A Guide to the Modeling Theory of Cognition and Modeling Instruction

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Science coursework has been included in the K-12 education system throughout the history of education in the United States, though mathematics and science classes gained special prominence after the launch of *Sputnik I* by the Soviet Union in 1957 (Bybee, 2010). Concerned that the United States was trailing the Soviet Union in scientific and technological research, the federal government began to pour large amounts of money into science education to develop the next generation of researchers. Groups of educators from universities, national science laboratories, and national science professional organizations began to write standards and create curriculum for K-12 science education, developing innovative methods for teaching science. One influential group, the Physical Science Study Committee (PSSC), produced curriculum and instruction that emphasized scientific thinking within the context of specific science content (Bybee, 2010; Haber-Schaim, 2006; MIT Libraries, 2012; Rudolph, 2006). Ideas from the PSSC were expanded in the ensuing decades, leading to the development of Modeling Instruction in the late 1980s by Dr. David Hestenes, physics professor at Arizona State University, and Dr. Malcolm Wells, high school physics teacher and doctoral student at Arizona State University (Hestenes, 1987).

A major problem in science education is the organization of content into discrete chunks that are to be memorized and tested, which has been an issue throughout the history of science education. Hestenes and Wells developed Modeling Instruction to expand the ideas of the PSSC by coordinating scientific thinking and science content around models, providing a structure for students' thinking. Each unit of study begins with a laboratory experience to engage students in science content and create a conceptual model, then students test and refine the conceptual model through problem-solving and further laboratories to determine the model's application and limits.

Through the modeling cycle, the process of creating and testing of a model, Modeling Instruction becomes a hands-on, student-centered approach to teaching both the process and content of scientific disciplines (Jackson, Dukerich, & Hestenes, 2008).

In addition to developing and refining materials for Modeling Instruction, Hestenes (2006, 2015, 2016) has created a Modeling Theory of Cognition. This theory connects constructivism, advances in cognitive psychology, and cognitive linguistics to provide a framework for how humans think. The Modeling Theory of Cognition is the foundation of Modeling Instruction, and the purpose of this paper is to describe the Modeling Theory of Cognition and Modeling Instruction in the context of a high school physics course, discuss two cases related to Modeling Instruction, and address challenges in Modeling Instruction by providing recommendations.

THEORY

The theory of learning that provides underlying ideas for the Modeling Theory of Cognition and Modeling Instruction is known as constructivism. "Constructivism's central idea is that human knowledge is *constructed*, that learners build new knowledge upon the foundation of previous learning" (Kanselaar, 2002). As constructivism has matured since the 1980s, several theories have developed distinct views about the nature of human learning. Despite the differences,

> there is important congruence among most constructivists with regard to four central characteristics believed to influence learning: 1) learners construct their own learning; 2) the dependence of new learning on students' existing understanding; 3) the critical role of social interaction, and; 4) the necessity of authentic learning tasks for meaningful learning. (Applefield, Huber, & Moallem, 2001, p. 38)

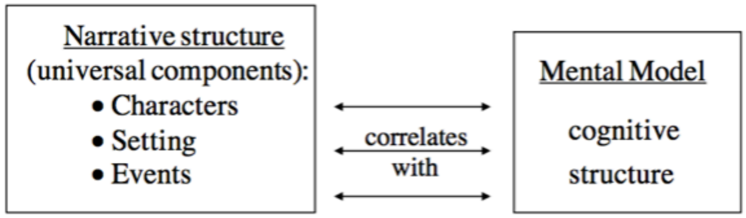

Figure 1. Prototypical example of cognition as the construction of a narrative; the narrative generates construction of a mental model. From "Modeling Theory and Modeling Instruction for STEM Education" by D. Hestenes, 2015, *epiSTEME 6 International Conference to Review Research on Science, Technology and Mathematics Education*. Copyright 2015 by David Hestenes. Reprinted with permission.

The Modeling Theory of Cognition and Modeling Instruction are unconcerned with the differences, and focus more attention on psychological ideas about learning and cognition and educational ideas about pedagogy.

The Modeling Theory of Cognition builds on constructivism by positing that humans construct mental models to understand the world. Figure 1 provides a prototypical example of cognition, which is the comprehension of a narrative. The narrative may be read or heard using language or observed using the senses, and both methods generate a mental model. The use of language activates a mental model for both the producer and receiver, facilitating a coordination of mental models between the producer and receiver. In this framing of cognitive linguistics, known as cognitive semantics, "language does not refer directly to the world, but rather to mental models and components thereof! Words serve to activate, elaborate or modify mental models" (Hestenes, 2006, p. 11).

The mental models created by a narrative are conceptual models, which are generated from concepts. Figure 2 gives a definition of a concept, containing three parts: A symbol is the public method of illustrating a concept, the form is the framework of the

Figure 2. Schema of a concept and conceptual model. "Modeling Theory and Modeling Instruction for STEM Education" by D. Hestenes, 2015, *epiSTEME 6 International Conference to Review Research on Science, Technology and Mathematics Education*. Copyright 2015 by David Hestenes. Reprinted with permission.

concept, and the meaning is an individual's interpretation of the concept. For example, consider the concept of "position." The symbols (*x, y, z*) are one option for public representation, the form is developed from the geometric structure of space and defined by a coordinate system, and the meaning is that an object is located at the place in space defined by the coordinate system and numbers for each of *x, y,* and *z*.

Figure 2 also provides a definition for a conceptual model, which follows the same idea as a concept. Representations are the public method for describing the concepts in a conceptual model, the structure is the framework of the concepts in a conceptual model, and the referent is an individual's interpretation of the concepts in a conceptual model (Hestenes, 2015). Four types of structure are sufficient for a conceptual model in any scientific discipline:

a) Systemic structure specifies composition, object properties, and causal links;
b) Geometric structure specifies configuration and location in a reference frame;
c) Interaction structure specifies interaction laws for causal links; and,
d) Temporal structure specifies changes in state variables (Hestenes, 2015).

In general, representations include verbal and written communication, mathematics, diagrams, graphs, and computational programming; however, each type of structure has

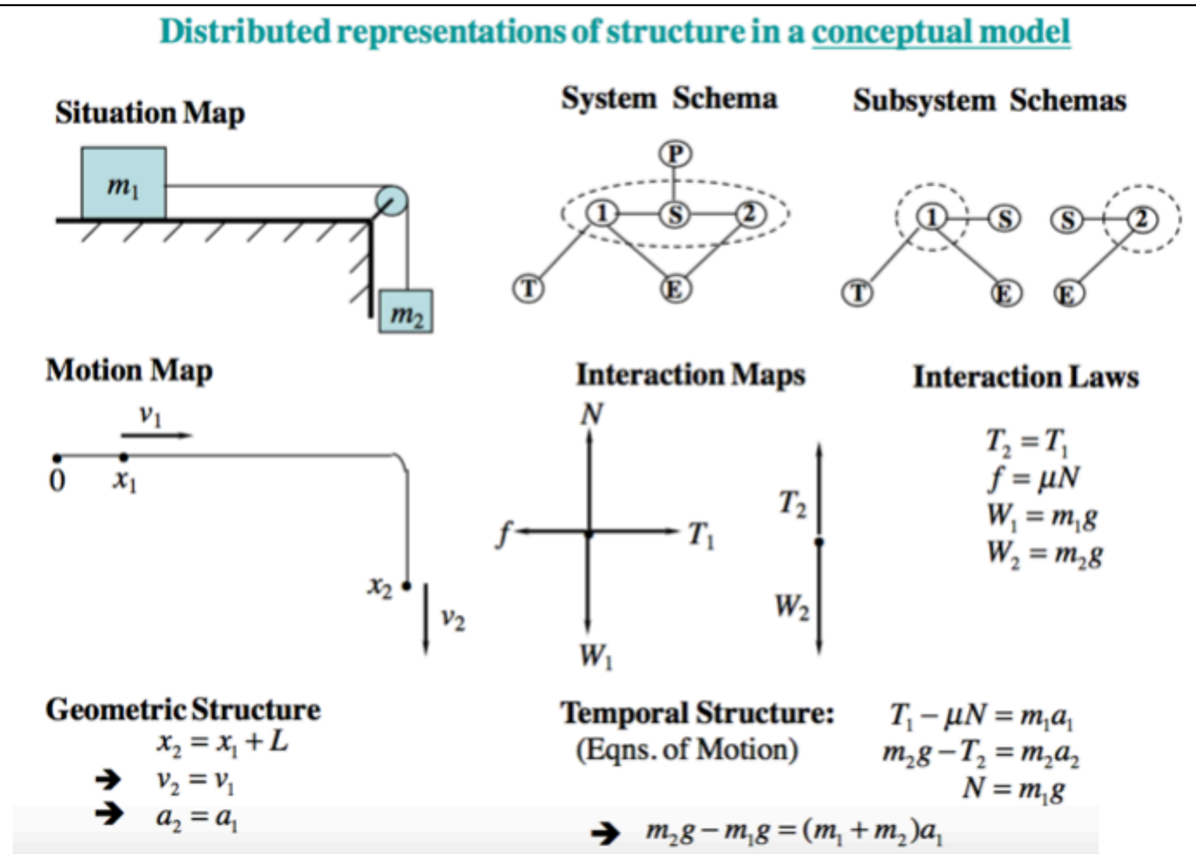

Figure 3. Example of structure in the unbalanced force model. From "Modeling Theory and Modeling Instruction for STEM Education" by D. Hestenes, 2015, *epiSTEME 6 International Conference to Review Research on Science, Technology and Mathematics Education*. Copyright 2015 by David Hestenes. Reprinted with permission.

specific representations. Figure 3 provides a full set of representations of the structure of the unbalanced force model, which is an important model in physics that is best known for Newton's second law ($\Sigma\vec{F} = m\vec{a}$).

Precisely defining a concept and conceptual model is crucial for the Modeling Theory of Cognition because conceptual models form the core of scientific knowledge. Modeling Instruction incorporates the ideas of the Modeling Theory of Cognition to integrate curriculum and pedagogy, and Figure 4 illustrates the relationship between theory, models, experiments, and applications. The "curriculum is organized around a

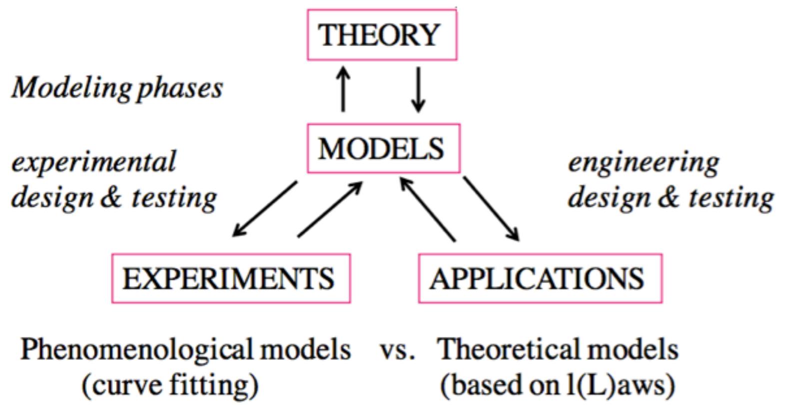

Figure 4. Overview of Modeling Instruction; scientific models are the content core and modeling is the procedural core of each science. From "Modeling Theory and Modeling Instruction for STEM Education" by D. Hestenes, 2015, *epiSTEME 6 International Conference to Review Research on Science, Technology and Mathematics Education*. Copyright 2015 by David Hestenes. Reprinted with permission.

small number of conceptual models as the content core of each scientific domain. [Modeling Instruction] pedagogy promotes scientific literacy centered on making and using models as the procedural core of scientific knowledge" (Hestenes, 2015, slide 27). Scientific practice is model-centered because models are basic units of coherently-structured knowledge from which humans can make logical inferences. Models can be directly compared to the physical world, and the structure of models is concretely embodied in the minds of individuals through their physical intuition.

To generate coherent models and organize instruction, students perform a modeling cycle to develop appropriate models that accurately describe the phenomena they study. The modeling cycle has two distinct parts: Model development, in which students perform a paradigm laboratory and engage in discussions to create a mental and conceptual model related to the physical world; and model deployment, during which students manipulate and test the model to determine the limits and applicability of the model. Throughout model deployment, students utilize the representations of structure to test and refine the model. Assessments in the form of whiteboarding, quizzes, and additional laboratories are used formatively, and the modeling cycle is completed with a laboratory practicum and summative unit assessment.

A major aspect of Modeling Instruction is whiteboarding, which are 24" x 36" erasable pieces that students use during all parts of the modeling cycle. This gives students the opportunity to make their thinking visible around scientific content and processes. When performing laboratories, students record, graph, and analyze data on their whiteboard for presentation during the post-lab discussion. Having visible information from all groups allows students to compare, contrast, and question data and analysis easily, creating a robust discussion about the results. As students solve problems, "small groups of students write up their results … [and] have to account for everything they do in solving a problem" (Jackson et al., 2008, p. 14). The students who are presenting are questioned by other students and the instructor to explicitly articulate their understanding, and any misconceptions are corrected through Socratic questioning.

CASES

Two cases have been chosen for this paper, and the first is the seminal study on Modeling Instruction performed by Dr. Malcolm Wells (1995) as his dissertation research. For the study, Wells taught two courses: An inquiry-based course with lab activities and in-class study groups, and a modeling course using lab activities and in-class study groups with an emphasis on models and modeling. A third course—led by a teacher with similar age, experience, training, and dedication—used traditional teaching methods, with a large amount of time dedicated to lecture and demonstrations.

To minimize extraneous variables in the study, "all three high school courses (inquiry, modeling, and traditional) were honors courses with about 24 students in each. By prior agreement between the teachers, all three covered the same topics in mechanics on nearly the same time line" (Wells, Hestenes, & Swackhamer, 1995). Using a pretest-posttest experimental design with the *Mechanics Diagnostic* as the test (Hestenes & Wells, 1992), Wells and the traditional teacher assessed their classes at the beginning and end of mechanics. Results from the study showed that the modeling course had a 34% increase, the inquiry course had a 22% increase, and the traditional course had a 13% increase between the pretest mean and posttest mean. These results "strongly support the conclusions that Malcolm's modeling method is a considerable improvement over his cooperative inquiry method and clearly superior to the traditional method" (Wells et al., 1995).

Wells faced challenges related to the construction of the modeling course because no pedagogy or curriculum existed outside of his work with Hestenes and the ideas from the PSSC. In addition, Wells' inquiry and modeling courses had pretest means below the traditional course, suggesting that the traditional course should have the highest posttest mean if the students learn at the same rate for each method. Despite these challenges, Wells modeling course outperformed the other two courses, providing evidence that high school students could perform physics reasoning through modeling.

The second case is from Dr. Eric Brewe (2008), who summarizes the positive and negative aspects of implementing Modeling Instruction in introductory physics at the collegiate level. This has implications for high school teachers who have Advanced Placement Physics C: Mechanics and Electricity and Magnetism courses, which are the equivalent of the first two semesters of calculus-based physics at the collegiate level

(College Board, 2014; College Board, 2016). Brewe argues that students in introductory physics courses should be treated as neophyte physicists that learn a small number of general models instead of discrete topics associated with textbook chapters. A model-based design of the introductory curriculum mimics expert physicists' knowledge structure, developing students' appreciation for the coherence of physics (2008).

One positive aspect of Modeling Instruction is the organization of content around a few general models that are continually revisited and refined, allowing students to return to topics and further develop their thinking. Reif and Heller (1982) "assert that optimum problem solving performance is predicated on coherent, hierarchical knowledge organization" (Brewe, 2008), which is the structure of Modeling Instruction. Another positive aspect of Modeling Instruction is that students make a connection between physics content and the nature of science, understanding that scientific knowledge is a work in progress. A third positive aspect of Modeling Instruction is multiple representations of physical situations, and a study by Larkin, McDermott, Simon, & Simon (1980) provided evidence that students had higher rates of success with problem-solving when using multiple representations. Brewe's (2002) dissertation research also "showed evidence of improved problem solving for students in a Modeling Instruction course" (Brewe, 2008) by using multiple representations.

Although Modeling Instruction is a superior method for teaching introductory physics (Brewe, 2002; Brewe, Sawtelle, Kramer, O'Brien, Rodriguez, & Pamelá, 2010; Hake, 1998), there are challenges with implementation. Modeling Instruction is best taught with a hands-on, inquiry approach, which is at odds with the typical large lecture method for introductory physics courses. Materials for Modeling Instruction do not exist at the university level, and many textbooks do not ascribe to the same ideas about learning as Modeling Instruction. Professors, who often lack the training or understanding of teaching other than by lecture, balk at teaching a different method and covering less material. These are formidable challenges, which has dampened the implementation of Modeling Instruction for introductory physics courses at the collegiate level.

RECOMMENDATIONS

Wells, Hestenes, and Swackhamer (1995) and Brewe (2008) identified challenges related to the implementation of Modeling Instruction in their courses. For Wells et al. (1995), the challenges were a lack of materials and lack of development of a Modeling Theory of Cognition. Both challenges have been met by members of the modeling community by creating and revising materials for Modeling Instruction in physics, physical science, chemistry, biology (Jackson et al., 2008; American Modeling Teachers Association [AMTA], 2015; AMTA, 2016). A recommendation is to continue the work by the modeling community and create Modeling Instruction materials for more courses, and the AMTA is currently developing materials for middle school, and is seeking to expand from preschool to upper-level collegiate courses in the next decade (AMTA, 2016). Another recommendation is for content experts to systematically develop the basic models in each course; the models have been established for mechanics but are difficult to find for electricity and magnetism and other courses. Hestenes (1987, 2006, 2015, 2016) is developing a Modeling Theory of Cognition, and a third recommendation is to assist Hestenes in the augmentation of the Modeling Theory of Cognition by refining the theory and producing information in plain language. The theory becomes dense without an appropriate background, which many teachers and professors who use Modeling Instruction do not possess.

Brewe (2008) faces difficult challenges because many are related to the structure of the university setting. To be successful in a course that utilizes Modeling Instruction, students need a small laboratory setting rather than a large lecture setting. A recommendation to alleviate this problem is transitioning all introductory science courses to smaller settings, creating the conditions for students to thrive with Modeling Instruction. Another challenge is the lack of materials specifically designed for Modeling Instruction in introductory physics and other science courses, and a recommendation is to create a cohort of professors to create these materials and research them through grant funding. The materials could include a textbook that places model creation at its core, providing a quality reference for students in a course that uses Modeling Instruction. The cohort of professors would also share their work with others in their departments, addressing the challenge of professors who are unwilling to deviate from a lecture-based course.

CONCLUSIONS

The Modeling Theory of Cognition and Modeling Instruction provide a powerful combination for learning science by focusing on the creation and application of a small number of mental models. The Modeling Theory of Cognition connects constructivism, cognitive psychology, and cognitive linguistics, and synthesizes these into a powerful theory of cognition. Modeling Instruction builds the curriculum and pedagogy on this theory, leading to a student-centered classroom that is active and engaging for all students. Laboratory activities provide data to create and test models, and open-ended problems allow students to apply and extend the model. Students make their thinking visible with whiteboards and Socratic seminars, presenting and defending their ideas. The Modeling Theory of Cognition and Modeling Instruction represent the best understanding of how humans learn and leverage this knowledge to help students understand and appreciate science more deeply. Students with a deep understanding of the process and content of science will be in an excellent position to succeed as they enter the workforce, and Modeling Instruction provides a method for students to develop this understanding.

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