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ABSTRACT

This paper reports on the evaluation of an 11-week curriculum created to foster seventh grade students' understanding of scientific modeling. In the curriculum, students engaged in model-oriented activities such as creating non-Newtonian computer microworlds to embody their conceptual models, evaluating their models with criteria, and reflecting on the nature of models. Various methods of assessing modeling are also discussed. The overall analysis suggests that students gained a significantly better understanding of the nature and utility of models without promoting similar gains in students' understanding of the process of creating and evaluating models. These results indicate that while modeling knowledge is difficult to obtain even from an extended model-focused curricula, progress can be made by further refining model-oriented curricula and assessments. (Contains 39 references and written modeling assessment results.) (DDR)

# Fostering Middle School Students' Understanding of Scientific Modeling

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Abstract

Scientific modeling is a critical component of the scientific endeavor. Therefore, students who take science should learn about and understand the nature of this process. However, there has been little evidence that students understand the modeling process even in the increasing number of classrooms that use computer models in significant ways. This paper reports on the evaluation of an eleven-week curriculum that we created in order to foster seventh grade students' understanding of scientific modeling. In the curriculum, students engaged in model-oriented activities such as creating non-Newtonian computer microworlds to embody their conceptual models, evaluating their models with criteria, and reflecting on the nature of models. This paper discusses various methods of assessing modeling as well as the results from the curriculum trials. Overall analysis suggests that students gained a significantly better understanding of the nature and utility of models without promoting similar gains in students' understanding of the process of creating and evaluating of models. These results indicate that while modeling knowledge is difficult to obtain even from an extended model-focused curricula, progress can be made by further refining model-oriented curricula and assessments.

## Introduction

During the past several decades, computer modeling and simulation software have transformed the nature of science and engineering. These tools have enabled scientists and engineers to create, test, and envision their theories as well as analyze data in ways never before possible. Reformers in education have envisioned a similar technology-led transformation in education. In particular, numerous researchers have promoted the use of computer modeling and simulation tools in order to foster student conceptual change (Lewis, Rader, & Brand, 1997; Mandinach & Cline, 1992; Mellar, Bliss, Boohan, Ogborn & Tompsett, 1994; Penner, Giles, Lehrer, & Schauble, 1997; Raghavan & Glaser, 1995; Richards, Barowy and Levin, 1992; Snir, Smith and Grosslight, 1995; Stewart, Hafner & Johnson, 1992; Tinker, 1993; White, 1993; White & Frederiksen, 1990; White & Frederiksen, 1998).

While these tools have shown great promise for their use in conceptual change, our research as well as that of others (Carey & Smith, 1993; Grosslight, Unger, Jay, & Smith, 1991, Schwarz, 1996) has found that few students understand the scientific modeling process[1] embodied in these curricula with which they are engaged. For example, we found that although students in the previous version of the ThinkerTools scientific inquiry and modeling curriculum were generally successful at creating laws to summarize their experimental results, few understood the nature or purpose of the modeling portion of our scientific inquiry cycle. Other research confirms that a modeling perspective is difficult to obtain in the classroom even from curricula with an added focus on the nature of modeling.

Teaching students about the nature of scientific models[2] and the process of modeling is important for a variety of reasons. Firstly, models and the process of modeling are fundamentally important components of the scientific endeavor. Students taking science should know about the nature of the products and processes of science (Andaloro, Donzelli, Sperandeo-Mineo, 1991). Secondly, gaining a more authentic understanding of the nature of science may help students construct fruitful epistemological theories (Driver, Leach, Millar, & Scott, 1996; Gilbert, 1991; Penner, Giles, Lehrer, & Schauble, 1997; Nadeau, & Desautels, 1984). For example, if a student understands that scientific knowledge is complex and dynamic, this may help them better reason about scientific evidence and better integrate their conceptual knowledge (Songer & Linn, 1991). Additionally, using computer simulation models can afford students (as well as scientists) the opportunity to embody, visualize, and test components of their conceptual theories, which may help them advance those theories at the same time as gaining a better understanding of the process of model generation (Snir et al., 1995) Finally, technological advances and the resulting "information age" have changed the type of expertise that citizens need to function well in society. Matthews (1994), Sagan (1996), and others point out that we will need sophisticated and transferable inquiry and problem-solving skills to function in the communities and workplaces of the future. Teaching students about the nature of scientific models and the process of modeling while using computer modeling software may foster this type of transferable inquiry and problem-solving expertise.

In order to address this important area of scientific expertise, we created the model-enhanced version of the ThinkerTools curriculum to foster an increased model-oriented perspective. In our curricula, students participate in activities that include (1) creating computer microworlds to embody their conceptual models of force and motion, (2) evaluating the accuracy and plausibility of their models with respect to data collected from real-world experiments, and (3) reflecting on the nature of the modeling enterprise itself. The curriculum ran in eight seventh

[1] We define scientific modeling as a process used in much of modern science and engineering that involves (1) embodying key aspects of a theory into a model– frequently a computer model, (2) testing that model, and (3) revising that model.
[2] For the purposes of our science curriculum, we define a scientific model very broadly as a set of representations, rules, and reasoning structures that allow one to generate predictions and explanations.

grade classrooms in a local urban middle school for approximately eleven weeks. The first author co-taught one class and was a teacher's aide in another class at the school. The curriculum covered several content topics including one-dimensional motion with and without friction, two-dimensional motion, and either gravity, mass, or gas/fluid resistance depending on the students' choice for a final research project.

In evaluating the effectiveness of the curriculum, we investigated students' knowledge about the nature of models and the process of modeling. This entailed studying several dimensions of student understanding (1) model content and attributes, (2) the nature of the modeling process, (3) the evaluation of models, and (4) the purpose of models and modeling. Data used to analyze these questions include written assessments before and after the curriculum, student project reports, and student interviews.

We hypothesized that our students would improve their understanding of models and modeling by participating in some of the model-oriented activities in the curriculum. However, we were also aware of the difficulty of instantiating large changes in students' knowledge of the nature of science from previous research (Carey & Smith, 1993). As a result, we estimated that students modeling knowledge after the model-enhanced ThinkerTools would vary between fairly unsophisticated understanding (similar to Grosslight et al.'s level 1+) to somewhat sophisticated understanding (similar to Grosslight et al.'s level 2) depending on aspects like the student's propensity towards metacognition, their previous scientific experiences, and their teacher's understanding of the scientific process.

## Background

Research and interest about the potential benefits of model-centered science instruction[3] has grown in the recent decade as science educators have seen computer modeling and simulation software transform the practices of science and engineering. For example, philosophers of science such as Gilbert (1991) and educators such as Nadeau and Desautels (1984) and Penner et al. (1997), espouse a model-centered approach in science classrooms in order to combat learning naive philosophies of science such as naive realism and empiricism. Scientists such as Andoloro et al. (1991) advocate using computer simulation in order to accurately reflect the methodology of much of modern science and physics. Authors such as Bliss (1994), Confrey and Doerr, (1994), Lewis, Rader, and Brand (1997), Papert (1980), and Rothenberg (1989) claim that computer models are a useful modeling tool and can help people externalize their thinking, thus making their theories concrete and allowing them to be tested, validated and refined.

Educators claim further benefits. Feurzeig (1994) and Sabelli (1994) state that using computer models helps make real data more accessible to students, making the scientific process more dynamic, and allowing students to study personally interesting and complex phenomenon. Jackson, Stratford, Krajcik, and Soloway, 1994, Raghavan and Glaser (1995), Richards et al. (1992), Snir et al., 1993, Stewart et al. (1992), White and Horowitz (1988), White (1993), and White and Frederiksen (1995) advocate the instructional use of computer models in order to either have students create scientific artifacts, to foster student conceptual change, or to develop students' scientific expertise. While these authors have studied and promoted the idea of using computer models and teaching general modeling in highly beneficial ways, few researchers, except some like White and Frederiksen (1995), and White (1993), have investigated students' understandings of the scientific modeling process they are using.

[3] By model-centered science instruction, we mean instruction whose main focus is on using or on constructing and revising scientific models.

However, additional literature about the general role of epistemological beliefs in learning and school performance provides some information about students' understanding of the scientific modeling process. While much of this literature covers other aspects of epistemological beliefs such as the nature of scientific knowledge or the nature of learning, some researchers have studied student beliefs about the nature of the scientific process including scientific modeling (Carey & Smith, 1993; Driver et al., 1996; Gobert & Discenna, 1997; Grosslight et al., 1991; Penner et al., 1997; Robinson, 1997). For example, Driver et al. (1996) studied British students' ideas about their characterization of scientific inquiry, the nature and status of scientific theories, and their ideas on the relationship between theory and evidence. Other authors such as Carey and Smith (1993), and Grosslight, Unger, and Jay (1991) have studied students' characterization of the nature of models and modeling in order to develop a three level scale of epistemological understanding. In their case, level 3, the targeted level of understanding, involves understanding that the model is constructed in the service of the development and testing of ideas, that the modeler takes an active role in constructing the model, and models can be manipulated and subjected to testing in the service of informing ideas. Finally, other authors have shown that specific beliefs about the nature of learning (Schommer et al., 1992) and the nature of physics knowledge (Hammer, 1994) correlate with student performance, while Linn and Songer (1993) and Songer and Linn (1991) showed that student beliefs about the static or dynamic nature of science directly influenced student knowledge integration– a process of organizing information into broader categories.

## Experimental Design

### Setting

The model-enhanced ThinkerTools curriculum was used during the 1996-1997 academic year in eight seventh grade classes at a local urban middle school with a diverse ethnic population and a high proportion of lower income students (During the 1996-1997 academic year, 34% of the students qualified for free or reduced school lunch). As previously mentioned, the first author co-taught one class (Teacher A, first period), was a teacher's aide in another (Teacher B, second period) (See table below for elaboration). The two teachers with which she collaborated (Teacher A and B) used the curriculum in their remaining six classes. The curriculum lasted approximately eleven weeks.

| Teacher | Period | Number of Students | First author presence in the classroom | Material covered |
|---|---|---|---|---|
| A | 1 | 30 | co-taught daily and videotaped | Module 1, 2, 3, 4 |
| A | 3 | 27 | was occasionally present to help and videotape | Module 1, 2, 3, 4 |
| A | 4 | 37 | not present | Module 1, 2, 3, 4 |
| A | 5 | 31 | not present | Module 1, 2, 3, 4 |
| B | 1 | 28 | not present | Module 1, 3 (partly), 4 |
| B | 2 | 25 | teacher's aide and videotaped daily | Module 1, 3 (partly), 4 |
| B | 3 | 25 | not present | Module 1, part of 3, 4 |
| B | 4 | 26 | not present | Module 1, part of 3, 4 |

Table 1: Description of model-enhanced ThinkerTools classrooms

### Intervention Content

We designed the model-enhanced version of ThinkerTools to teach students about the nature of models and the process of modeling. As previously mentioned, the main pedagogical goals for student learning included: understanding (1) the nature of models (model content and attributes), (2) the nature of modeling, (3) how to evaluate models, and (4) the utility of modeling. In the model-enhanced version of ThinkerTools, the main types of modeling activities that addressed these pedagogical goals included creating computer microworlds governed by student rules about force and motion, evaluating models, and reflecting on the properties of models and the nature of the modeling enterprise.

During the curriculum, students carried out research on force and motion by following the inquiry cycle four times. The inquiry cycle is a simplified but authentic version of the scientific method used in the ThinkerTools curriculum. (See figure 1 below)

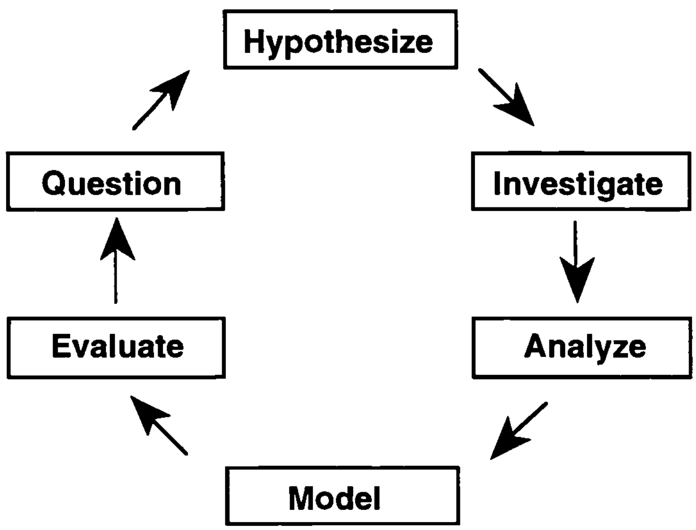


Figure 1. The ThinkerTools scientific inquiry cycle

Students researched four topics which included one-dimensional motion with and without friction, two-dimensional motion, and a research project on one of the following topics: gravity, mass, or gas/fluid resistance. In the first module, for example, students began with the question, "what is the motion of an object when no forces like friction are acting on it?" In the hypothesis phase of the inquiry cycle, students then made alternative hypotheses about the answer to this question such as the object would slow down, speed up, or travel at a constant speed. During the investigation phase of the inquiry cycle, students conducted real-world experiments such as giving a smooth plastic puck an impulse and measuring the object's speed over one and two meters. They then reduced the amount of friction between the puck and the floor by adding a balloon and stopper to the puck, acting like a mini-hovercraft, and repeated the experiment, measuring the objects' speed over one and two meters. In the analysis phase of the inquiry cycle, the students then analyzed the differences in speed between the first and second meters for the pucks with different amounts of friction.

In the modeling phase of the inquiry cycle, the students analyzed their data and formed a tentative rule. In the first module of the curriculum, the students performed a thought experiment to create a tentative rule to characterize what would happen to the motion of an object with no friction. (In the three remaining modules, students created a rule derived from their real world data.) Students then went to the computer and chose the model that most closely corresponded to their rule including Newtonian and non-Newtonian rules. (See figure 2 below of the software screen shot)

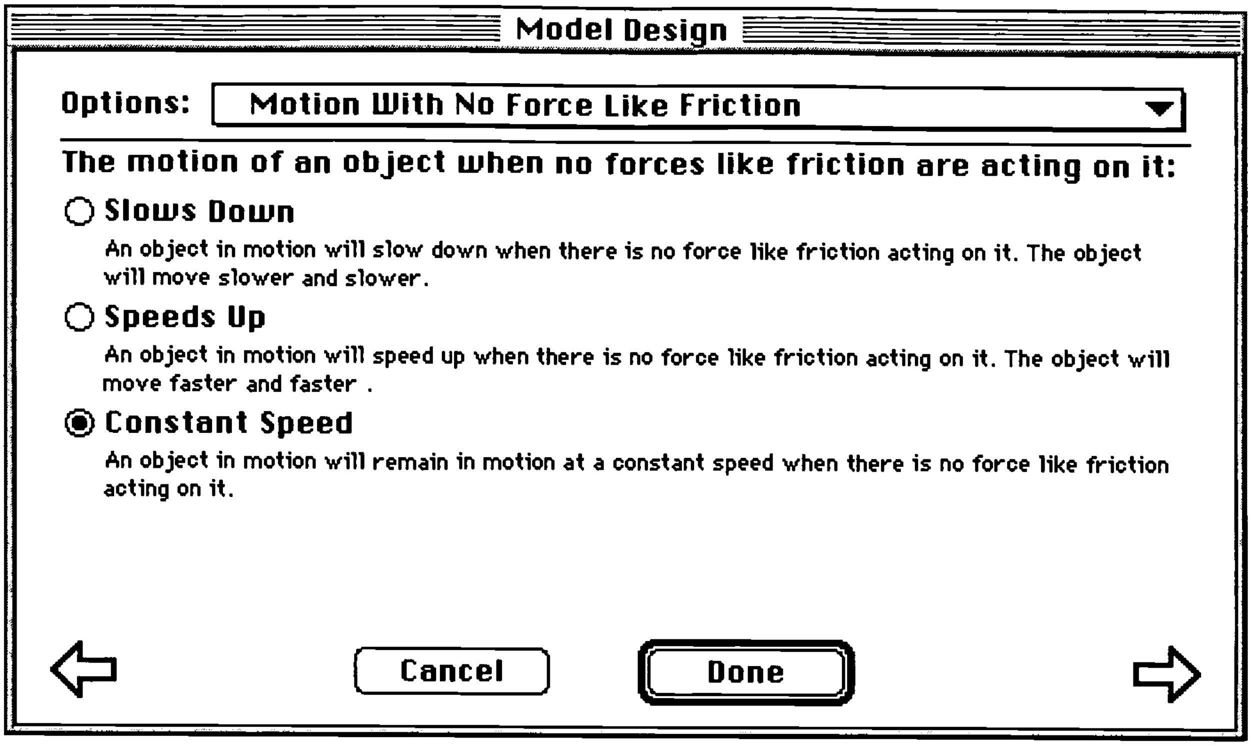


Figure 2: This screen shot illustrates how the software enables students to choose from among alternative laws of motion.

For example, if their data indicated that reducing the amount of friction caused an object to travel further and remain at approximately a constant speed, they might have chosen the Newtonian qualitative model "constant speed" to indicate that with no friction, an object would travel at a constant speed. Once students at the computer had chosen among three or four qualitative or semi-qualitative rules, they then typed in a causal or mechanistic explanation to the prompt, "I think this is true because:" Finally, the student ran a simulation which used their model in order to envision its consequences. Alternatively, they could have created an entirely new microworld with dots, walls, targets and other properties that used their models. (See figure 3 below for an example simulation from that model)

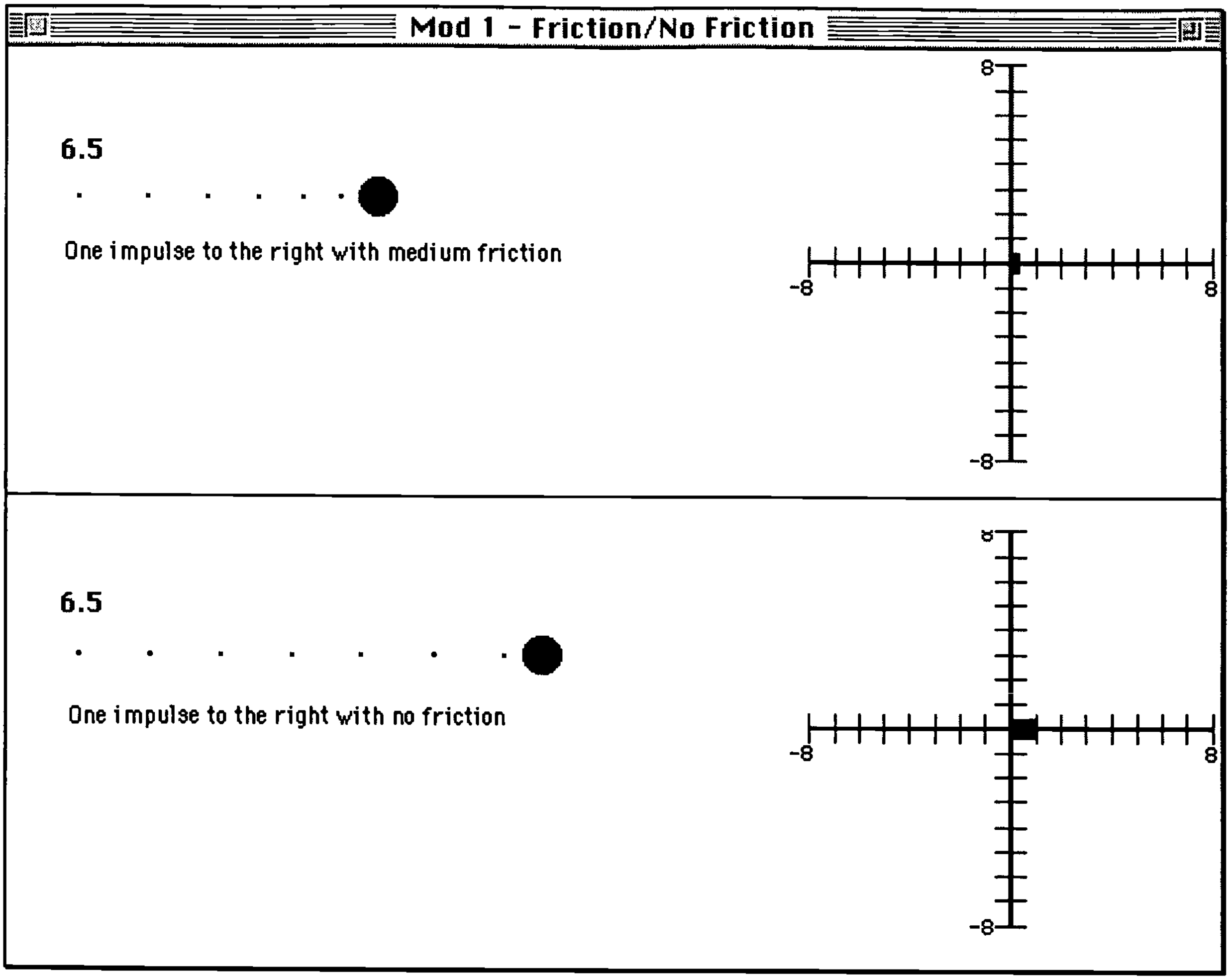


Figure 3: A screen shot from a simulation activity in which students run an experiment and see the implications of the laws of motion they have selected.

Allowing students to choose and envision their own models based on data from their experiments is the essence of scientific modeling. This activity was meant to address the pedagogical goals of teaching students about the nature of models (a model can be as simple as a rule that allows someone to explain and predict a phenomena; models are not necessarily real or correct but good ones are better estimates of a phenomenon; there are multiple models for the same phenomenon), the nature of modeling (modeling involves embodying key parts of a theory into a rule, among other aspects), and the utility of modeling (models are particularly useful for envisioning or testing that theory). Additionally, we designed the ThinkerTools software so that students could choose and explore different previously programmed models close to their own intuitions instead of programming their own intuitive-based models. We made this decision based on the idea that teaching students how to program in addition to the already long eleven week ThinkerTools curriculum was too time-consuming and impractical.

There were several other software features designed to foster student learning about the nature of models and modeling. After students had run the simulation to test or envision their theory, they were encouraged to run their simulation in "single step mode." During single step mode, the computer talked aloud about its behavior and modeling rule for each time step. For example, suppose that I chose the rule, "constant speed" about motion with no force like friction and responded to the "I think this is true because:" prompt by typing, "there are no forces applied to me to change my motion." While running the simulation in single step mode, after the initial impulse and at each major interval of time, the computer said aloud, "Without a force like friction, I will stay the same speed because there are no forces applied to me to change my motion." We hypothesized that students would be highly motivated to use single step mode to listen to the rule embodied in their chosen models. Single step model also addressed the pedagogical goal of teaching students about how the computer model works. We hoped that they would learn that the computer steps through time and causes the objects on the screen to behave according to rules that may be programmed or chosen.

The other main feature of the software was that students could run each simulation according to Newton's laws, called Newtonian model design. While students were still in the modeling phase of the inquiry cycle, and right after they have chosen single step mode, they were encouraged to compare the model they had chosen with the Newtonian model. We introduced he Newtonian model as the model proposed by Isaac Newton, "a famous physicist from the 17th century who invented important models of force and motion." In this way, students had a chance to compare and observe the scientifically normative model without being told that this was the 'correct' model which they must obtain. The process also addressed the pedagogical goals of understanding the importance of testing, comparing and contrasting models.

During the modeling phase of the inquiry cycle, students also read and reflected on several reading passages about models and modeling. These sections, entitled "collaborative thinking about models" included three passages about what a scientific model is, how the ThinkerTools computer program worked, and the utility of computer models. For example, in the passage on what a model is, students compared and contrasted three different maps of the area around their school in order to discuss advantages and disadvantages of different kinds of representations. Students read the passages in pairs and summarized the content to each other in order to reflect about the nature of modeling. After everyone in the class had gotten a chance to read the passage, we had the class discuss student responses and ideas.

Another reflection component of the modeling curriculum involved students watching a videotape of modern uses of computer simulation models. The video segment included a computer simulated tornado storm, a simulation of two galaxies colliding, some impulse-based simulations of objects moving on surfaces, and a short clip of the video animation movie "Toy Story." After the students finished watching the video, they discussed the various computer simulations and their utility in society, addressing the pedagogical goal of the purpose of scientific modeling, particularly for visualizing phenomena and performing difficult experiments or experiments not otherwise possible. Watching and discussing the video allowed students to see important images of computer models while motivating them to understand scientific modeling.

In the last stage of the inquiry cycle, evaluation, students evaluated their models with respect to modeling criteria such as accuracy and plausibility, applicability to other situations, and limitations. We chose four main criteria for characterizing good models: accuracy, plausible mechanism, utility, and consistency. For their evaluations, students gave their chosen model a score of one through five with respect to their model criteria which they justified with a written response as well as an occasional oral response to other members of the class. Evaluating models with criteria was a critical component of this curriculum. Philosophically, it is important that students understand that there a multiple scientific models, none of which entail absolute reality, and that some models are better than others with respect to the various criteria. Further, in order to make the modeling evaluation process similar to the evaluations within a scientific community, students compared and contrasted their model choice to other students' choices with respect to the evaluation criteria in class debates.

Data Coding, Collection, and Analysis

Before describing our methods of data collection and analysis, we first describe our framework for assessing modeling knowledge. Our assessments have been framed to test four dimensions of student modeling knowledge. (For dimensions, see table 2 below.) First, did students learn about the nature of models? In other words, did students learn what a model is, what models represent, and that there can be different kinds of models for the same object? Secondly, did students learn and understand the process of modeling? Did they understand that the modeling process involves embodying key aspects of a theory into a model, testing that model, and revising that model? Thirdly, what did students understand about the evaluation of models? Did they learn that there are ways to evaluate models to determine whether one is better than another? Did they learn about criteria used to decide this? And finally, did students in the model-enhanced version of ThinkerTools learn about what models can be useful for and how scientists and students can use models in science?

**1. Nature of models/theories/explanations:**

**Kinds of models and Model attributes**: What is a model? What is the best definition of a model? What are some examples? What makes those examples models? Why is ThinkerTools a computer model? What does the modeling portion of the inquiry cycle mean?

**Model content**: What do models represent? What are models modeling? (objects? systems?)

**Multiple models**: Can there be different models for the same object/phenomena? (ex: different models of an atom) Can you build models of different theories?*(This is related to whether knowledge is simple or complex.)*

**Constructed nature of models:** Do models represent absolute reality, are they useful constructions, or are they useless ideas that are relative? *(This is related to the nature of modeling category and addresses students' philosophy of science perspectives of realism, relativism, and constructivism.)* Can you build a model of an incorrect theory? If a computer model doesn't behave like the real world, why do you think that is?

**2. Nature of modeling/inquiry/experimenting:**

**Modeling process**: What is the process involved with constructing a model? Is this a process that involves embodying alternative theories into models, testing those models - evaluating them, and thinking about their limitations and applications- and revising those models including deciding which model is most reasonable?

**Designing and creating models**: How are models constructed? Are models designed for a purpose? Does the designer play a role in deciding what's important? How are attributes determined? Are attributes of the model exact copies of the object/process or abstracted features? What do you have to think about when making a model? How close does the model have to be to the thing itself? How do you know what's important to include? (ex: what parts of an atom do you have to model for modeling how atoms interact? all, some, etc.)

**Changing models**: Would a scientist ever change a model? Why? When?

**3. Evaluation of models/theories/explanations:**

**Model evaluation**: Is there a way to decide whether one theory is better than another? If so, how does one decide if one model is better than another? When one evaluates a model, is one testing how workable that model really is or is one testing the underlying assumptions of that model?

**Model criteria**: What kinds of criteria are used to evaluate models? (These might include: accuracy, realism, validity; plausibility, consistency, utility for serving a given purpose; simplicity; elegance.) *(This category is related to the purpose of modeling category.)* Do ways of evaluating models change much over time?

**4. Purpose/Utility of modeling:**

**Purposes of models**: What are models for? (These might include: defining/developing theories, predicting/testing theories, refining theories, visualizing phenomena, and explaining phenomena.) Are models best used to verify reality or to develop and test ideas? What's the best use of a model?

**Utility of models in science and science classes**: How could you use models in science or science class? How might a scientist use a computer model like ThinkerTools? How could students use a computer model like ThinkerTools to learn science?

**Utility of multiple models**: What's the purpose of having multiple models of the same phenomena/object? How could they be used to test theories?

Table 2: Dimensions of modeling knowledge

We have assessed these dimensions of students' modeling knowledge by using several instruments and methods of data collection. Those include (1) a pre and post modeling questionnaire, (2) students' final research projects, and (3) retention interviews about modeling with twenty students from two classes two and a half months after the end of the curriculum. Please note that we conducted this research in the tradition of the design experiment with no strict control group for the model-enhanced curricula classrooms. As a result, we have determined the effect of the classroom curriculum by calculating pre/post curriculum gain of model understanding on the assessments as well as achievement of specific modeling knowledge.

Our primary modeling assessment, the modeling questionnaire, included items about the nature, evaluation and purpose of models in various question formats. Those formats included among other types, a sorting task (circling all types of items that are models), enhanced multiple choice questions ("What is the best definition of a model and why?"), and enhanced true/false questions ("Could a scientist create an incorrect model and why?"). In our analysis, we calculated statistical differences in multiple choice items and coded some long answer responses in order to determine whether the responses improved.

Student final research projects provide some indication of the presence and forms of student models. In order to analyze these projects, we coded types of student models students used in their research projects.

The interview included questions about all dimensions of modeling and lasted between thirty to fifty minutes. It included contextualized questions about models and modeling related to students' final projects ("Did you get a chance to try out the different rules for your research findings in the modeling step of the inquiry cycle? Why should a student do this?"), decontextualized questions about the nature of models and modeling ("In general, is any model just as good as another?" "Do scientists ever change or revise their models?"), and two activities, ("Here are two examples of scientific models of gravity. How would you decide which is the best model?" and "Suppose that you wanted to find out how long it takes for a student to get between classes at your school. Using the inquiry cycle, describe how you might investigate this question."). We have transcribed half of the student interviews to determine student understanding of scientific modeling along the dimensions of model understanding as well as how much information and knowledge students have retained from the curriculum. From these transcriptions, the first author summarized students' statements to several questions to the interviews along several of the dimensions of modeling knowledge.

## Results

### Knowledge about the nature of models

There is clear evidence that students significantly increased their understanding of the nature of models from the model-enhanced version of ThinkerTools. In the first item of the written modeling assessment, for example, students were asked to circle items which they thought were models. Types of items ranged from a pencil or bicycle or a globe to scientific rules or theories. Analysis of data from all four of Teacher A classes on this question indicates that there was significant improvement on the students' understanding. For example, only 14% of students thought a causal rule was a model in the pre-test whereas 48% of them believed it was a model in the post-test ( $\chi2$ (1, $n$=71) = 22.15, $p < .001$) . There were significant changes to students categorization of all the items that were models except items students already believed were models (like globes, a diagram of an atom, or a toy car), and no significant changes in other items such as the pencil, bicycle or tree, for which 80% of students agreed were not models. (See appendix for complete results)

Our goal was to expand students understanding of a model beyond the typical meaning of a toy or small copy of an object, to a set of rules, representations, and reasoning structures that allow a person to predict and explain phenomena. While this assessment item assesses superficial understanding of model knowledge (what the word 'model' means), it nonetheless gives some indication that students understanding of the concept became more sophisticated to include sets of rules, theories and simulations. Further, it is important to note that some students might have interpreted all objects in this assessment item as models since the objects were represented by simplified and idealized representations of themselves. Students would be correct in this interpretation. This sophisticated interpretation, however, occurred in relatively few cases (roughly 5-10%).

An additional item on the modeling assessment that asks students what is the best definition of the word 'model' from the point of view of building a scientific theory shows modest improvement. 30% of students in the pre-test chose one of the most sophisticated options, "a set of rules that allow you to predict and explain," or "a simplified or idealized picture of something" compared to 46% in the post-test ( $\chi2$ (1, $n$=61) = 4.17, $p = .04$). (see appendix for modeling question) It is interesting to note that even in the post-test, 18% of students still picked the final response, that they "really didn't know." These responses indicate that there is clearly room for improvement in students' understanding the nature of a model and supports the literature that indicates modeling knowledge is difficult to obtain.

Several other items on the modeling assessment about the nature of models do not add much additional information on student modeling knowledge gain because of a ceiling effect in the assessment item. For example, 94% agreed in the pre-test and post-test that there can be different models of the same thing. In other words, students understood the concept of multiple models. 86% of students in the pre-test and 92% of students in the post-test agreed that if they and their partner had different theories, they could have a computer programmer create two different computer models for each of their theories. Again, students understood the concept of multiple models. Analysis of students' long answers to this question about the purpose of multiple models showed great improvement, however. 53% of their responses improved towards answers such as "to compare each theory and see who's right" compared to 30% of responses that stayed the same and 16% that got worse. Finally, 92% of students agreed in the pre-test and post-test that a scientist could create an incorrect model. Students have some constructed understanding that models do not have to be correct. One interpretation for the ceiling effects has been mentioned in the work of Gilbert. His research shows that replacing the words "law" or "theory" with the word "model" in assessment items moves students towards a constructivist stance in answering questions about the nature of science.

There are two other modeling assessment items that investigate students' ideas about the constructed nature of models. In other words, do students think models represent absolute reality or are they useful constructions? In one question, 83% of students in the pre-test agreed that "Even the best scientific theories and models aren't necessarily true; they're just ways of helping us understand the world" compared to 87% in the post-test ( $\chi 2$ (1, $n$=63) = 1.0, $p$ = .31) (Long answer analysis shows no significant improvement in students' responses).

Additional evidence about students understanding of the nature of models comes from student project reports, and student interviews. Analysis of student projects from four teacher B classes indicates that after the curriculum, most students had a basic understanding of what a model is within the inquiry cycle. 88% of students that did a final project included some sort of model in their project report which means that they included something under the heading of model which was an interpretation that went beyond restating their data. Further, most of these models were in the form of a general purpose rule that often included some sort of explanation. For example, one student wrote, "Falling objects speed up as they fall. I think this is because gravity is always applying force on everything ... This rule was the closest I could find to my real world experience. Regardless of mass, the height dropped from or weight, the object will speed up, until confronted with an obstacle."

Student interviews several months after the curriculum ended show that students maintained a substantial understanding of the nature of models. Out of the currently coded nine students who participated in modeling interviews, students' responses ranged from fairly unsophisticated, 'a model is a diagram, picture, or object that can be shown,'[4] to a medium level of sophistication, 'a model is a rule that predicts something,' to very sophisticated such as PL's response, "Well, it can be a theory or rule about what you think happens in real life, or it can be a representation of something. Any representation of a real thing, like a car model, or a theory. It's a representation of the real world." The first author scored the students' response based on how abstract their model was. Out of the nine currently coded student interviews, seven demonstrated medium to high levels of sophistication about the nature of a model. This success appears to have little relationship with previous academic achievement, teacher, or previous experience with the ThinkerTools curriculum.

<u>Knowledge about the modeling process</u>

Students did not make similar gains in their understanding of the process of modeling from the model-enhanced version of ThinkerTools. For example, one question on the written model assessment addressed how students think models are constructed. In the model assessment item, "If a scientist wanted to create a scientific model of an atom in order to predict how that atom will interact with other atoms, what parts of the atom would a scientist include in the model?" More students chose the response, "every single part of the atom" after the curriculum ( $\chi 2$ (3, $n$=71) = 5.69, $p$ = .13) (See table 4 below).

[4] When student responses are written within single parentheses, this indicates that their statements are not exact quotes but summaries of their statements.

| Question 10. If a scientist wanted to create a scientific model of an atom in order to predict how that atom will interact with other atoms, what parts of the atom would a scientist include in the model? | Pre-Test | Post-Test |
|---|---|---|
| A. Every single part of the atom. | 22 (31%) | 30 (42%) |
| B. Only the main parts of the atom | 15 (21%) | 8 (11%) |
| C. Only parts useful for predicting how it will interact with other atoms. | 34 (48%) | 33 (46%) |

Table 4

While this item is somewhat difficult to interpret, two aspects should be noted. First, student did not construct computer models in this curriculum, and therefore can only reflect upon the types of models they have seen. As a result, the less sophisticated option A, became more popular in the post test. Secondly, many students chose option C overall, showing some degree of sophistication about the process of modeling.

The other modeling assessment item that asks students about the nature of the modeling process stated, "Would a scientist ever change or revise a scientific model?" 87% of students in the pre-test stated yes, and 94% in the post-test agreed ( $\chi 2$ (1, $n$ = 68) = 2.27, $p$ = .13). Long answer analysis to this questions shows no significant improvement in students' responses because of the ceiling effect on this question.

Information about students' knowledge of the modeling process was difficult to obtain from the interview for several reasons. Students in the model-enhanced version of ThinkerTools constructed preliminary models and chose among models similar to their preliminary ones. Therefore, questions about the process involved with constructing the model is less relevant for students in this curriculum. Further, students' scientific research was always structured within the inquiry cycle. Therefore, understanding the modeling process of (1) embodying a theory into a model, (2) testing the model, and (3) revising that model is inherent to the ThinkerTools inquiry process and was difficult to test. As a result, questions relating to the students' modeling process are indirect and relate to what students understood of the modeling forms, and the purpose of the models.

Nonetheless, student interviews indirectly indicate that two months after the curriculum finished, students maintained some understanding of the modeling process. To obtain this information, the first author scored the forms of student models from students' self-reports of final projects in the interview as well as models from their inquiry thought-experiment at the end of the interview. In scoring model forms, the first author expected to gain insight in students' understanding of the purpose and process of modeling. The student model forms ranged from fairly unclear or unsophisticated such as 'a model as a construction to show someone else to see if they thought it made sense,' to a more sophisticated form of ' a model as a predictive/descriptive rule,' to one of the most sophisticated forms 'a model as a predictive explanatory rule or a predictive representation.' Overall, students showed a fair amount of sophistication about model forms. Seven of nine students showed at least a medium level of sophisticated in their modeling forms. Again, this success appears to have little relationship with previous academic achievement, teacher, or previous experience with the ThinkerTools curriculum.

Knowledge about the evaluation of models

Students' gains in their understanding of the evaluation of models from the model-enhanced version of ThinkerTools was mixed. In one item on the written modeling assessment, for example, students were asked whether they agree or disagreed with the following statement: "Since scientists disagree about why dinosaurs became extinct, it's clear that no one understands exactly how it happened. Therefore, any scientific model or theory of how it happened is just as good as any other." In the pre-test, 59% of students agreed compared to 67% of the students on the post-tests ( $\chi2$ (1, $n$=64) = 1.31, $p$ = .25). We had hoped that the curriculum would encourage students to understand that this statement was false – that models are evaluated with criteria and that some have more value in certain situations than others. However, these students begin with a relativistic orientation[5], and apparently, this item indicates that the curriculum further encouraged this orientation. In fact, long answer analysis shows significant change towards the relativist position. 56% of students' reasoning in their long answers stayed the same while 25% decreased in sophistication towards answers like "If nobody knows how it happened, any answer could be true."

Student interviews two months after the curriculum elaborate students' reasoning. When students were asked whether in general 'Is any model as good as another?' seven out of nine students said 'yes' with answers ranging from unsophisticated notions that 'as long as you worked hard on your research, all models were all the same,' to more sophisticated response of 'all models are equally good when there is no way to know which one is right.' Both students with more sophisticated responses said, 'not all models are as good as any other' 'because some people don't conduct their research carefully' and 'some models are less well-thought out than others.' Since seven of the nine students answered that all models are as good as each other, most scored a medium-level of sophistication on this question, indicating that while they had explicit criteria with which to evaluate models in the curriculum, this did not help to distinguish among models, and students moved towards a relativist position. Again, this success appears to have little relationship with previous academic achievement, teacher, or previous experience with the ThinkerTools curriculum.

Another item on the written assessment asked students whether they agreed with the statement, "When a scientists evaluates a scientific model, she looks for certain qualities such as how accurate and reasonable the model is." 89% in the pre-test agreed compared to 95% in the post-test ( $\chi2$ (1, $n$= 62) = 1.6, $p$ = .20). Long answer analysis for this question shows significant improvement towards having students mention criteria such as accuracy, plausibility, utility, and consistency. 68% improved their responses, and 27% of the responses remained the same quality. Finally, students were asked whether they agreed with the statement, "Ways of evaluating scientific models or theories don't change much over time." 38% of students agreed in the pre-test compared to 36% in the post-test. It is not clear what the students understood from this question since many of their long answers seemed to indicate that they interpreted the question as 'models don't change much over time.'

In initial analysis, students demonstrated somewhat less sophistication about model evaluation in the interviews, although results are not necessarily indicative of students' overall understanding of model evaluation from the interview. Out of the nine interviews, three students could not remember any model evaluation criteria. (Future interview analysis will give more complete results of student understanding of model evaluation criteria.) Again, students responses ranged from not remembering any model evaluation criteria and thinking of evaluating a project by 'looking over the material' to remembering that evaluation criteria existed and that model utility was important, to knowing that models had to be accurate and plausible. For

[5] A relativistic orientation is one in which a person believes that all claims have equal value since there is no absolute method of distinguishing among them.

example, when I asked PL what criteria he might use to evaluate his research findings, he stated, "Well, I looked if my data seemed like plausible, and I looked to see if my model could be used to predict anything really accurately." Again, most students scored a medium or medium to poor level of sophistication for this question which in retrospect is not as informative as other items in the interview. As previously stated, further interview analysis will help to clarify these results.

In videotaped student project presentations at the end of the curriculum, student project work also indicated some deeper level understanding of the process of modeling as well as the model evaluation criteria. The following example illustrates some of this understanding. A ThinkerTools student, JP, was presenting his project on gas/fluid resistance in order to answer the question, what is the motion of an object dropped through a thick fluid like honey. He and his partner had performed an experiment and analyzed their data which indicated that over a long period of time, the object slowed down in this very thick fluid. During his project presentation, he stated,

> We estimated the rule before we went onto the computer, and our rule was that, um, when an object is affected by friction, it slows down. So we went on the computer and we tried out that one. [the computer modeling rule 'slows down'] ... and the object slowed down so much that it didn't even go all the way [fall to the bottom of the container] which wouldn't happen in real life. So we tried um, ... the one where you could use it at a constant speed, and that seemed to work right, which puzzled us a little bit, because that's not what our data showed. So we were a little inconsistent there. So, on our ratings at the end, our self-assessment, that kind of messed us up 'cuz ... we had to be careful. We weren't exactly all-too careful, obviously, and the data showed that we messed up.

JP's real world data seem to indicate that the objects are slowing down. But, the computer model simulation shows that if the objects were slowing down, they would eventually stop. Since this doesn't happen in the real world, Mark realizes that their real world analysis was incorrect, and that he had an inconsistency in this data that he needed to resolve. This student showed a sophisticated understanding of modeling in that he understood that computer modeling is useful for testing theories.

<u>Knowledge about the utility of models</u>

Finally, students make striking gains in their understanding of the utility of models from the model-enhanced version of ThinkerTools. The written modeling assessment provides the strongest evidence for students' improvement in this understanding. For example, when students were asked the question, "From a scientific point of view, which is the best use of a model?" 41% of students in the pre-test chose the most sophisticated answer, D, "to develop and test ideas" compared to 60% in the post-test ( $\chi 2$ (1, $n$=63) = 7.2, $p$ = .007). In another evaluation question, students were asked, "If you were an astronomer trying to determine the path of a comet in our solar system, which of the following would you rather have? A. A scale model (a smaller version of our solar system), or B. A computer simulation or computer model of our solar system." 71% of students in the pre-test picked B, the computer simulation. This compares to 83% of students choosing B in the post-test ( $\chi 2$ (1, $n$=58) = 3.77, $p$ = .052).

Two additional long answer only questions on the modeling assessment showed significant improvement in students understanding the utility of models. In one question, "How could computer models help scientists with their research?" 63% of responses improved towards answers like, "it allows them to test things they normally couldn't test like frictionless environments" or "they could test their theories" while 25% of the remaining responses remained the same quality. In the second question, "How could computer models help students learn science?" students showed some, although not as dramatic improvement. 50% of students improved their responses towards answers such as " It helps them understand the science" or "it lets them experiment" or even "it lets them test their ideas" compared to 40% of responses whose quality remained the same.

Finally, interviews indicate that students demonstrated a fairly robust understanding of the purpose of the model design software in the curriculum, and of the utility of scientific models in general. When students were asked what the purpose was of the model design rules on the computer, responses ranged from the ambiguous response of 'to show a better way of understanding in case they didn't get it right,' to 'to be able to conduct experiments not otherwise possible and choose the rules and see which one was the best,' to most sophisticated, 'to show you what you picked so you could see which one looked better and to make you think about which one was right.' In general, students showed a fair amount of sophistication in this question and averaged fell in between the categories medium and medium to high level of sophistication in their response. This result appears to have little relationship with previous academic achievement, teacher, or previous experience with the ThinkerTools curriculum.

Secondly, when students were asked what they thought scientific models could be useful for, there was a great range of responses in the interview questions. An example of the least sophisticated response was 'scientific models can be used for anything. They're not useful for scientists, but for students learning science, they can help them learn to construct better models.' A more typical response was 'a scientific model can help explain what and why something happens. For scientists, they explain why things happen. For students learning science, models can be useful to help them visualize and understand.' The most sophisticated response indicated that 'scientific models can help people find out information. They can help construct cars, and predict what they will be like. For scientists, scientific models can help them visualize and test things that are not otherwise possible such as DNA. For students learning science, scientific models can help them see other people's models, as well as helping them visualize and manipulate the models.'

## Summary of Results

To summarize, analysis of all multiple choice items on the written modeling assessment for all Teacher A students indicates an improvement in student understanding of modeling. When all assessment items were scored and given the points for the sophistication of their responses, the overall pre-test mean was 62% compared to an overall post-test mean of 70% 'correct' ($t_{71} = 6.15, p < .001, \sigma = .64$). One third of the points for this assessment were derived from the first item on the assessment, the modeling categorization task, and a third of the remaining questions showed ceiling affects. Therefore, this gain particularly reflects students improvement in their understanding of the nature of models, and in the utility of models.

Analysis of the long answers from the modeling assessment supports the multiple choice analysis showing large gains in student understanding of the utility of models for scientists and for learning science, the utility of multiple models, some gains in students' understanding of the evaluation of models (what criteria to use), and an increase in students' relativist orientation towards model evaluation (any model is as good as any other).

Finally, initial analysis of student interviews shows that in general, students had a robust understanding of the nature of models, a strong understanding of the utility of models, and again a somewhat relativist orientation towards the evaluation of models.

How do these results compare with those from Grosslight, Unger, Jay, and Smith (1991)? Initial analysis seems to indicate that after the model-enhanced version of ThinkerTools, there is some evidence that our seventh graders understood more about the nature and process of modeling than the seventh graders they surveyed. Certainly, in comparing the same interview questions, "What comes to mind when you hear the word 'model'? Are there different kinds of models? What are models for? Can you use models in science? Do you think scientists would ever have more than one model for the same thing? Would a scientist ever change a model?" our seventh graders responded with some sophistication. However, it is difficult to determine students' epistemologies concerning the relationship between reality and models from the above questions, particularly since the main question about constructing models, "What do you have to think about when making a model?" was not relevant to our students and as a result, not asked. There is some evidence that our seventh graders had a mixture of constructivist, nearly relativist orientation towards the nature of science while at the same time, some strong empiricist views as well. Our seventh grade students could be categorizes as having reached Grosslight et al.'s level 2 or mixed level 1 and 2 understanding of models and the nature of modeling. In a level 2 understanding of the nature of models:

> the student now realizes that there is a specific, explicit purpose that mediates the way the model is constructed. Thus the modeler's ideas begin to play a role, and the student is aware that the modeler makes conscious choices about how to achieve the purpose. The model no longer must exactly correspond with the real-world object being modeled. Real-world objects or actions can be changed or repackaged in some limited ways (e.g., through highlighting, simplifying, showing specific aspects, adding clarifying symbols, or creating different versions). However, the main focus is still on the model and the reality modeled, not the ideas portrayed per se. Further, tests of the model are not thought of as tests of underlying ideas but of the workability of the model itself. (Grosslight et al., 1991, p. 817-818)

## Future Directions

We plan to conduct further analysis of our seventh graders' model understanding to gain greater depth and insight into these interpretations. Further analysis will include coding remaining interviews and interview questions as well as coding the remaining research book data, long answer data analysis, and written model assessment data from teacher B's classes (in order to compare teacher effects). We will also be conducting regression analysis on students previous ThinkerTools experience and academic achievement to clarify results. Further, we are pursuing analysis of individual student modeling profiles to track the progression of modeling knowledge. These results are likely to be informative. For example, we hypothesize that each student advanced essentially one level in their model understanding. In other words, a student who knew nothing of models at the beginning of the curriculum might have learned that a model can be a visual object that copies another. Similarly, a student who began by thinking of a model as a small copy or toy might have moved towards thinking of a model as an abstract representation. An alternative hypothesis for which there has been some initial evidence suggests that lower academic-achieving students gained more modeling knowledge than higher academically achieving students because they had a better understanding and appreciation for the purpose and process of the computer modeling in the curriculum. Perhaps running the computer modeling simulation was not self-evident for these lower-achieving student as it was for some narrowly-focused and higher-achieving students. Results are forthcoming.

## Conclusions

While interactive computer models and modeling as a methodology of science are being advocated for use in science classrooms, "there is still a need to examine student understanding and use of models in general and the characteristic knowledge and misunderstandings they hold about models." (Benchmarks for Scientific Literacy, Project 2061) Further, it is critical that students understand the very process of science with which they are involved, as well as their overall understanding about the nature of science because modeling is one of the most important components of the scientific endeavor.

This paper has examined how a curriculum focused on scientific modeling can foster student understanding of the nature of models and the process of modeling. In the model-enhanced ThinkerTools curriculum, we found that teaching this model-enhanced curriculum fostered student's understanding of the nature and utility of models without promoting similar gains in students' understanding of the process of creating and evaluating models.

Future analysis about the evolution of students modeling knowledge as well as the analysis of the relationship between previous ThinkerTools experience, academic achievement and modeling knowledge gain will further clarify these results. Teaching students about models and the process of modeling is a challenging yet promising way to encourage their development of sophisticated epistemologies of science. Future research on refining model-oriented curricula and assessments as well as classroom trials will be essential to this progress.

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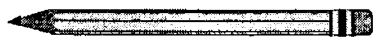
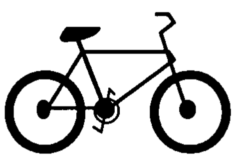
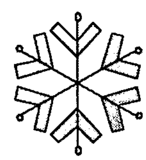
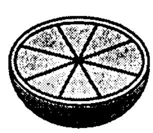
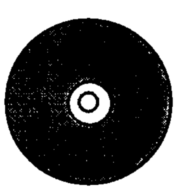
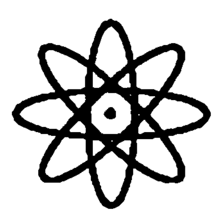
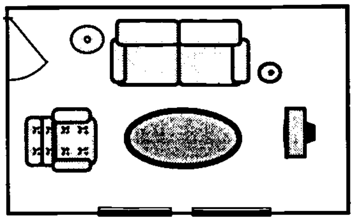
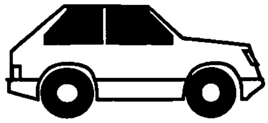
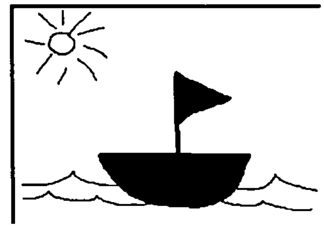
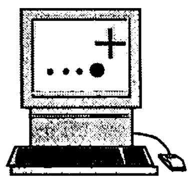
Written Modeling Assessment Results

## Questions About Models

Question 7. Circle all of the items which you think are models:

| | | |
|---|---|---|
| a scientific theory like Einstein's theory of relativity<br>***Pre: 21% Post: 52%***<br>***$p < .001$*** | <br>a pencil<br>*Pre: 24% Post: 17%*<br>*$p < .15$* | a computer simulation like SIM CITY<br>***Pre: 52% Post: 68%***<br>***$p < .05$*** |
| <br>a bicycle<br>*Pre: 37% Post: 35%*<br>*$p = .85$* | <br>a globe or map<br>*Pre: 83% Post: 87%*<br>*$p = .47$* | <br>a snowflake<br>*Pre: 24% Post: 24%*<br>*$p = 1.0$* |
| a rule like "roughly every twenty-four hours, the sun rises in the east and sets in the west because the earth rotates on its axis"<br>***Pre: 14% Post: 48%***<br>***$p < .001$*** | <br>an orange<br>*Pre: 23% Post: 21%*<br>*$p = .80$* | a video animation like the movie TOY STORY<br>***Pre: 35% Post: 52%***<br>***$p < .01$*** |
| <br>a compact disc<br>*Pre: 32% Post: 25%*<br>*$p = .25$* | an equation like Newton's second law which says that force applied on an object is equal to the mass of that object times the object's acceleration. (F = m x a)<br>***Pre: 21% Post: 55%***<br>***$p < .001$*** | <br>a diagram of an atom<br>*Pre: 76% Post: 82%*<br>*$p = .32$* |

| | | |
|---|---|---|
| <br>a set of diagrams and plans for a building or a room<br>*Pre: 81% Post: 86%*<br>$p = .32$ | <br>a toy car<br>*Pre: 76% Post: 77%*<br>$p = .76$ | <br>a picture or drawing<br>*Pre: 48% Post: 58%*<br>$p = .19$ |
| <br>a ThinkerTools simulation<br>***Pre: 46% Post: 83%***<br>$p < .001$ | <br>a tree<br>*Pre: 14% Post: 14%*<br>$p = 1.0$ | <br>a person who displays clothes<br>*Pre: 49% Post: 59%*<br>$p = .14$ |

**Question 9: The following choices are all definitions of the word 'model'. From the point of view of building a scientific theory, which is the best definition of a model?** (Please circle one response)

(A) A small copy of an object (Pre: 37% Post: 31%)

(B) A set of rules that allow you to predict and explain (Pre: 16% Post: 34%)

(C) A simplified or idealized picture of something (Pre: 13% Post: 13%)

(E) A set of plans for constructing a building or bridge

(F) A mannequin or someone who displays clothes

(G) I really don't know! (Pre: 26% Post: 18%)

**Question 10. If a scientist wanted to create a scientific model of an atom in order to predict how that atom will interact with other atoms, what parts of the atom would a scientist include in the model?** (Please circle one response)

(A) every single part of the atom (Pre: 31% Post: 42%)
(B) only the main parts of the atom (Pre: 21% Post: 11%)
(C) only parts useful for predicting how it will interact with other atoms (Pre: 48% Post: 46%)

**($p = .13$)**

**Question 11: Can there be different kinds of models of the same thing? For example, are there different kinds of models for an atom?**

(Please circle one response)

(A) YES (Pre: 93% Post: 92%)
(B) NO

**Question 12: If you and your partner had different theories, do you think you could have a computer programmer create two different computer models for each of your theories?**

(Please circle one response)

(A) YES (Pre: 86% Post: 92%)
(B) NO

**If you think it's possible to create two different computer models, explain how this might be useful. If you don't think it is possible to create two different computer models, explain why it's not possible.**

53% responses their quality (long answer analysis done with a chi-suqare fit of the uniform distribution for the sample. $p < .001$)

**Question 13: Could a scientist create an incorrect model?**

(Please circle one response)

(A) YES (Pre: 92% Post: 92%)
(B) NO

**Question 14: Would a scientist ever change or revise a scientific model?**
(Please circle one response)

(A) YES (Pre: 87% Post: 94%)
(B) NO **(p = .13)**

**Why or why not?**
66% responses remained the same quality (long answer analysis done with a chi-suqare fit of the uniform distribution for the sample. $p < .001$)

**Question 15:** Do you agree or disagree with the following statement? (Please circle one response)

**"Even the best scientific theories and models aren't necessarily true; they're just ways of helping us understand the world."**

(A) Agree (Pre: 83% Post: 87%)
(B) Disagree

**Explain your choice:** 62% responses remained the same quality (long answer analysis done with a chi-suqare fit of the uniform distribution for the sample. $p < .001$)

**Question 16. Scientific models are:** (Please circle one response)

(A) real and useful (models represent absolute reality) (Pre: 25% Post: 31%)
(B) not necessarily real and useful (models don't necessarily represent absolute reality) (Pre: 70% Post: 68%)
(C) not real and not useful (models don't represent absolute reality)

## Questions About Evaluating Models

**Question 17:** Do you agree or disagree with the following statement? (Please circle one response)

**"Since scientists disagree about why dinosaurs became extinct, it's clear that no one understands exactly how it happened. Therefore, any scientific model or theory of how it happened is just as good as any other."**

(A) Agree (Pre: 59% Post: 67%)
(B) Disagree

**Explain your choice:** 56% responses remained the same quality, 25% get worse (long answer analysis done with a chi-suqare fit of the uniform distribution for the sample. $p < .001$)

**Question 18:** Do you agree or disagree with the following statement? (Please circle one response)

**"When a scientist evaluates a scientific model, she looks for certain qualities such as how accurate and reasonable the model is."**

(A) Agree (Pre: 89% Post: 95%)

(B) Disagree

**If you agreed, describe some additional qualities. If you disagreed, explain why a scientist does not evaluate a model with certain qualities.**

58% responses improved (long answer analysis done with a chi-suqare fit of the uniform distribution for the sample. $p < .001$)

**Question 19:** Do you agree or disagree with the following statement? (Please circle one response)

**"Ways of evaluating scientific models or theories don't change much over time"**

(A) Agree (Pre: 38% Post: 36%)

(B) Disagree

## Questions About the Usefulness of Models

**Question 20. From the scientific point of view, which is the best use of a model?** (Please circle one response)

(A) to be a toy

(B) to copy an object or process

(C) to help someone construct an object

(D) to develop and test ideas (Pre: 41% Post: 60%)

**($p < .01$)**

**Question 21:** Do you agree or disagree with the following statement? (Please circle one response)

**"Computer models and simulations can help us understand things like the motion of a comet in space or traffic patterns in a city"**

(A) Agree (Pre: 90% Post: 90%)

(B) Disagree

**Question 22. Two biology research groups have different models or theories about how a dangerous virus (like HIV) might replicate. How useful would it be for them to build and test computer models of each other's theories?** (Please circle one response)

(A) Very useful (Pre: 56% Post: 61%)

(B) Somewhat useful (Pre: 41% Post: 46%)

(C) Not useful

**Question 23. If you were an astronomer trying to determine the path of a comet in our solar system, which of the following would you rather have?**

(Please circle one response)

(A) A scale model (a smaller version of our solar system)

(B) A computer simulation or computer model of our solar system (Pre: 71% Post: 83%)

**Question 24: How could computer models help scientists with their research?**

63% responses improved (long answer analysis done with a chi-suqare fit of the uniform distribution for the sample. $p < .001$)

**Question 25: How could computer models help students learn science?**

50% responses improved (long answer analysis done with a chi-suqare fit of the uniform distribution for the sample. $p < .001$)

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