The modeling method of instruction in physics: How to do it!

Colleen Megowan-Romanowicz
Assistant Professor of Science Education
Arizona State University

Modeling instruction is one of the most successful reforms to the teaching of physics in the last 50 years. It is predicated on the notion that it is the nature of humans to think using "models"—conceptual representations of real things. Firmly grounded in cognitive science and based upon the belief that science content cannot be separated from pedagogy, modeling instruction uses an iterative cycle of ***model construction****,* ***model testing and elaboration*** *and* ***model application*** *to help students learn physics deeply and coherently. Even more important, it helps them learn to think like a scientist. In this paper I describe how modeling instruction is practiced, how teachers learn to use it in their classrooms and how teachers learn to teach using modeling instruction.*

I started teaching high school science in 1978. I loved it and my students loved learning science. As the years passed, I gained experience and skill. Although I received recognitions for being a good teacher, I was troubled that a significant fraction of students left my class with only a fragmentary understanding of basic physics concepts. They were not stupid—I just did not know how to reach them.

When I learned modeling instruction in 1998 *everything changed*. Other than occasional presentations like this one, I have not lectured in 12 years. Modeling instruction allows me to see and hear what my students are thinking. More importantly, it gives my students the opportunity to see and hear what their classmates think. My conceptual model of how physics should be taught and learned has shifted.

A brief history of modeling instruction

In 1983, high school physics teacher Malcolm Wells was a graduate student of theoretical physicist David Hestenes. Ibrahim Halloun, who was also Hestenes' student at the time, was working on an assessment he called the *Mechanics Diagnostic,* the pre-cursor of the Force Concept Inventory (FCI).[1,2]

The results of Halloun's research utilizing this test revealed that student misconceptions about force are surprisingly robust, and that these naïve beliefs often persist despite instruction--regardless of the teaching method or the instructor's qualifications [1]. Wells, an excellent teacher who had already adopted a student-centered inquiry approach based on Learning Cycles [3], was shocked by how poorly his students did after instruction on Halloun's simple measure of student beliefs.

In an effort to address this problem, Wells designed a classroom teaching experiment for his dissertation research project, redesigning the mechanics portion of his physics course to focus on the eight fundamental conceptual models of mechanics described by Hestenes [4]. Adding his newly acquired understanding of the structure of models and the stages that characterized the activity of modeling to his existing instructional design based on Robert Karplus' learning cycles, [5] Wells developed a two-stage *Modeling Cycle:* 1) *model development*, consisting of description, formulation, ramification and validation and 2) *model deployment,* in which the model developed in stage 1 was applied to a variety of novel physical situations [6]. It is this cycle that forms the basis for the three phases into which modeling instruction is currently divided.

Results from this model-centered collaborative inquiry approach to teaching physics were dramatic. Students' posttest scores on the Mechanics Diagnostic Test increased by a standard deviation or more, in most cases exceeding those of students in elite private universities. Based on these findings, Hestenes received National Science Foundation (NSF) funding to develop and disseminate this new approach to physics instruction. Modeling Workshops were created to train teachers and groups of trained teachers developed a mechanics curriculum anchored by a suite of paradigm labs used to introduce each of the models. Subsequent grants allowed for the Modeling Instruction Program to be scaled up, hosting workshops in 4 different locations around the US. The teachers who attended these workshops developed second semester physics topics of electricity and magnetism, light and mechanical waves, adding them to the tried and tested physics mechanics curriculum. An $8^{th}/9^{th}$ grade Physical Science Modeling course was also developed that blended physics and chemistry ideas.

Subsequent NSF grant funding has resulted in the creation of a Master of Natural Science (MNS) degree program for high school physics teachers at Arizona State University, the creation of Chemistry modeling curriculum along with a series of two Chemistry Modeling Workshops, and a Physical Science with Mathematics Modeling Workshop. MNS courses include several integrated offerings--Integrated Physics and Chemistry, Integrated Mathematics and Physics, Physics and Astronomy, Astrophysics, Energy and the Environment—and several contemporary physics offerings—Spacetime Physics, Light and Electron Optics, Matter and Light, and Structure of Matter. All these courses are centered on conceptual models and structure the learning experience with Modeling Cycles. In late 2009 the NSF granted funding to develop a Science, Technology, Engineering and Mathematics (STEM) Modeling MNS degree program for elementary certified teachers to prepare them to teach science and mathematics in middle school.[7]

Malcolm Wells passed away in late 1994 but his innovative approach to teaching and learning lives on. A 2007 survey found that 9% of US physics teachers utilize Modeling Instruction.[8]

The *Force Concept Inventory* (FCI), a refinement of the *Mechanics Diagnostic* that was used to measure student gains in Wells' research in the early 1980s [9] continues to document robust conceptual gains by students in classrooms where Modeling Instruction is practiced. A 1998 study of over 6000 students by Richard Hake showed gains for students in classrooms utilizing interactive engagement methods (such as Modeling) of up to two standard deviations over those of students in classrooms where the more traditional lecture-demonstration format is used [10].

As of this writing, over 3000 US teachers have taken Modeling Workshops. Modeling teachers are also found in Europe, Japan, Singapore and Australia. The spread of this reform teaching method from teacher to teacher and school to school has not resulted in the commercialization of Modeling curriculum materials, which continue to be freely available to every teacher who takes a workshop.

Next, I will provide a theoretical framework to explain what modeling instruction is and how it works.

What is a model?

The central feature of modeling instruction is a collection of conceptual *models* and the primary activity in which students engage is called *modeling*. What, exactly, is meant by these expressions?

Put simply, *models* are representations of structure in a material system[11]—conceptual constructs made up of elements, operations, relations and rules[12]. David Hestenes, the founder of the Modeling Instruction Program, calls models *mental representations of real things*.

Models of material things have different kinds of structure: [11]

- systemic structure: the relationships of elements in a system with one another and with the external environment
- geometric or spatial structure: the positions of elements in a system with respect to one another and with respect to a reference frame
- temporal or event structure: the temporal change in the structure of a system
- interaction structure: the causal links between elements in a system
- object structure: the intrinsic properties of the individual elements in a system

What is modeling?

Modeling is a cycle of activities that takes place in three stages: *model construction*, *model testing and elaboration* and *model application*. These activities lie at the core of what we call *Modeling Instruction*, and it is these instructional practices that form the framework for the classroom activities that I will attempt to describe for you today.

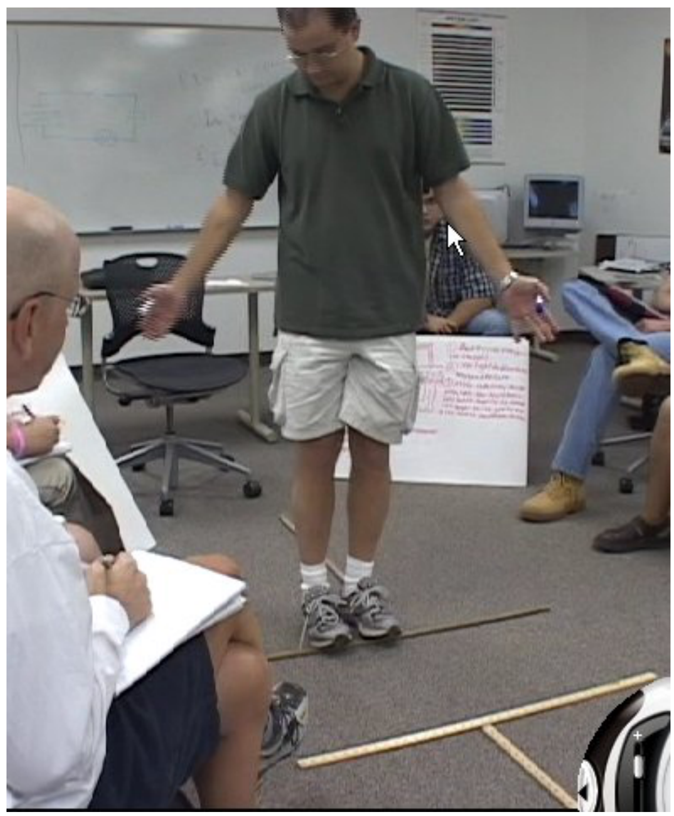

Figure 1. The teacher models the behavior of a charge on the plate of a capacitor during a board meeting.

What is Modeling Instruction?

Modeling instruction is a guided inquiry approach to teaching science and mathematics. The modeling method provides a framework for science instruction that is an approximation of how scientists "do science." Students engage in the activity of building, testing and deploying conceptual models of physical relationships. Modeling curricula structure this learning process by organizing the content around a relatively small number of basic models (see Figure 2 for a list of the conceptual models employed to teach physics) that characterize common patterns in physical phenomena. As students' familiarity with these patterns increases, they become more adept at recognizing and applying their structural characteristics in unique situations.

A typical Modeling Instructional unit begins with a paradigm lab. These laboratory activities are carefully designed based on physics education research about students' misconceptions and naïve beliefs.[13, 14]

In the class discussion that precedes the laboratory activity, students observe a phenomenon, discuss what they observe, identify a relationship between two elements that they wish to quantify and correlate, and make predictions about the expected outcome. Then they work together in small groups to conduct the laboratory investigation, gathering data that they analyze and then represent on 60 cm x 80 cm student whiteboards. Whiteboarded lab results are shared and discussed with the whole class in a "board meeting" (Figure 1). The class gathers in a circle with their whiteboards and discusses the results and conclusions, coming to a consensus on the nature of the relationship between physical quantities. Ultimately students arrive at a set of representations for the model they have constructed that includes a diagram, a graph and an equation that quantifies the relationship. Once the model under investigation has been parameterized in this way, students engage in a series of deployment exercises and tasks that are carefully sequenced to help them elaborate on this conceptual model and apply it in a variety of contexts and physical situations.

Physics Conceptual Models

Mechanics

- Constant velocity particle (objects in translation with constant velocity)
- Particle undergoing uniform acceleration (objects in linear translation with constant acceleration)
- Free particle (inertia and interactions)
- Constant force particle (force as cause of acceleration in linear translation)
- Energy (explaining particle translation via conservation of energy)
- Central force particle (objects in circular translation)
- Impulsive force particle (conservation of linear momentum)

Electricity & Magnetism

- Charged particle (Charge behavior and interactions)
- Electrical Potential (The E-Field)
- Flowing charge (E-Field causes bulk charge flow in conducting materials)
- Magnetic fields and forces (interaction of moving charge and magnetic field)

Light

- Light as a particle
- Light as a wave
- Light as a photon

Mechanical Waves

- Oscillating Particle
- Mechanical Waves in one dimension
- Mechanical Waves in two dimensions

Figure 2. The conceptual models of the introductory physics curriculum.

There is little or no lecturing in a modeling instruction classroom. The teacher typically poses a problem at the opening of each class and students gather in small groups and work together to find a solution. The teacher sets a time limit for completion of group work and moves from group to group listening and occasionally offering a comment or asking a question. At the appropriate time, the teacher convenes a board meeting and steps back so that students must take charge of the conversation. Each new class-work task (typically one or two per 50 minute class period) is whiteboarded by these small groups, followed by sharing and sense-making with the whole class. Worksheets provide additional homework or class-work practice problems. At the end of a modeling cycle, students may participate in a performance assessment - a lab practicum - and they also complete a written examination. (See the sample unit in the appendix for examples).

The quality of classroom discourse is critical to the success of Modeling Instruction. The key to establishing a good discourse community is to design a classroom culture that removes the teacher from "center stage" and calls for the students to depend on one another to advance the group's understanding of the model under investigation. This is a very different classroom dynamic from the typical culture of schooling, and requires the teacher to develop skill at redirecting student questions to the group rather than simply giving the answers. Teachers may choose to withdraw entirely from a board meeting and leave students to argue through a solution with one another (remaining nearby, of course, so they can listen and take notes about how student thinking evolves), or they might join the conversation as an equal participant with students. Skillful teachers find a way to draw students who are uncertain into the conversation so that the group must improve their explanation until even the most confused of their classmates understands. Typically at the close of a board meeting the teacher will request that one student summarize their understanding of the model. This presents another opportunity to probe the group for weaknesses and misconceptions.

Modeling instruction curriculum units have been written for each of the models in Figure 2 with teacher's notes, paradigm labs, worksheets, lab practicum activities and a variety of ancillary materials (e.g., video clips, spreadsheets and java applets). These can be viewed and downloaded by American Modeling Teachers Association (AMTA) members at https://www.modelinginstruction.org . There are also modeling physics units that have been adapted for use in 9th grade physics and 8th grade physical science. All modeling instructional materials are made available free to teachers who have completed a Modeling Workshop and can be found at the URL given above. They are not available for purchase.

More detailed descriptions of various aspects of modeling instruction and a wide array of journal articles, dissertations, reports and supplemental resource materials can be found at the ASU Modeling Instruction Program legacy website: http://modeling.asu.edu and at the AMTA public website, https://www.modelinginstruction.org .

Modeling Theory

Over the past 25 years, David Hestenes, the founder of Modeling Instruction, has developed a Modeling Theory of Cognition. Hestenes' theory borrows from cognitive linguistics to characterize *mental models* as "private constructs of the mind" that can be raised to the level of *conceptual models* by encoding the structure of the model symbolically in a way that activates the mental models of others.[11] He asserts that language does not refer to the external world but rather to one's mental model of the real world. "Words serve to activate, elaborate or modify mental models…".[11] Figure 3 is a simplified illustration of his theory.

A mental model is usually both descriptive and explanatory. In order to share a mental model with others, an individual must represent it in some way, e.g., in words, symbols, images or gestures. This encoding of one's mental model into some representational schema elevates it from a private construct to a shared construct or *conceptual model.* A conceptual model can then be *tested* against observed phenomena in the real world to determine whether it is aligned with observable evidence and produces good predictions. If so, then it becomes a useful tool for making sense of the physical world. If not, then it must be revised to account for the new data and tested again.

This cycle of model construction, testing and application is a ubiquitous activity of living things and can be seen in animals and humans alike in the construction and use of tools for the solving of problems.[15]

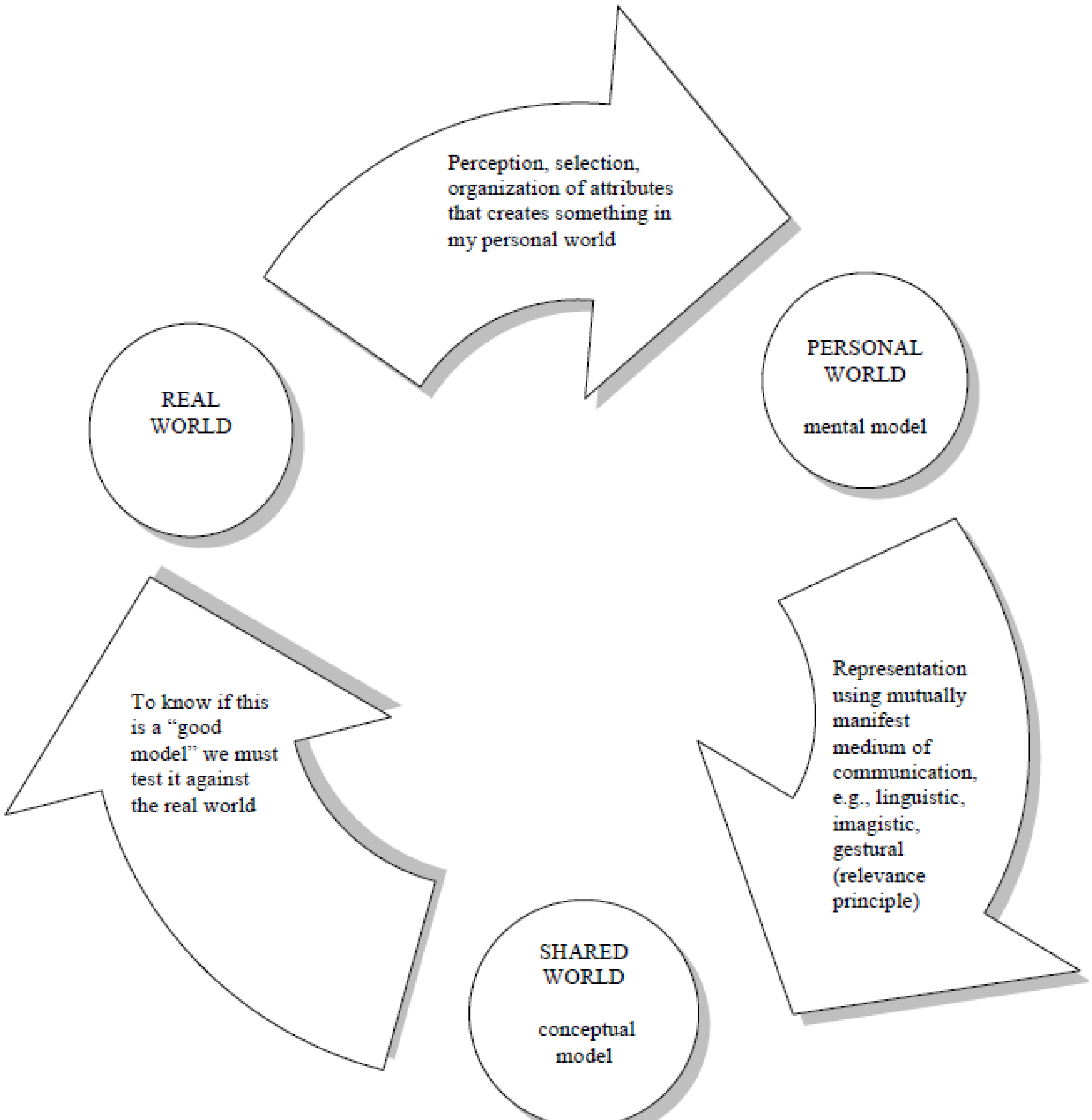

Figure 3. A modeling theory of cognition.

Cognition and Modeling

Cognition can be defined as *the utilization of information that one understands to reason about or make sense of something.* The practice of Modeling Instruction is rooted in cognitive science. Modeling instruction takes advantage of the fact that cognition is situated—that is, grounded in the context of everyday activity.[16] Cognition is culturally mediated. It is transmitted socially by humans who pool their cognitive resources, employing the metaphors of their culture to help one another make sense of a complex world. Cognition is embodied—that is, scaffolded by our sensory-motor system, which helps us to make sense of our surroundings with respect to our physical and temporal location and interactions with other elements of the physical world. And finally, cognition is distributed. It can involve cognitive resources that extend well beyond what goes on in our internal mental space. Indeed, our propensity for the use of tools requires that we enlarge our view of human cognition to include other resources that extend beyond the boundary of the individual. Hollan and Hutchins [17] propose that cognitive activity is often distributed across *tools, artifacts, representations and groups of people*. I will illustrate this below as we take a closer look at the Modeling Instruction classroom environment.

How to do modeling instruction—in physics or any other subject

The modeling cycle: model construction

The first, and perhaps most difficult task a teacher encounters in using modeling instruction to help students learn is understanding deeply what a conceptual model is.

Let us consider the constant velocity model—the first conceptual model of kinematics. There are many ways in which to describe and represent this but first the student must notice and recognize the characteristics of an object in motion at a constant velocity. The modeling cycle begins with a paradigm lab—a laboratory exercise that elicits the constant velocity model. Typically a teacher will set a battery powered car in motion and ask the students to observe. After observing the car move across the room several times, students are asked what they observe, and one by one as students announce their observations, the teacher records each on the board. Students will usually say things like "the car is moving in a straight line", the car's light is blinking at a constant rate", "the car is moving at a steady speed," "the car moves about the same distance in each second," "the car is red." When no more observations are forthcoming, the teacher will prompt the students to identify which of these observations can be directly measured. After they come to the conclusion that they can measure change in time and change in position (or displacement), the teacher will challenge them to "find the relationship between change in position and change in time for the battery powered car." Students are given cars and measuring tools (measuring tapes and stop watches or motion sensors) and they work together in small groups, first to come up with an experimental procedure, and then to collect the necessary data.

The Modeling Cycle
Stage 1: Model construction
Model is identified and parameterized
Stage 2: Model elaboration
Model is refined, extended and tested
Stage 3: Model application
Model is used to solve complex problems in a variety of contexts

Figure 4. The three stages of the modeling cycle.

After they have collected sufficient data they record their results on whiteboards so that they can share their findings with their classmates. They must represent their data in multiple ways: graphically, diagrammatically and mathematically. Figure 5 shows a typical student whiteboard.

After all groups of students have whiteboarded the results of their investigation, the entire class is brought together into a large circle so that everyone can view what all groups have shown on their boards and discuss their results. This is called a "board meeting." Students are encouraged to take the lead in discussing and comparing their findings. Eventually they reach a consensus on the answer to the question: what is the relationship between change in position and change in time? The teacher remains on the periphery of this discussion as much as possible, encouraging students to look to one another for help in making sense of their observations. The discussion is finished when everyone agrees on the meaning of the graph, diagram and the general equation they have derived from the data they gathered, and when students are successfully able to verify that all three representations--graph, diagram and equation—say the same thing.

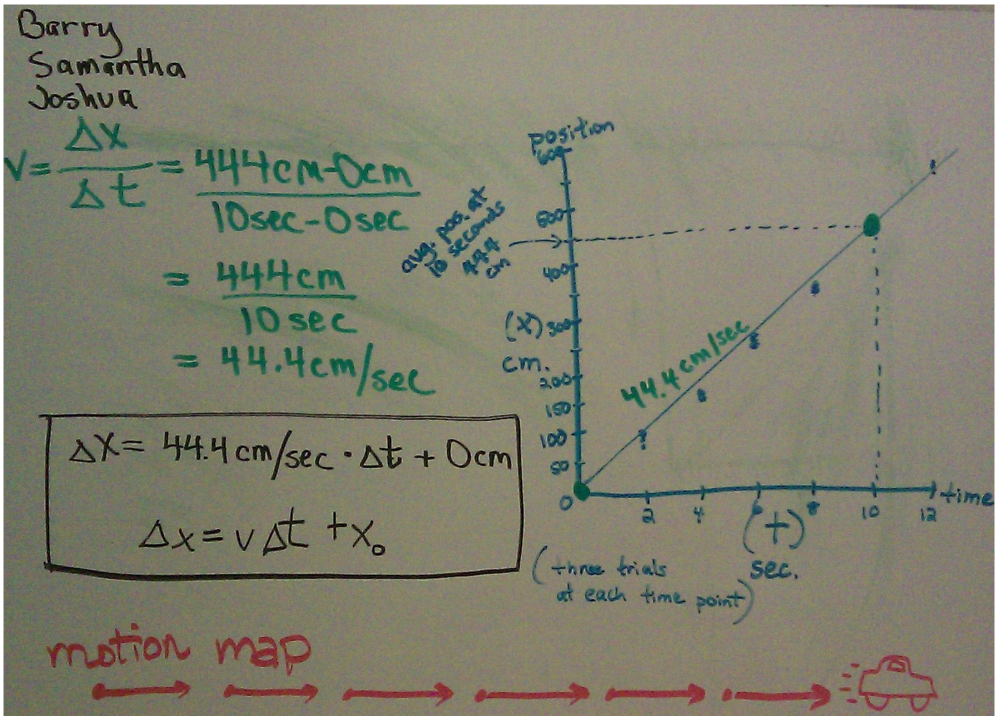

Figure 5. A student group's whiteboard of the results of their constant velocity lab.

Model elaboration and testing

Once the class has achieved consensus regarding the relationship under investigation they are given a variety of tasks or problems that allow them to explore and practice with the model graphically, diagrammatically and mathematically. As with the paradigm lab, this is done by the students in small groups. A modeling task is assigned to the whole class. They work on representing solution strategies in small group and then they convene in a board meeting to discuss their solutions, with the teacher again guiding from the side rather than leading the discourse. In exploring the constant velocity model, students may examine the consequences of motion in the negative direction, motion that begins somewhere other than at the origin, the relative motion of two objects traveling at different velocities, and the velocity of an object at rest (zero velocity). They are challenged to develop definitions of terms such as displacement, distance, time instant, time interval, speed, and in so doing they develop a more detailed, coherent conceptual model of constant velocity. This phase of the modeling cycle allows students to learn how to manipulate the model, discerning the rules by which various operations may (or may not) be performed. It includes a series of class work tasks preceded by homework assignments that encourage students to explore similar problems before attempting to solve them in their small groups.

Model application

When students appear to have a solid grasp of the model and how it can be used, they are assigned problems in a variety of different contexts that require its use to arrive at a solution, e.g., cars, cyclists, sprinters, trains, airplanes, a running dog, a cartoon character falling off a cliff (see figure 6).

Some problems may be assigned as homework and others given as whiteboarding exercises in class. Often, a final lab practicum is given prior to the written examination for the instructional unit. For the constant velocity unit, students might be asked to calculate the exact positions of two battery powered vehicles with respect to one another or to a coordinate system at several different instants in time.

Once students have mastered a conceptual model they are assessed. They are challenged to solve both qualitative and quantitative problems using multiple representations. An important element of every board meeting discussion is making sense of how the graph, diagram and algebraic solutions tell the same story. The written examination also probes individual students' ability to do this.

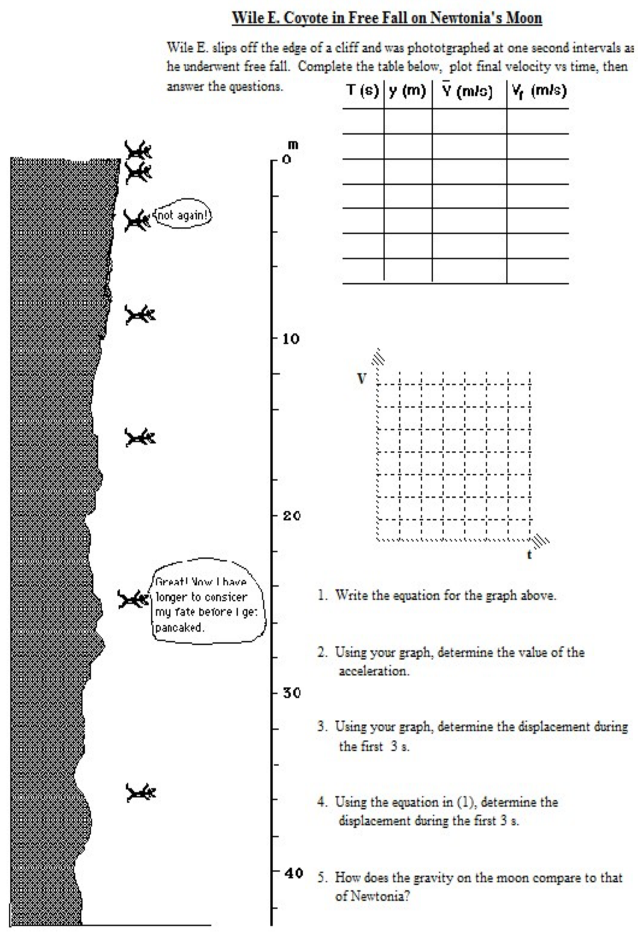

Figure 6, A sample application problem.

Student discourse

The management of student discourse is central to the teacher's practice of modeling instruction. There are two kinds of modeling discourse community: the small group, typically three or four students (three works best); and the whole group—the entire class. Both are mediated by the use of whiteboarded representations. Whiteboarding allows student thinking to be exteriorized, giving the teacher an excellent opportunity to *listen* and learn about students' conceptual models as they are in the process of being constructed and tested.

Whole group discourse sets the stage for each activity. Whole group discourse also follows small group work, giving students the opportunity to help one another make sense of how a particular model applies to a problem situation and consolidate what they have learned from each exercise.

Small group discourse permits individuals to work collaboratively at finding a solution pathway they can all agree upon. Grouping students in this way makes it possible for the teacher to move around the classroom, *listening* to students' conversations and *observing* the solution strategies that each group attempts. This also gives the teacher an opportunity to *suggest* ideas or questions to individual students or groups who may have a unique view of the problem, or encourage individuals to volunteer their thoughts during the whole group discussion. For students, there is less potential embarrassment in conversation with a small group of peers than there is in a whole group discussion. Thus students who might otherwise remain silent are more likely to try out explanations, ask questions or make suggestions when working with their small group partners. This is another instance in which the teacher will gain insight into students' thinking because he will have opportunities to hear from many more students as he wanders from group to group listening to them think aloud as they prepare their whiteboard. Once students understand the task they have been assigned, very little input from the teacher is typically necessary for small groups to negotiate solution strategies and prepare a whiteboard.

When students are called together for a board meeting to share their whiteboarded solutions, the teacher may need to play a more active role in making sure the conversation is fruitful. It is important to establish expectations about student involvement in whole group discourse. Students should be encouraged to volunteer to go first in explaining their thinking about the problem under consideration. Their peers must listen carefully so they can ask useful questions. At the beginning of the school year, the teacher may have to demonstrate good questioning skills to the students, asking "how do you know…?" or "what if…?" questions when a student group presents their solution or he may have to prompt students to explain how various representations illustrate the same relationship. The teacher might also prompt an individual student to relate a conversation that he overheard in his small group discussion. If the discussion comes to a halt and the teacher believes there are still students in the class who do not understand the problem, he may ask one of these confused students to explain the problem and when they get stuck, insist that his classmates find a way to explain the situation to him so that he fully understands. At the end of a whole group discussion or board meeting, the main ideas about how the model was applied should be summarized by a student if possible, or by the teacher through Socratic questioning. The point of whole group discourse is to map the problem onto a shared conceptual model, and then manipulate this model to find a solution.

Another approach to whole group sense-making involves formal presentations by small groups of students where a single group comes to the front of the classroom, displays their board, describes how they worked out the solution and then answers whatever questions their teacher or classmates might ask them. This tactic is primarily used when class time is spent in going over homework problems. A recent study has shown that it is less effective than board meetings, and its use is beginning to decline[18,19] in favor of board meetings.

Whiteboarding: negotiating shared understanding

Whiteboards are an important cognitive and communicative tool. They are a place for students to represent what they have discovered or negotiated in collaboration with their peers. They show the processed data that maps a problem space as they have come to understand it and illustrates the group's assertions about the problem space.[18] Whiteboards are where *private mental models* become *shared conceptual models*.

There are several important advantages of student whiteboards.

- They are *large.* Whiteboards are large enough for several different representations of the same problem, and large enough that multiple students can draw or write on them simultaneously. This allows for the conversation that takes place among students in a small group to focus on more conceptual matters such as how various representations correspond with one another, rather than on procedural matters such as whether or not an algebraic manipulation has been performed correctly.

- Whiteboards are *erasable*. The ease with which they are erased encourages students to share partially formed ideas that can be extended or improved upon in consultation with the group until they arrive at something that illustrates their thinking to everyone's satisfaction.

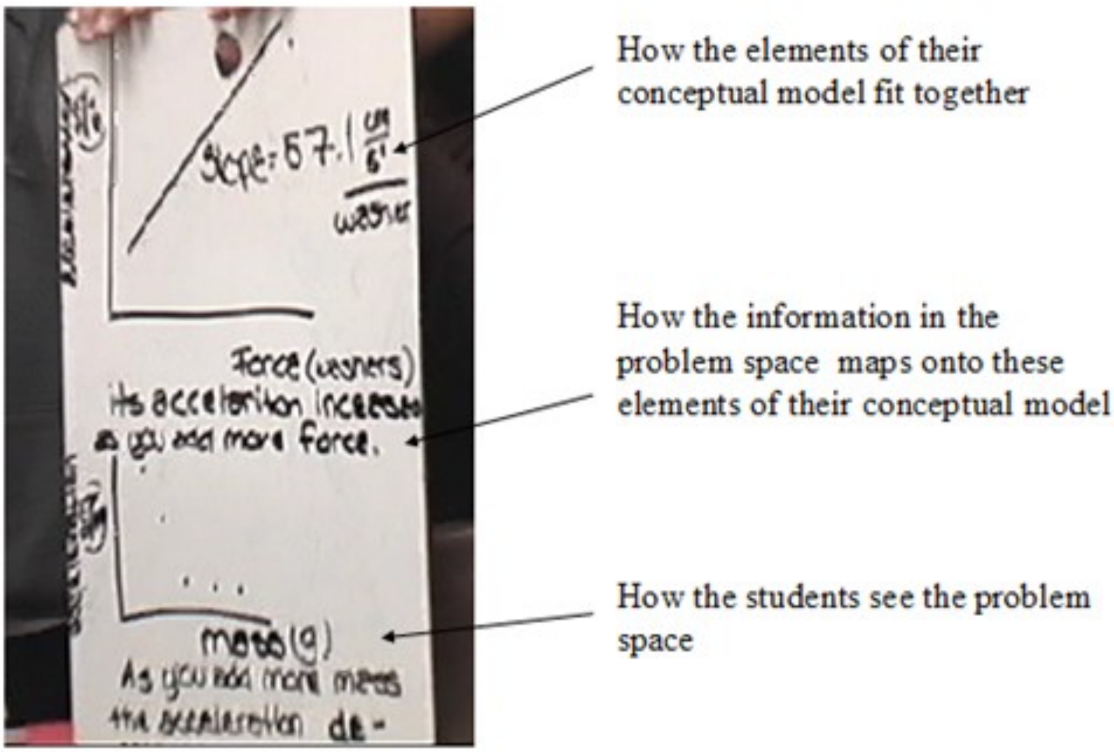

Figure 7. What a whiteboard reveals about student thinking.

- Whiteboard content is *shared and negotiated*. A finished whiteboard contains the consensus conceptual model of the small group that prepared it. In order to complete a whiteboarding exercise all members of the team should participate in the conversation and agree aboout the representations on the board because any one of them might be called on to explain what it shows to the entire class. The necessity for developing a shared model is critical to promoting discourse within small groups.

Classroom culture

By the time most students reach physics class they are experts at "playing the school game." They know how to determine a teacher's expectations and limits, and are accomplished at identifying classroom behaviors that will yield the best grade in exchange for the least effort. In general, "motivated students," as defined by the instructor, are those who are interested in succeeding in a class, and success is usually measured by the accumulation of points.

Modeling instruction is founded upon the idea that these routine social norms of conventional schooling can and should be rewritten. Central features of the culture of a modeling physics classroom are inquiry, observation, collaboration, communication, and reasoning. The teacher is not a giver of knowledge but rather an asker of questions.

Although a modeling instruction classroom has the same tools that have become familiar to students in their years of schooling—pens, pencils, rulers, whiteboards, calculators and computers—they learn to use them for *sense-making* rather than just *answer-making*. Computers and calculators become data acquisition and analysis tools. Worksheets provide problems or situations to think about and discuss with their peers. Whiteboards are a medium for communication and distributed cognition.

While success in a modeling physics classroom is measured in the conventional way—by the accumulation of points—these points are, ideally, earned for interacting with peers to successfully construct, validate and apply models rather than for simply giving correct answers.

Changing classroom culture requires deliberate efforts on the part of both teachers and students. Teachers set expectations about student engagement and performance within the first few weeks of the school year. Once these expectations are understood by students they are very difficult to change. Since modeling instruction involves very different expectations than most students have encountered in previous science courses, teachers must be explicit about their expectations for student engagement in all activities at the very beginning of the course. In addition, it is advisable to introduce all the various types of modeling classroom activities you will want them to engage in during the first two or three weeks of the course as this is when students are most open to learning new classroom behaviors. Thus students should be introduced to pre-lab discussions, inquiry-based laboratory activities, whiteboarding, board meetings, practicing-with-the-model problems, and laboratory practicum assessments as early as is feasible during the school year.

There are two keys to motivating active student engagement in the learning environment: arousal and control. Teachers must arouse students' curiosity and interest by posing interesting, relevant questions; and students must be allowed as much freedom as possible in completing laboratory and problem solving exercises.

Strategies

Zooming in and zooming out: The conversation that attends collaborative whiteboard preparation is fundamentally different from other student conversations around problem solving in the classroom. When students discuss problems they are attempting solve on individual worksheets or in other personal written work, they tend to talk about procedural details such as algebraic manipulations, formula selection, unit conversation or simply, the answers, (e.g., "what did you get for number 5?"). If we use the camera as metaphor for how they view a task, it as if they are *zoomed in* on the fine details of the problem.

Whiteboards help students *zoom out* to view the big picture. Students in the process of producing a whiteboard more often discuss elements of conceptual rather than procedural knowledge as they work to help one another understand how different representations illustrate the same situation.

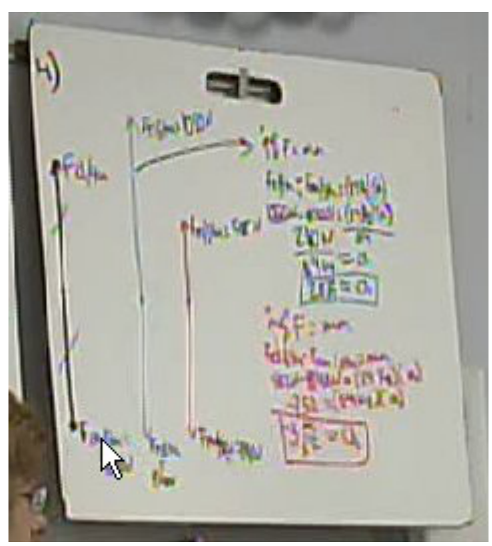

Figure 8. Spatial representations typically lead students to a more "zoomed out" view of the problem.

Spatial representations: Making and coordinating multiple representations of a problem is also critically important. Typically, students are prompted to formulate their solution problem using at least 3 different modes of representation. Research has shown that reasoning across multiple representations and, in particular, reasoning from spatial representations fosters the development of more coherent conceptual model than reasoning from a single propositional (algebraic) interpretation[18]. Student discourse about spatial representations tends to be zoomed out while discourse about algebraic expressions is usually zoomed in.

Tactics

To encourage fruitful discourse teachers must learn to wait after asking a question. Research on teacher wait time in traditional lecture-discussion format courses reveals that teachers wait about a second after posing a question before they rephrase it, call on someone or answer it themselves.[20, 21] The same studies reveal that when teachers wait longer—up to 7 seconds—they will get much better results, in the form of increased student participation and improved student understanding. Furthermore, if the teacher establishes at the beginning of the course that he will not provide the answer to his own question but rather will wait for students to pool their thinking in order to come up with a response, students are more likely to adopt the habit of trying to contribute ideas to the group that can be used in fashioning an answer.

Another tactic that helps students develop active learning habits is to require them to assume responsibility for questioning one another in board meetings. It is easy for the teacher to do the questioning himself as he knows which questions will move the group toward the answer he wants. Early in the course the teacher may need to do a great deal of questioning in order to demonstrate fruitful questioning techniques for the students, but as soon as possible, the teacher should pass along the responsibility for asking questions to the students. Initially it may be helpful, even necessary, to reward students for asking good questions in whole group discussion. (In this instance praise is the best reward, but points may also be given.) It is also worthwhile to discuss the nature of "good questions" with students. Help students develop a list of useful questions that ultimately lead to a better understanding for the entire group. "How do you know…?" and "what if…? are two types of questions that are excellent probes for testing a newly constructed conceptual model.

When the students take on the burden of questioning, the teacher has a better opportunity to look and listen for students with a weak or faulty understanding. By gently revealing these gaps in student understanding, the teacher can guide his or her classmates to assist the struggling student. It is the teacher's responsibility to see that the group's understanding of a problem is summarized at the end of a board meeting, but he need not do this by simply telling the students what they should now know. It is far better to have one or more students do the summarizing, perhaps with a few teacher or student questions to insure completeness.

Norms

In order for whiteboard-mediated classroom discourse to work well, there must be clear, explicit expectations about how a whiteboard should be prepared and what it should show. These are norms that primarily impact small group interactions.

The first rule of whiteboard preparation is that every member in the small group is expected to contribute. It is up to the group to decide how these contributions appear in the final product, but one thing the teacher is looking for as he circulates during whiteboard preparation is active participation by every member of each group. At times, group members disagree and despite lively discussion are unable to come to a consensus on the best way to proceed. When this happens a group may prepare multiple whiteboards, each representing a different view of how the problem should be solved. If this occurs it is often best to let this group go first when the board meeting convenes as the story of their disagreement is likely to initiate a good class debate. If everyone agrees (which is the usual state of affairs) then a single whiteboard is prepared that represents the consensus view of the group. This whiteboard must show multiple representations of the problem space and every member of the group that prepared it should be able to explain the group's reasoning in preparing their whiteboard. One other necessary and important element of a properly executed whiteboard is clear labeling. There must be no ambiguity in any of the modes of illustrating the problem which might lead students to a misunderstanding of what is meant by the representations shown.

There are also important discourse norms that should be observed in a modeling classroom. Teachers should expect students to assume leadership in board meeting discussions, just as they must lead the discussions in their small groups during whiteboard preparation. This allows teachers to take a more peripheral role so that they can listen carefully and analyze students' conceptual model. As the teacher moves from group to group during whiteboard preparation, it is often helpful for him to interject good questions within small group conversations and encourage students to raise these questions during the board meeting. The teacher should also express appreciation for students' contributions to board meeting discussions by complimenting good questions, especially early in the school year so that students will be encouraged to continue to contribute.

Students must be reminded to acknowledge each others' contributions even when they disagree with them, and they should be encouraged to disagree—even with the teacher. Both students and the teacher should challenge one another to justify statements, and not just when they believe the speaker is wrong. An individual's question should not be left behind until he fully understands the answer.

Assessment

What should the teacher look for to determine whether or not coherent conceptual models are being constructed by his students? There are several elements that cut across all modeling activities:

- Can students synthesize explanations and justifications using the language of physics?
- Are students able to understand and apply the representational tools correctly?
- Can students utilize multiple representations to illustrate the same problem?
- Is the conceptual model they have constructed complete, with all elements, operations, relations and rules in place?
- Can students apply their model to solve new problems from different contexts?

Most assessment is formative, taking place as the teacher observes laboratory activities, small group whiteboard preparation and whole group discussion, but summative assessment in the form of end-of-unit lab practicum exercises and written tests also reveal the answers to these questions. Both are necessary because, although modeling is fundamentally a socially distributed activity, ultimately each student must take away his own personal mental models from the course and apply them to his own unique life situation. Modeling instruction provides opportunities for both forms of assessment in the course of routine classroom practice, and assessments can be found at the end of each instructional unit (see the appendix at the end of this paper for a sample).

How does a teacher learn to do modeling instruction?

Since 1993, teachers have been learning to teach using modeling instruction by attending summer Modeling Workshops. These workshops are led by pairs of expert high school modeling teachers who understand the demands of the school environments from which their workshop attendees come. A typical modeling workshop lasts three to four weeks and meets six to eight hours per day. Workshop enrollment averages 25 teachers.

During the workshop, teachers act out the roles of students as they work through the curriculum materials. They work together, preparing whiteboards, participating in board meetings, doing homework exercises and taking tests. Teachers are adept at modeling student behavior under these conditions and will often add an air of realism to the learning environment by acting out both the best and worst behaviors they see in their own classrooms on a regular basis. In this way they learn to anticipate and, to some extent, prepare themselves and one another for the challenges they may encounter when implementing modeling instruction in their classroom during the following school year. They gain insight into meeting these challenges by observing how their workshop leaders--both experienced modelers—handle the situations they contrive.

After workshop completion, teachers return to their classrooms and implement the techniques they have learned. The first year is often a difficult one. Most teachers feel they are moving much more slowly through the course content than they should because they are not yet expert at managing classroom discourse. However, most first-year modelers are pleased to see that their students learn physics more deeply than they have in previous years and inevitably, when they administer the Force Concept Inventory post-test to their students at the end of the year, they are pleased at the conceptual gains that students have made.

During the school year, in order to help teachers remain connected to one another and to their workshop leaders, there are periodic Saturday meetings with speakers on advanced topics and plenty of opportunities to network with their first-year-modeler colleagues. There is also an online community of modelers that publishes a daily listserv. Everyone who has taken a modeling workshop can opt to receive this. Currently the listserv has about 2000 subscribers. Teachers post questions, comments, reflections and sometimes, cries for help. Long time practitioners of modeling instruction share their collective wisdom with new modelers. In addition to this daily modeling communique, archives of the listserv are available on the ASU Modeling Instruction Program website (http://modeling.asu.edu). All these factors work together to support teachers through the transition from their old way of teaching to becoming a modeler.

Most teachers return for a second Modeling Workshop after their first year using modeling instruction. They may choose from several second semester physics topics including light, electricity and magnetism and waves. The teachers learn to design modeling curriculum materials during this second workshop experience and continue to hone their classroom discourse management skills.

In addition to the Modeling Physics Workshops mentioned above, there are two Chemistry Modeling Workshops, a Physical Science Modeling Workshop and a Physical Science with Mathematics Modeling Workshop for teachers in other sciences. A Biology Modeling Workshop is presently in development by a group of experienced modelers in Pennsylvania. And recently I received funding to create an integrated middle school science and mathematics modeling master's program for in-service teachers who desire certification to teach science and mathematics in the middle grades.

With over 3000 teachers trained in modeling instruction worldwide the Modeling Instruction Program has spent considerable time and energy in recent years building a community of expert modelers and extending modeling instruction to other disciplines and additional grade levels. There are seven regional centers around the US that regularly offer summer workshops and many others that sponsor workshops on an occasional basis (workshops were held in 41 different locations in the US this summer as well as in Singapore).

Most educational reforms thrive for a few years and then fade away as their leaders die, retire or simply move on to other interests. Modeling instruction continues to grow and is looking to a future when its current leaders are no longer actively involved.

In 2000, the Modeling Instruction Program created a Master of Natural Science degree program for high school science teachers at Arizona State University. All those enrolled participate in a seminar entitled Leadership Workshop, in which they learn grant writing, classroom research techniques, leadership and mentoring skills. In 2005, several alumni of this Leadership Workshop course founded the American Modeling Teachers Association (AMTA), a professional organization which is an affiliate of the American Association of Physics Teachers (AAPT) and the American Chemical Society (ACS). As grant funding for the various aspects of the Modeling Instruction Program expires, the AMTA is poised to continue the work of the program without any loss of fidelity. In this way the Modeling Instruction Program strives to produce a sustainable infrastructure that will continue to grow and change with the needs of teachers and their students by providing them with a robust cognitive tool kit for the 21st century.

References:

1. Ibrahim Abou Halloun and David Hestenes, "The initial knowledge state of college physics students," American Journal of Physics **53** (11), 1043-1055 (1985).
2. Ibrahim Abou Halloun and David Hestenes, "Common sense concepts about motion," American Journal of Physics **53** (11), 1056-1065 (1985).
3. A. E. Lawson, "Ttite," in *United States-Japan Seminar on Science Education* (Honolulu HI, 1986); A. E. Lawson, *Science Teaching and the Development of Thinking*. (Wadsworth, 1994); A. E. Lawson, *Teaching Inquiry Science in Middle and Secondary schools*. (Sage, Thousand Oaks CA, 2010).
4. David Hestenes, "Wherefore a science of teaching?," The Physics Teacher (April 1979), 235-242 (1979); David Hestenes, presented at the Maximum Entropy and Bayesian Spectral Analysis and Estimation Problems, 1983 (unpublished).
5. R. Karplus, "Teaching for the development of reasoning," Research in Science Education **10** (1), 1-9 (1980).
6. M. Wells, D. Hestenes, and Gregg Swackhamer, "A Modeling Method for High School Physics Instruction," American Journal of Physics **63** (7), 606-619 (1995).
7. D. Hestenes, C. Megowan-Romanowicz, S. Osborn-Popp, J. Jackson, and R. Culbertson, "A Graduate Program for High School Physics and Physical Science Teachers," American Journal of Physics **accepted** (2010).
8. M. Neuschatz, M. McFarling, and S. White. “Reaching the Critical Mass: Findings from the 2005 Nationwide Survey of High School Physics Teachers,” American Institute of Physics (2008), http://www.aip.org/statistics/trends/reports/hs05report.pdf.
9. David Hestenes, Malcolm Wells, and Gregg Swackhamer, "Force Concept Inventory," The Physics Teacher **30**, 141-158 (1992).

[10] Richard R. Hake, "Interactive-engagement versus traditional methods: A six-thousand-student survey of mechanics test data for introductory physics courses," American Journal of Physics **66** (1), 64-74 (1998).
[11] D. Hestenes, presented at the GIREP Conference, Modeling in Physics and Physics Education, 2006 (unpublished).
[12] Richard Lesh and Helen M. Doerr, "Beyond Constructivism," Mathematical Thinking and Learning **5** (2&3), 211-233 (2003).
[13] L. McDermott and P. Shaffer, "Research as a guide for curriculum development: An example from introductory electricity. Part I: Investigation of student understanding," American Journal of Physics **60** (11), 994-1013 (1992); L. C. McDermott, "Students' conceptions and problem solving in mechanics," in *Connecting Research in Physics Education with Teacher Education* (International Commission on Physics Education, 1997).
[14] A. A. diSessa, "Knowledge in Pieces," in *Constructivism in the Computer Age*, edited by G. Forman and P. Pufall (Erlbaum, Hillsdale NJ, 1988), pp. 49-70.
[15] Michael Tomasello, *The Cultural Origins of Human Cognition*. (Harvard University Press, Cambridge MA, 2001).
[16] John Seely Brown, Allan Collins, and Paul Duguid, "Situated Cognition and the Culture of Learning," Educational Researcher **18** (1), 32-42 (1989).
[17] James Hollan, Edwin Hutchins, and David Kirsch, "Distributed Cognition: Toward a New Foundation for Human-Computer Interaction Research," ACM Transactions on Human Computer Interactions **7** (2), 174-196 (2000).
[18] Colleen Megowan, *Framing Discourse for Optimal Learning in Science and Mathematics*. (Arizona State University, Tempe AZ, 2007).
[19] C. Megowan-Romanowicz, "The structure of modeling discourse in science and mathematics classrooms," in *Modeling Students' Mathematical Modeling Competencies*, edited by R. Lesh, P. Galbraith, C. Haines, and A. Hurford (Springer, New York, 2010), pp. 341-352.
[20] M. Budd Rowe, "Wait time: Slowing down may be a way of speeding up!," Journal of Teacher Education **37** (1), 43-50 (1974).
[21] K. Tobin, "The role of wait time in higher cognitive level learning," Review of Educational Research **57** (1), 69-95 (1987).