings** Pendulum lab, Graphical Methods, lab report format, grading of lab notebook **Reading:** Hestenes, “Wherefore a science of teaching” (on modeling website)
Wed Day 2	**(am)** Discussion of reading, clarification if Unit I lab. lab write-ups, worksheets/test unit 1, **(pm)** white boarding, presentation criteria, discuss unit materials **Unit II: Particle with Constant Velocity,** Battery-powered vehicle lab, post-lab discussion, motion maps, deployment **Readings:** McDermott, "Guest Comment: How we teach…" Arons, ch 1 (special attn: sections 8, 9, 11, 12)
Thu Day 3	**(am)** Discussion of readings, problems, worksheets/presentations **(pm)** Introduce ultrasonic motion detector and video analysis, Unit II Test, discussion of adaptations **Readings:** Hake, "Socratic Pedagogy in the...", Arons 2.1-2.6
Fri Day 4	**(am)** Discussion of readings, **Unit III: Uniformly Accelerating Particle Model**, ball-on-rail lab, white board results **Readings:** Hestenes, "A Modeling Method for HS Physics Instruction."

Week 2

Mon Day 5	**(am)** Discussion of readings, post-lab extension: instantaneous velocity, acceleration, motion maps, model deployment lab, and deployment worksheet/white board **(pm)** Intro to *Graphs and Tracks,* instructional comments, descriptive particle models, more deployment exercises. wrap up unit III materials, test, **free fall w/ picket fence, video analysis or motion detector;** **Reading:** Arons 2.7-19, Mestre, "Learning and Instruction in Pre-College..."
Tues Day 6	**(am)** Discussion of reading, **Unit IV: Free Particle Model-inertia & interactions** inertia demo (Newton 1), the force concept, force diagrams, statics lab, the normal force demo questioning strategies **(pm)** Tension forces, spring scales, force probes, paired forces, **turn in journals (expected to include formal presentation of labs, article reflections and material adaptations to educational environment)** **Reading:** Minstrell, “Explaining the at rest condition…”,
Wed Day 7	**(am)** discussion of readings; deployment worksheets/white board, **(pm)** Discussion of reading, more deployment exercises unit IV materials, test **Reading:** Beichner: Tug-K article and test
Thu Day 8	**(am)** discussion of readings; **Unit V: CDP Model-force and acceleration**, weight vs. mass lab, lab write-up modified Atwood's machine lab (compare different equipment) **(pm)** white board results of previous days labs, post-lab extension: derivation of Newton 2, lab write-up Reading: **Arons 3.1-4,** Camp and Clement introductory reading
Fri Day 9	**(am)** discussion of readings; Newton 3, critique activities, deployment worksheets/whiteboard **Reading:** Arons 3.5-9, Hammer, “More than misconceptions…”

Week 3

Mon Day 10	**(am)** Discuss reading, Finish whiteboarding, Unit V test **(pm)** friction lab: pre lab and data collection, white board. Model development **Reading:** Arons 3.15-24, Biechner, "Video based labs …."
Tue Day 11	**(am)** Discuss reading, deployment activities, alternative tests, unit test **(pm)** **Unit VI: Particle Models in Two Dimensions,** combinations of FP and CDP models, deployment, turn in journals **Reading:** Arons 3.10-14;
Wed Day 12	**(am)** worksheets/whiteboard, projectile motion lab, **(pm)** explore use of Video Technology, alternative tests, Test **Reading:** Arons 4.1-5;
Thu Day 13	**(am)** Discuss Readings, **Unit VII: Work, Energy, & Power,** Stretched spring lab, work on lab notebooks, graph, whiteboard prep & practice critiques. **(pm)** finish critiques, worksheets, **Reading:** Making Work Work, by Gregg Swackhamer (on modeling webpage)
Fri Day 14	**(am)** discuss readings, Gravitational potential energy, work-kinetic energy lab, **Reading:** Arons 4.8-9, Hestenes: Modeling Methodology for Physics ..."

Week 4

Mon Day 15	**(am)** Further discussion of working/heating as means of changing internal energy of system; discussion of readings **(pm) Unit VIII: Central Force Model**, uniform circular motion lab, collect/analyze data; **Reading:** Arons 5.1-4
Tue Day 16	**(am)** discuss reading, deployment worksheets, instructional comments **(pm)** central force applications, and extensions. Turn in journals **Reading:** Arons, 5.5-6
Wed Day 17	**(am)** discuss readings, circular motion lab practicum. Alternative tests and testing. FCI posttest **(pm) Unit IX: Impulsive Force Model,** conservation of linear momentum lab, use of air tracks, PASCO carts and video analysis, collect data, plot p_{final} Vs $p_{initial}$, **submission of lesson plans for those contracting for an A grade** **Reading:** Hestenes, Wells, and Swackhamer, “Force Concept Inventory”
Thu Day 18	**(am)** discussion of readings, deployment worksheets, instructional comments. **(pm)** worksheets/tests on Impulsive force. **Reading:** Hake, “Interactive engagement vs. traditional methods…”
Fri Day 19	**(am)** MBT test and discussion, implementation discussion, look at 2nd semester models

Appendix 3

Modeling Workshop II

Survey of Participant Experiences

Academic Year 98-99

Name: ____________________________________

This survey is intended to assist the staff of the *Modeling Instruction* project in the evaluation of the project as required by the National Science Foundation. Most of the survey consists of multiple choice questions, with opportunities to comment following each section of related questions. The final section is a series of short answer questions; space for general comments is provided at the end.

Please answer all questions based on your experience during the academic year **98–99**.

Please write *N/A* next to any question that does not apply to your situation.

If there are issues related to a given section that you would like to comment on, please write your comments in the provided space, and continue on the back of the respective page if necessary.

Your cooperation is greatly appreciated.

Method (Modeling Cycle):

1. How often do you ask students to work in groups in your physics class?	1 Regularly	2 Frequently	3 Sometimes	4 Seldom	5 Never
2. How often do you ask different groups to debate their ideas in class?	1 Regularly	2 Frequently	3 Sometimes	4 Seldom	5 Never
3. How often do you use whiteboards?	1 Regularly	2 Frequently	3 Sometimes	4 Seldom	5 Never
4. How often do you lecture?	1 Regularly	2 Frequently	3 Sometimes	4 Seldom	5 Never
5. How often do you use handouts provided in last summer's workshop?	1 Regularly	2 Frequently	3 Sometimes	4 Seldom	5 Never
6. How often do you use a standard physics textbook?	1 Regularly	2 Frequently	3 Sometimes	4 Seldom	5 Never
7. How often do you follow the modeling cycle phases of model *development* and *deployment*?	1 Regularly	2 Frequently	3 Sometimes	4 Seldom	5 Never
8. How do you rate your own understanding of the instructional modeling cycle?	1 Very good	2 Good	3 Fair	4 Poor	5 Nil
9. Which of the modeling cycle components referred to above are most helpful for your students (check all that apply)?	1 Modeling phases	2 Group work	3 Whiteboards	4 Handouts	5 Other
10. What is your students' overall reaction to the modeling cycle?	1 Very favorable	2 Favorable	3 Neutral	4 Not that favorable	5 Not favorable at all
11. How do you rate your overall implementation of the modeling cycle?	1 Very good	2 Good	3 Fair	4 Poor	5 Nil

12. In your opinion, and with respect to its impact on your students' understanding of the course materials, how does the modeling cycle compare to traditional lecturing?	1 Much better	2 Better	3 About the same	4 Worse	5 Much worse
13. By comparison to what you originally expected, how good was the impact of the modeling cycle on student understanding of physics?	1 Much better	2 Better	3 About the same	4 Worse	5 Much worse

Comments:

Technology:

14. Is there standard laboratory equipment in your regular classroom?	1 YES	2 NO			
15. Is your classroom or laboratory equipped with MBL or CBL materials?	1 MBL	2 CBL	3 Neither		
16. How many computers do you regularly have access to in your classroom/laboratory?	1 8 or more	2 6 or 7	3 4 or 5	4 1 to 3	5 None
17. How many students work at each laboratory station (check all that apply)?	1 One	2 Two	3 Three	4 Four	5 Five or more
18. How often do you use computers or graphing calculators in your teaching?	1 Regularly	2 Frequently	3 Sometimes	4 Seldom	5 Never
19. How often do you engage students in experimental activities?	1 Regularly	2 Frequently	3 Sometimes	4 Seldom	5 Never
20. What is your students' reaction to the use of computers/graphing calculators in their activities?	1 Very favorable	2 Favorable	3 Neutral	4 Not that favorable	5 Not favorable at all
21. In your opinion, and with respect to its impact on your students' understanding of the course materials, how do MBL/CBL activities compare to traditional laboratory activities?	1 Much better	2 Better	3 About the same	4 Worse	5 Much worse
22. By comparison to what you originally expected, how good was the impact of MBL or CBL on student understanding of physics?	1 Much better	2 Better	3 About the same	4 Worse	5 Much worse

Comments:

Model-based Content:

23. How well was the Mechanics part of your course structured around *basic models*?	1 Very well	2 Good	3 Fair	4 Poor	5 Nil

24. How do you rate your own understanding of *models* and *modeling* in Mechanics?	1 Very good	2 Good	3 Fair	4 Poor	5 Nil
25. How well were parts of your course other than Mechanics structured around *basic models*?	1 Very well	2 Good	3 Fair	4 Poor	5 Nil
26. By comparison to last year, how much material were you able to cover this year?	1 Much more	2 More	3 About the same	4 Less	5 Much less
27. By comparison to year, how deep was your coverage of the same materials this year?	1 Much more	2 More	3 About the same	4 Less	5 Much less
28. What is your students' reaction to structuring the content of your course around *models* instead of using the traditional sequence of materials?	1 Very favorable	2 Favorable	3 Neutral	4 Not that favorable	5 Not favorable at all
29. In your opinion, and with respect to its impact on your students' understanding of the course materials, how does model-based content compare to traditional course content?	1 Much better	2 Better	3 About the same	4 Worse	5 Much worse
30. By comparison to last year, how good was the impact of model-based content on student understanding of physics?	1 Much better	2 Better	3 About the same	4 Worse	5 Much worse

Comments:

Assessment:

31. By comparison to last year, how did your students do on your exams this year?	1 Much better	2 Better	3 About the same	4 Worse	5 Much worse
32. By comparison to last year, how well did your students do this year on national, state or other regional exams?	1 Much better	2 Better	3 About the same	4 Worse	5 Much worse
33. How often do you assign practicums or special long term projects?	1 Regularly	2 Frequently	3 Sometimes	4 Seldom	5 Never
34. If applicable, how did students do this year on such projects by comparison to previous years?	1 Much better	2 Better	3 About the same	4 Worse	5 Much worse
35. How often do you use non-traditional assessment means like journals or portfolios?	1 Regularly	2 Frequently	3 Sometimes	4 Seldom	5 Never
36. If applicable, how did students perform this year on such means by comparison to previous years?	1 Much better	2 Better	3 About the same	4 Worse	5 Much worse
37. How serious are your students in taking the FCI?	1 Very serious	2 Serious enough	3 A little serious	4 Not serious at all	5 I do not know

38. How serious are your students in taking the VASS?	1 Very serious	2 Serious enough	3 A little serious	4 Not serious at all	5 I do not know

Comments:

Classes:

39. What type(s) of physics courses did you teach this year?	1 Regular	2 Honors	3 AP	4 Technical	5 Other
40. If applicable, which of these courses benefited the most from the *modeling* approach (check all that apply)?	1 Regular	2 Honors	3 AP	4 Technical	5 Other
41. By comparison to last year, how was the level of competence your students started at this year?	1 Much better	2 Better	3 About the same	4 Worse	5 Much worse

Comments:

School Environment:

42. How supportive is your school administration of the modeling approach?	1 Very well	2 Good	3 Fair	4 Poor	5 Nil
43. How supportive are your peers at school of the modeling approach?	1 Very well	2 Good	3 Fair	4 Poor	5 Nil
44. How good is the cooperation among physics teachers in your school district?	1 Very good	2 Good	3 Fair	4 Poor	5 Nil
45. Did you have any class interruption this year? If so, please explain in comments below.	1 YES	2 NO			

Comments:

46. Which of the following three categories *best* reflects the socioeconomic status of your **school**?	1 Upper Income/ Advantaged	2 Middle Income	3 Low Income/ Disadvantaged

Comments:

47. Which of the following three categories *best* reflects the socioeconomic status of your **students**?

1	2	3
Upper Income/ Advantaged	Middle Income	Low Income/ Disadvantaged

Comments:

48. Which of the following *best* describes your approach to grading students with respect to **on-going assessment and feedback** (homework grades, lab grades, etc.)? (please circle)

(a) Grades maximally distinguish student performance (e.g. grading "on a curve").

(b) Grades reflect a pre-set level of performance (e.g. all students could receive an "A" if their work meets a certain standard).

(c) Other approach; Please explain below.

Comments:

48. Which of the following *best* describes your approach to grading students with respect to **semester/ final grades and major examinations**? (please circle)

(a) Grades maximally distinguish student performance (e.g. grading "on a curve").

(b) Grades reflect a pre-set level of performance (e.g. all students could receive an "A" if their work meets a certain standard).

(c) Other approach; Please explain below.

Comments:

Optional:

Additional comments regarding your teaching experience during the 98-99 academic year

Graph of FCI vs. PE 98-99 goes here.

Appendix 5

Interview Protocols

The following interview questions will guide interviews with teachers involved in Modeling instruction (this interview will take place after all classroom observations and subsequent interviews have been completed):

Basic background information: college major, years teaching physics, years since Modeling Workshop, classes taught, student demographics, etc.

How would you define science and scientific knowledge?

How would you describe the role of a science teacher?

What do see as the critical factors that affect your teaching practices?

Please describe your typical approach to teaching physics.

Why did you decide to attend a Modeling Workshop?

Has your teaching practice changed as a result of attending a Modeling Workshop? How?

What do you think it is about Modeling that prompted you to change your teaching practices?

In what ways is the Modeling pedagogy important to your own teaching? Why (or why not)?

How would you describe the theory of learning behind the Modeling pedagogy?

- Where do you think this philosophy comes from?

What do you see as the desired outcomes for Modeling instruction?

- Short term?
- Long term?

How do you measure the effectiveness of your instruction?

How have your curriculum and/or pedagogy evolved over the years since you returned to the classroom following the Modeling Workshop? Why? What about pacing and coverage?

How have others responded to your efforts to implement Modeling Instruction?

- Your departmental colleagues? How closely aligned is your approach with those of your subject/departmental colleagues?
- Your department head?
- The school administration?
- Students?
- Parents?
- Others?

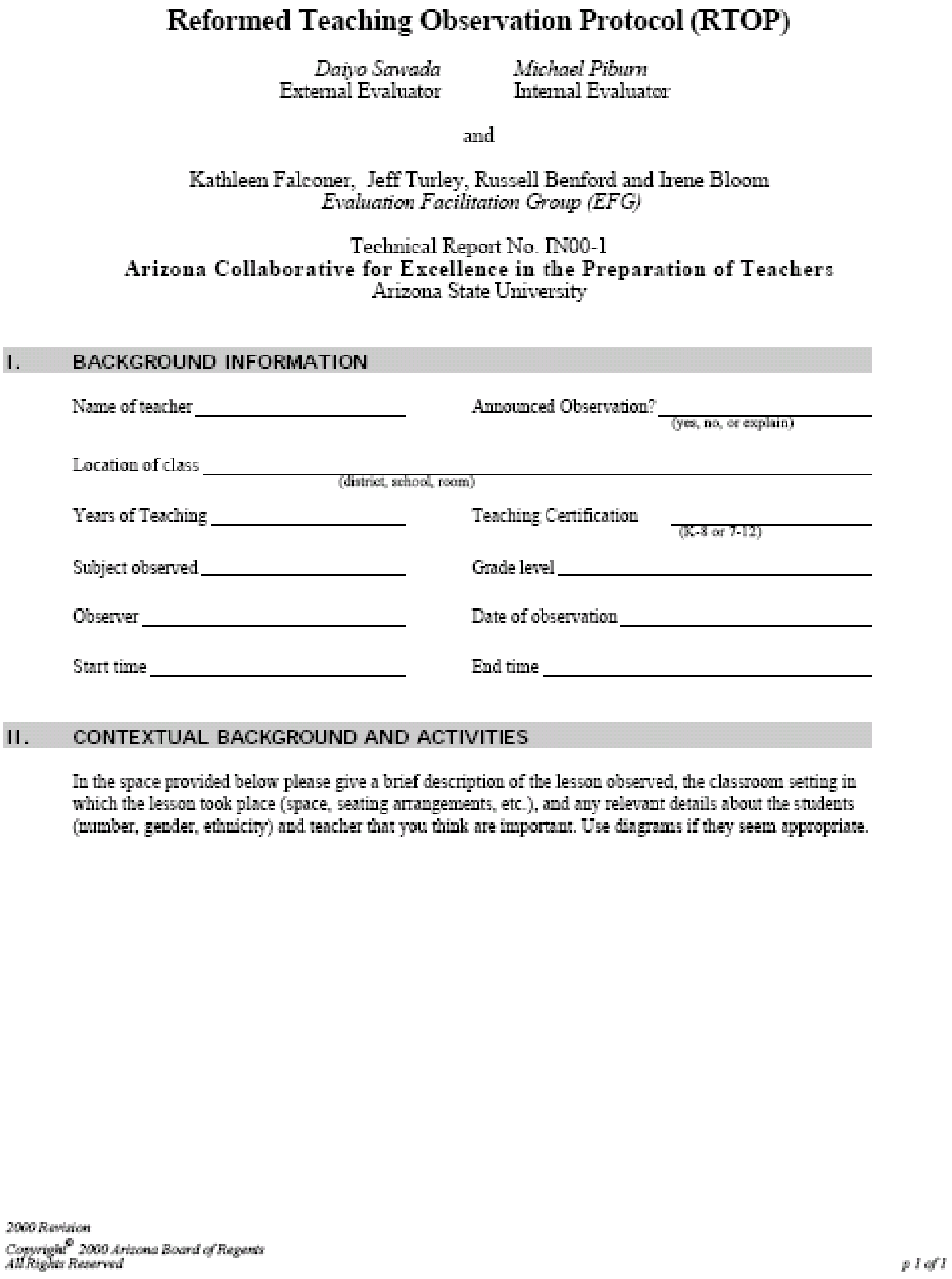
How, if at all, does the school, district, or state context impact your implementation of Modeling?

- What role does the school's leadership structure play?

  - What influence do district or state education policies have, e.g., the state's subject learning standards and/or student assessments, and/or the district's grade level expectations?

The following questions are for the interview immediately following a classroom observation (see Appendix 6 for the classroom observation protocol). The intent of these questions is to elucidate a teacher's perspective on the extent to which the lesson just observed is aligned with the teacher's learning goals.

1. What were your specific student learning goals for this lesson?
2. Which activities supported each of your student learning goals?
3. How did these particular activities support your student learning goals?
4. To what extent do you feel you achieved your student learning goals?
5. In what ways did anything interfere with your student learning goals?
6. What was particularly effective about the lesson? In what way was it effective?
7. Was there anything you felt was ineffective about the lesson? In what way was it ineffective?
8. How would you characterize your students' response to the lesson?
9. How will you assess student learning for this lesson?
10. How has your presentation of this material changed since your attendance at a Modeling Workshop?



Reformed Teaching Observation Protocol (RTOP)

Daiyo Sawada External Evaluator
Michael Piburn Internal Evaluator

and

Kathleen Falconer, Jeff Turley, Russell Benford and Irene Bloom
Evaluation Facilitation Group (EFG)

Technical Report No. IN00-1
Arizona Collaborative for Excellence in the Preparation of Teachers
Arizona State University

I. BACKGROUND INFORMATION

Name of teacher ____________________
Announced Observation? ____________________ (yes, no, or explain)

Location of class ____ (district, school, room)

Years of Teaching ____________________
Teaching Certification ____________________ (K-8 or 7-12)

Subject observed ____________________
Grade level ____________________

Observer ____________________
Date of observation ____________________

Start time ____________________
End time ____________________

II. CONTEXTUAL BACKGROUND AND ACTIVITIES

In the space provided below please give a brief description of the lesson observed, the classroom setting in which the lesson took place (space, seating arrangements, etc.), and any relevant details about the students (number, gender, ethnicity) and teacher that you think are important. Use diagrams if they seem appropriate.

2000 Revision

Record here events which may help in documenting the ratings.

Time	Description of Events

2000 Revision

III. LESSON DESIGN AND IMPLEMENTATION

Never Occurred — Very Descriptive

1) The instructional strategies and activities respected students' prior knowledge and the preconceptions inherent therein. 0 1 2 3 4

2) The lesson was designed to engage students as members of a learning community. 0 1 2 3 4

3) In this lesson, student exploration preceded formal presentation. 0 1 2 3 4

4) This lesson encouraged students to seek and value alternative modes of investigation or of problem solving. 0 1 2 3 4

5) The focus and direction of the lesson was often determined by ideas originating with students. 0 1 2 3 4

IV. CONTENT

Propositional knowledge

6) The lesson involved fundamental concepts of the subject. 0 1 2 3 4

7) The lesson promoted strongly coherent conceptual understanding. 0 1 2 3 4

8) The teacher had a solid grasp of the subject matter content inherent in the lesson. 0 1 2 3 4

9) Elements of abstraction (i.e., symbolic representations, theory building) were encouraged when it was important to do so. 0 1 2 3 4

10) Connections with other content disciplines and/or real world phenomena were explored and valued. 0 1 2 3 4

Procedural Knowledge

11) Students used a variety of means (models, drawings, graphs, concrete materials, manipulatives, etc.) to represent phenomena. 0 1 2 3 4

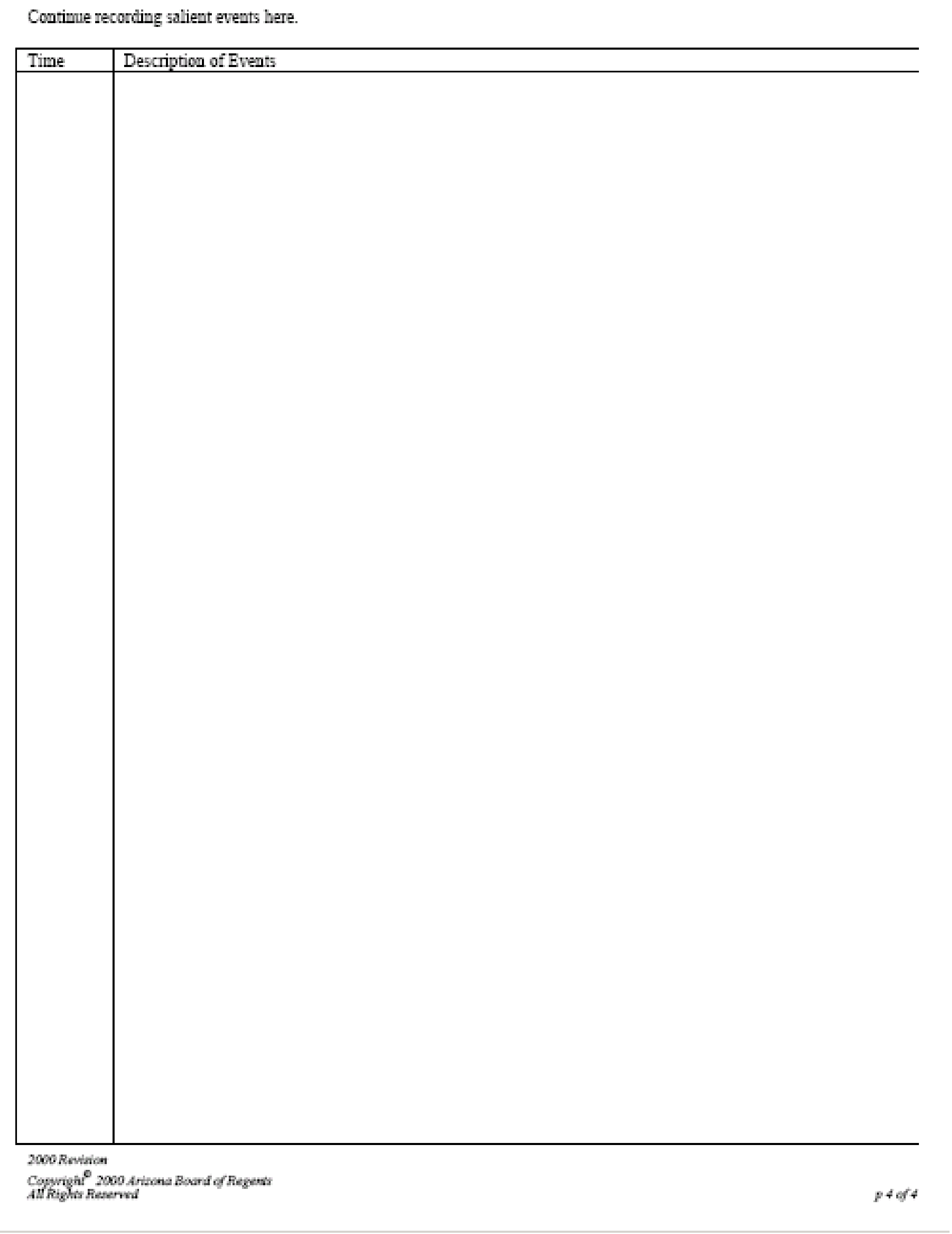
12) Students made predictions, estimations and/or hypotheses and devised means for testing them. 0 1 2 3 4

13) Students were actively engaged in thought-provoking activity that often involved the critical assessment of procedures. 0 1 2 3 4

14) Students were reflective about their learning. 0 1 2 3 4

15) Intellectual rigor, constructive criticism, and the challenging of ideas were valued. 0 1 2 3 4

2000 Revision

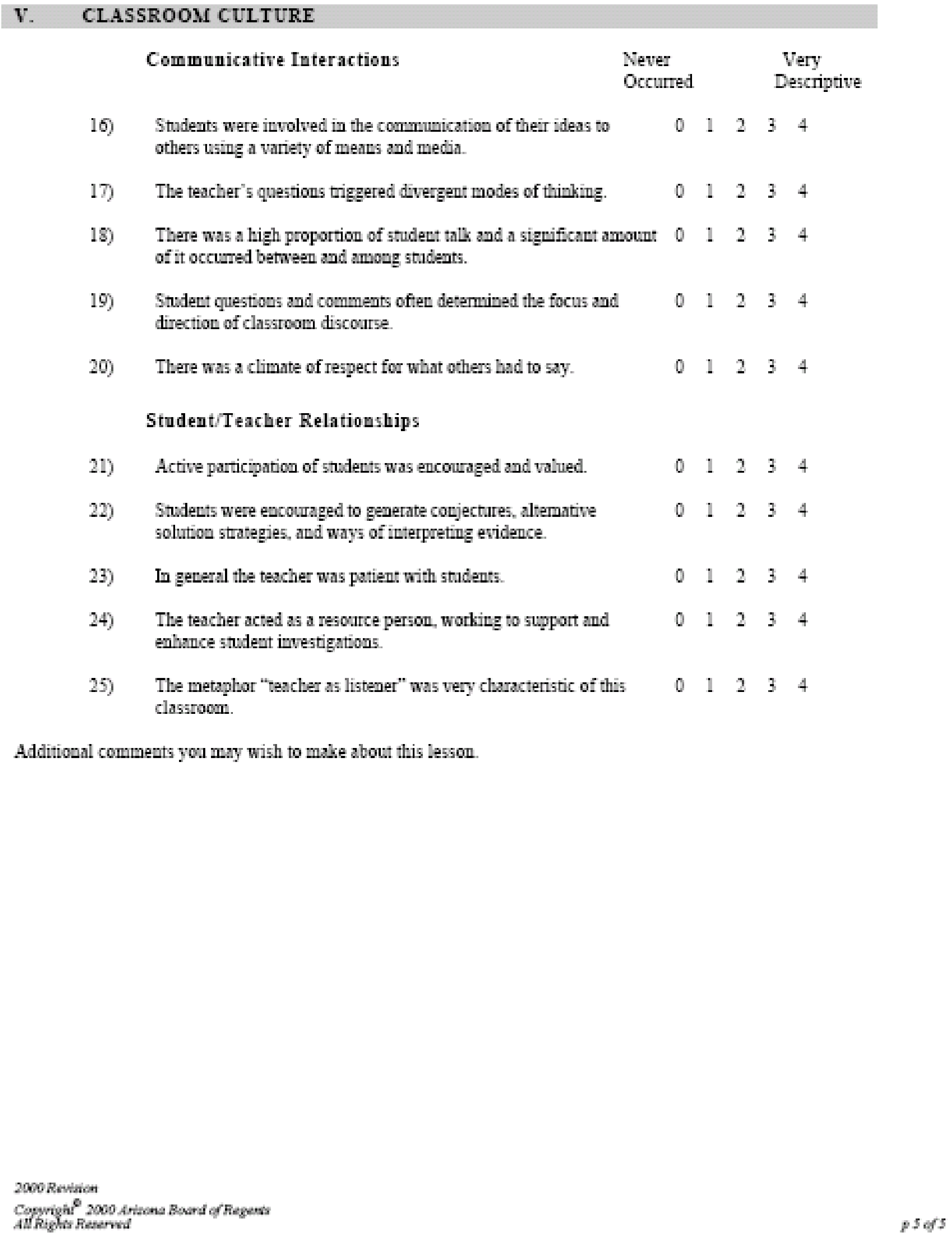


Continue recording salient events here.

Time	Description of Events

2000 Revision

p 4 of 4



V. CLASSROOM CULTURE

	Communicative Interactions	Never Occurred				Very Descriptive
16)	Students were involved in the communication of their ideas to others using a variety of means and media.	0	1	2	3	4
17)	The teacher's questions triggered divergent modes of thinking.	0	1	2	3	4
18)	There was a high proportion of student talk and a significant amount of it occurred between and among students.	0	1	2	3	4
19)	Student questions and comments often determined the focus and direction of classroom discourse.	0	1	2	3	4
20)	There was a climate of respect for what others had to say.	0	1	2	3	4
	Student/Teacher Relationships					
21)	Active participation of students was encouraged and valued.	0	1	2	3	4
22)	Students were encouraged to generate conjectures, alternative solution strategies, and ways of interpreting evidence.	0	1	2	3	4
23)	In general the teacher was patient with students.	0	1	2	3	4
24)	The teacher acted as a resource person, working to support and enhance student investigations.	0	1	2	3	4
25)	The metaphor "teacher as listener" was very characteristic of this classroom.	0	1	2	3	4

Additional comments you may wish to make about this lesson.

2000 Revision

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Appendix 7

Modeling Instruction Survey

97–98 academic year

This survey is intended to: (a) identify aspects of the modeling approach that help students learn physics meaningfully, and (b) evaluate the project as required by the *National Science Foundation.*

Please:

- Allocate enough quality time to fill out this survey with the utmost care possible.
- Write your name and the date on the ParSCORE answer sheet, and bubble in your answers to the survey questions using a No. 2 pencil. The answer options for all questions are given below.
- Answer all questions based on your actual practice during last academic year (97–98), and not on any other consideration you might have about physics instruction or the modeling project.
- Understand that the list of items in this survey is neither exhaustive nor exclusive, and that no one item is considered beforehand as indicative of the quality of instruction.
- Write, on a separate sheet(s), any comments you have about any survey items or related issues you deem necessary for good modeling instruction.
- Return the ParSCORE answer sheet along with your comments in the enclosed envelope by **November 30, 1998**.
- Keep this questionnaire and copies of the returned materials for future reference.

Your cooperation is greatly appreciated.

Please tell us how often you do each of the following 100 items in your physics course(s). Mark only one answer for each question on the ParSCORE sheet using a No. 2 pencil. The answer options are:

Ⓐ	*Regularly,*	i.e., every time the issue arises.
Ⓑ	*Often,*	i.e., about every other time.
Ⓒ	*Sometimes,*	i.e., about one fourth of the time.
Ⓓ	*Seldom,*	i.e., about once a semester
Ⓔ	*Never*	

1. Provide the students with examples of applicable real world situations when introducing a new construct (i.e., a concept, a law, a model, or any other conceptual entity).
2. Revisit the same construct and show how it applies in different contexts after having introduced this construct and shown how it applies in specific contexts.
3. Provide the students with counter-examples of real world situations where a construct does not apply after having introduced this construct and shown how it applies.
4. Introduce a new construct on a need basis, i.e., only after letting students realize that constructs that they know so far are not adequate to describe or explain a given situation or set of situations.
5. Express to the students the relationship among various constructs qualitatively (i.e., without any mathematical formalism).
6. Compare and contrast related scalar and vector concepts (e.g., distance and displacement, speed and velocity).
7. Do dimensional analysis to set up or verify the units of a concept.
8. Teach students to develop well-defined rules for the allowed mathematical operations with any concept or law (e.g., the rule that says that no force vectors can be added unless the respective forces are acting on the same object).
9. Teach students to make the distinction between a descriptive construct (e.g., one of kinematics) and an explanatory one (e.g., one of dynamics).
10. Plan your instruction based on the models laid out in our modeling theory.
11. Maintain a story line of contextual nature (i.e., revisit the same real world situations under new conditions) as you go from one model to another.
12. Maintain a story line of conceptual nature (e.g., conservation laws) as you go from one model to another.
13. Compare the implications of the same concept (e.g., velocity or force) within the context of different models.
14. Compare the implications of the same law (e.g., Newton's laws) within the context of different models.
15. Ask students to identify "objects" and "agents" and the respective properties when dealing with a situation that involves an interaction between two or more objects.
16. Revisit situations already covered in mechanics when you teach (or intend to) courses other than mechanics.
17. Use examples from the history of physics.
18. Use examples from scientific fields other than physics.
19. Discuss explicitly the role of mathematics in physics.
20. Use motion maps (paths <u>and</u> arrows showing velocity and acceleration at different positions) when dealing with objects in motion.

21. Show corresponding arrow diagrams when dealing with vector concepts (e.g., force or velocity superposition diagrams).
22. Use different mathematical representations (diagrams, graphs, equations...) for the same situation.
23. Compare different mathematical representations in a way that shows the scope and limitations of each representation.
24. Give students a mathematical representation of a construct and ask them to interpret it qualitatively.
25. Make the distinction between average values expressed in the form of ratios and instantaneous values expressed in the form of derivatives when dealing with time-dependent concepts like velocity or acceleration.

STOP *Please take a break now before you move on to the following questions.*

26. Teach students to first identify givens and unknowns and then search for the right equation(s) in solving non-trivial problems.
27. Teach students to identify the appropriate model before they even know what the “questions” are about in solving non-trivial problems.
28. Assign open-ended problems that do not ask explicitly to find a specific concept.
29. Assign problems with superfluous data that are not needed to solve the problems.
30. Assign problems with missing information and which require that students make their own assumptions.
31. Ask students explicitly to solve the same problem in more than way.
32. Ask students to justify their way of solving a non-trivial problem.
33. Ask students to check their “answers” and establish their validity.
34. Give a “solution” to an undefined problem and ask students to make up a real world situation for which the solution applies.
35. Give the solution to a new problem and then ask for students’ questions.
36. Ask students to compare their own solutions for assigned problems to the correct solution developed in class and identify the sources of error in their solutions.
37. Follow up the solution of a given problem with a similar problem to which the same solution applies.
38. Follow up the solution of a given problem with a seemingly similar problem to which the solution of the former problem does not apply.

39. Teach students to develop a step-by-step prescription for solving typical problems after solving a number of problems that are within the domain of the same model.
40. Teach students to develop rules for reasoning by analogy.
41. Get students engaged in experimental activities in class.
42. Prescribe in some detail the steps that students need to go through in running an experiment.
43. Have students figure out on their own the “dependent” and “independent” variables that may be involved in an experiment.
44. Ask students to formulate their own hypotheses about these variables.
45. Ask students to formulate qualitatively the relationship among various variables.
46. Lay out explicitly the plans for reports that students need to turn in after running an experiment.
47. Ask students to analyze experimental data from different perspectives in their lab reports.
48. Ask students to extrapolate experimental results beyond the formulation of relationships among various variables.
49. Ask students to justify in their reports their way of analyzing experimental data.
50. Ask students to do error analysis in their lab reports.

STOP *Please take a break now before you move on to the following questions.*

51. Assign typical textbook problems as homework.
52. Assign home experiments.
53. Give students reading assignments to do before discussing the respective topic in class.
54. Give assignments in which students must apply what they learn in physics to aspects of their daily life.
55. Allow students to try out original ideas of their own in class.
56. Spend more than a quarter of a class period lecturing.
57. Ask students to give examples of real world situations where a construct applies.
58. Ask students to give counter-examples of real world situations where a construct does not apply.
59. Present students with a variety of real world situations and ask them to classify these situations following schemes of their own.
60. Cause student misconceptions about a discussed topic to surface explicitly.

61. Point out a misconception when it surfaces in students’ discourse, and provide the correct alternative.
62. Ask students to substantiate any claim they make in class.
63. Ask students to critique claims made by their peers in class.
64. Have students use whiteboards to present their findings in a laboratory experiment.
65. Have students use whiteboards to present their solutions to homework problems.
66. Have more than one group of students do whiteboard presentations in a given class period.
67. Set yourself a predetermined purposeful agenda for whiteboard presentations.
68. Allow students to prepare their whiteboards according to their own preferences.
69. Ask students to work in teams for more than half a class period.
70. Ask students to do their homework assignments in teams.
71. Ask students whether they were left with any unresolved issues by the end of a class period.
72. Solicit from the students a summary of the fundamental lessons learned in a class period.
73. Indicate to the students the materials they need to memorize from a textbook or any other written text.
74. Require that students get the correct numerical answer to receive some credit on homework problems.
75. Require that students get the correct numerical answer to receive some credit on test problems.
76. Return homework assignments to students and give them a chance to correct their mistakes on their own before you do the final grading.
77. Return quizzes or tests to students and give them a chance to correct their mistakes on their own before you do the final grading.
78. Ask students to grade their peers’ assignments.
79. Give assignments in which students need to discover the need for new constructs or new approaches that have not been covered in class yet.
80. Give quizzes that meet your own predetermined performance standards irrespective of students’ competence.

STOP *Please take a break now before you move on to the following questions.*

81. Teach that any physics construct must correspond to some objects or phenomena in the real world.
82. Teach that physicists look for patterns in real world objects and phenomena.

83. Teach that any scientific endeavor must be conducted within the framework of a well-defined theory.
84. Teach that the primary or salient features of real world objects and phenomena may not be exposed directly to our senses.
85. Teach that scientific constructs are human inventions and not actual aspects of the real world.
86. Teach that scientific constructs are only partial representations of some aspects of the real world.
87. Teach that all scientific constructs are arrived at by approximation and that no construct may be absolute.
88. Teach that scientific constructs may apply anywhere in the universe.
89. Take time after class to evaluate what goes on in a class period.
90. Share ideas that work in your class with your colleagues.
91. Share problems that you face in your class with your colleagues.
92. Solicit the assistance of educational researchers at institutions of higher education.
93. Design instruction to meet requirements of standardized or mandatory tests.
94. Design instruction explicitly to help students develop coherent worldviews.
95. Refer to research-based instruction materials other than those of the modeling workshops in designing physics instruction.
96. Refer to the National Science Education Standards in designing physics instruction.
97. Refer to physics/science education journals in designing physics instruction.
98. Refer to works on educational theories like Constructivism or Conceptual Change.
99. Refer to works on the history of science in designing physics instruction.
100. Refer to works on the philosophy of science in designing physics instruction.

Thank you