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Understanding Models and their Use in Science: Conceptions of Middle and High School Students and Experts

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Abstract

Thirty-three 7th-grade mixed-ability students and 22 11th-grade honors students were interviewed about their conceptions of models and their use in science. Three analyses are presented in order to: (1) portray the character of students' spontaneous answers; (2) examine the criteria students use to decide whether specific items are models or not; and (3) describe how different general levels of understanding models reflect different epistemological viewpoints. Four experts were also interviewed for purposes of comparison. We found that students in both groups have conceptions of models that are basically consistent with a naive realist epistemology. Thus, they are more likely to think of models as physical copies of reality that embody different spatiotemporal perspectives than as constructed representations that may embody different theoretical perspectives. As student ideas become more sophisticated, however, they increasingly include the fact that models are designed for particular purposes, especially to help communication. All of our experts expressed ideas consistent with a constructivist framework, drawing a distinction between abstract and physical models and articulating ways that models are used for the construction and testing of ideas. Our findings suggest that students need more experience using models as intellectual tools, more experience with models that provide contrasting conceptual views of phenomena and more discussions of the roles of models in the service of scientific inquiry.

Models of natural phenomena and theoretical constructs have been widely used as instructional tools in science education. Pictures of atoms, equations describing the relationship between mass and gravity, and snap together plastic representations of anatomical systems are just a few examples of models found in middle and high school science classrooms. Little is known, however, about how the students in these different classes conceptualize the nature of models, e.g., what models are for, how and by whom they are made, under what conditions (if any) they should be changed, whether or not there can be multiple models for the same thing, and what models actually represent.

In this article, we describe what we have learned about student conceptions of models and their use in science from our clinical interviews with two groups of students: 33 mixed-ability 7th graders and 22 11th graders from an honors class. We have analyzed their responses in three ways. First, we present students' typical answers to specific questions about models. Second, we examine the students' criteria for deciding whether certain physical items could be called models or not and the consistency with which these criteria were applied. Third, we present an analysis of what the students' answers reveal about their underlying epistemologies of science.

Four adults who were considered experts on scientific models were also interviewed. Expert answers were analyzed in order to inform our assessment of the strength of the interview, our evaluation of the potential and limitations inherent in the students' ideas, and our recommendations for classroom practices that could further students' understanding of models and their use in the inquiry process.

Students' Thinking about the Nature of Science

There is increasing recognition in the science education community that students frequently come to science class not only with naive theories about the particular subject matter they are studying, but also with naive epistemologies, and that students must make changes in their naive epistemologies if they are to understand the scientists' specific theories (see e.g., Champagne, Gunstone, & Klopfer, 1985; Roth, 1984; E. Smith, 1987; Snir, Smith, & Grosslight, 1988). At present more work has gone into characterizing students' naive theories about mechanics, matter, heat, etc., than into characterizing their underlying epistemologies of science. Thus, a central goal of our work is to understand how different groups of students think about the nature of scientific knowledge and how it is acquired.

Although the literature on children's naive epistemologies of science is meager, there is a considerable literature on the development of children's theories of mind (e.g., see Astington, Harris, & Olson, 1988) and children theories of knowledge (e.g., Broughton, 1978; Chandler, 1987; Kitchener & King, 1981; King, Kitchener, Davison, Parker, & Wood, 1983; Perry, 1970; Wimmer, Hogrefe, & Perner, 1988) using a diverse range of data collection methods.

Chandler (1987) argues that preschool children are naive realists concerning their personal knowledge of reality. For them, knowledge consists of a series of discrete facts which can be immediately and unproblematically apprehended by being in the right place at the right time. Knowledge thus originates with and is determined by one's perceptual experiences. During the elementary school years, students elaborate on but essentially maintain an inherently naive realist epistemology. Students become increasingly aware that "the complete story is not always automatically apparent, that partial facts contain partial truths, and that persons are fully knowledgeable only when fully informed" (Chandler, p. 147). They are still realists in the sense that the only impediments to knowledge acquisition are "scenic rather than personal in character" (p. 147). With the onset of adolescence, however, a fundamental shift in children's epistemology becomes evident. According to Chandler, adolescents become increasingly aware of the personally constructed nature of meanings, a shift that begins to undermine their belief in absolute truth and objective reality. Thus, they begin to develop more relativist epistemologies, with no objective criteria to support a choice between one world view and another. "The price of all this new-found uncertainty is generic doubt, not the kind of mundane, case-specific doubt of middle childhood, but a wholesale, transcendental kind of doubt that threatens to annihilate the whole of one's system of beliefs" (p. 150). Chandler concluded by identifying a variety of moves that adolescents and adults may make to cope with this doubt: dogmatism, skepticism, or (ultimately) postskeptical rationalism and commitment in the face of doubt.

Other researchers (Kitchener & King, 1981; King et al., 1983; Perry, 1970) elaborate similar epistemological progressions (commitment to absolute truth, relativism, and the return to belief in knowledge in a relativistic world) when interpreting how students confront the competing knowledge claims of authorities in particular fields (i.e., science, history, religion, literature, the arts). Perry's work also implies that college students may hold different epistemological positions in different domains. In general, the researchers claim that students make the shift to relativism during the early college years as the result of specific educational experiences.

Thus, the literature is in rough agreement on the sequence of moves children and/or students make in developing their epistemologies. There is less agreement on the ages at which some of these shifts are made and the factors that cause them (e.g., representational abilities emerging in adolescence or a university education). We believe further work should not simply assume that students' epistemologies develop unilaterally across domains. Further research should attend to identifying variations and interactions in student epistemologies across different domains.

Recent work by Carey, Evans, Honda, Jay, and Unger (1989) investigated seventh-grade students' epistemology of science and whether the students could be encouraged to articulate a more sophisticated epistemology following an innovative curriculum unit. Carey et al. questioned seventh graders about their general conceptions of science (what scientists do, what the purpose of science is, how scientists learn about the world), and their results suggest that, prior to instruction, seventh graders are still within the grips of naive realism when thinking about scientific knowledge: scientists learn by observing the world, and knowledge is fundamentally a set of directly observable facts. Although students made progress in defining and distinguishing between hypotheses and data as a result of instruction and could see how ideas were tested in limited ways by experiments, they still did not espouse a sophisticated constructivist view of science. That is, they did not see the goal of science as the construction of "ever deeper explanations of the natural world" (p. 521), or appreciate how theories are developed and changed through cyclic and cumulative processes of testing and revision.

An expert view might be that science involves, in large part, the construction, application, verification, and revision of theoretical models. Indeed, in a recent article, Gilbert (1991) suggested that it would be helpful for science education to proceed from a definition of science as a "process of constructing predictive conceptual models" (p. 73). An unexplored question is whether students may reveal more sophisticated understandings of science when questioned about the nature of models. Gilbert (1991) claimed that college students appreciate the constructed "artificial" nature of models before they realize the constructed "artificial" nature of scientific knowledge. He did not, however, probe students with clinical interviews. (We also question his equating knowledge as "artificial" with knowledge as "constructed.") In the present study, we interview seventh-grade students to explore their conceptions of models in order to probe students' epistemology of science in a way that complements the interviews conducted by Carey et al.

Another question left unanswered by Carey's work concerns the typical epistemological views of other groups. Carey assumes that scientists hold sophisticated constructivist conceptions of knowledge in their field. However, it is unclear which features of constructivism are most central to their views or whether these views are also held by different groups of students. Thus, we questioned a group of experts and a group of 11th-grade honors science students to probe for more sophisticated constructivist conceptions than we expected to find among 7th-grade students.

Teaching with Models

With the growing interest in developing curricula to facilitate conceptual change, there is increased attention to students' mental representations of the phenomena presented to them in science classes and interest in developing innovative pedagogic models across the science curricula to help students understand the scientists' ways of conceptualizing phenomena. In particular, with the advent of the microcomputer, researchers have begun to explore the pedagogical potential of dynamic microcomputer-based simulations, with several groups paying particular attention to the design and application of models which provide explicit representations for scientific concepts and their relations (e.g., White & Horwitz, 1987; Wiser, Kipman, & Halkiadakis, 1988; Snir et al., 1988).

In developing these curricula, some investigators (e.g., Snir et al., 1988) have talked explicitly with students about the nature of models and have hypothesized that enriching students' conceptions of the nature of models may facilitate student learning from models. Based on anecdotal reports, Smith (1984) suggested that students interpret models too literally, leading to students' misassimilation of these models. However, to test such hypotheses one needs to develop a way of assessing student's general conceptions of models. Specific studies are also needed to determine whether students have systematic conceptions about models, whether there are differences in students' conceptions about models in different populations, and ultimately, whether the nature of their conceptions has an impact on how they learn from a modeling curriculum.

Method

The present exploratory study assessed students' understanding of models and their use in science. Three types of analysis were completed in order to (a) capture the range and character of students' spontaneous answers to our specific questions, (b) investigate the consistency with which students use various criteria for describing what models are, and (c) develop and justify a scoring scheme describing different levels of students' understandings of models, which reflect different epistemological viewpoints. After the coding schemes were developed, the experts were interviewed for comparison. The experts could be scored using our coding schemes and interesting student/expert similarities and differences were apparent.

Subjects

Two populations of students participated in this study: 33 7th-grade students (sampled across the range of ability levels in the school) and 22 11th-grade students (in an honors science class). Both groups were from middle-class suburbs of Boston. The 7th graders attended the same school as the 7th graders in the Carey et al. study.

The four adult experts are a science museum director, a high school physics teacher who regularly uses models in class, a professor of engineering and education, and a researcher whose main interest lies in the domain of thinking and representations. Three are from the Boston area and one is from the San Francisco area.

The Interview

A clinical interview was developed, piloted, and revised to elicit students' initial understanding of models. Our questions were developed through brainstorming sessions influenced by Carey's work and our own work (see e.g., Smith, Snir, & Grosslight, in press) developing conceptual models for teaching specific content. The interview began by asking students briefly about the nature and purpose of science. These questions helped set the tone of the interview, but were not elaborate enough to merit coding. Students were then asked an extensive series of questions about models such as: "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? What do you have to think about when making a model? Do you think scientists would ever have more than one model for the same thing? Would a scientist ever change a model?" The interviewers probed student answers further with follow-up questions such as, "Could you give an example? How would that happen?" Thus, the interview was designed to elicit both the student's general conception of the term "model" as well as the student's specific conception of how models might be used in science. In addition, fairly early in the interview, four physical items (a toy airplane, a subway map, a picture of a house, and a schematic diagram of the water cycle which was taken from a middle school science textbook) were presented and the students were asked to explain whether they thought these could or could not be called models. Two of these (the subway map and diagram of the water cycle) were a more schematic type of model than students tended to think of themselves, yet most students readily regarded them as models. We introduced these specific examples for their reflection and asked them to generate specific examples of scientific models before we asked them the general questions about designing models, using multiple models in science, and changing models in science.

Development of the Scoring Systems

After a preliminary review of a sample of these interviews, three coding schemes for analyzing the data were developed. The first coding scheme built a data base of the kinds of responses students gave to various questions. The second coding scheme captured students' explicit criteria for deciding whether particular physical items could be called models or not. The third coding scheme categorized students' general understanding of models as related to epistemological viewpoints.

Our scoring procedure was not imposed a priori on the data, but emerged from a detailed analysis of the types of things students said in the clinical interviews. When developing the third coding scheme, we tried to see if the three general levels that emerged from the Carey et al. study had parallels in the case of understanding models. In so doing, the construction of first- and second-level understandings emerged clearly from the student data; however, we felt it necessary to extrapolate beyond the range of student responses to construct the third level of understanding. As reported below, the expert responses further justify our description of level 3 understanding.

Results

Analysis of Student Responses

The purpose of this analysis is to present the types of responses students gave to the interview questions and to compare the responses of our two groups of students. Because the 11th graders in our sample represent a more homogeneous honors science class and the 7th graders a broader spectrum of science classes, one cannot necessarily conclude that the group differences are strictly age related.

Tables 1–6 summarize the range of answers coded in the data base. In the sections that follow, we summarize the main trends that emerged from the data base analysis. The tables present the percentage of students replying to a set of questions in a given manner. A student could give several different responses to a question.

Table 1: Kinds of models. Table 1 summarizes students' answers to the questions: "What comes to mind when you hear the word 'model?' Are there different kinds of models? How would you describe what a model is to someone who didn't know what a model is?" Virtually all students in both grades referred to concrete objects (e.g., replicas of airplanes and buildings) as models of concrete objects (real airplanes and real buildings). Very rarely did they refer to models as representations of ideas and/or abstract entities (e.g., mathematical or theoretical models). While the "things" being modeled were of a very concrete nature (even an "idea" was usually limited to an idea of how the airplane should look) there were some interesting findings as to what students thought about how these things could be represented. Honors 11th graders were more apt to talk about two-dimensional visual models such as drawings, diagrams, maps, and computer displays. A good proportion of both groups described models as being just like the real thing but different in scale; however, the honors 11th graders were more likely to talk explicitly about this relationship. In neither grade did the students spontaneously mention the role of the modeler very often.

Table 2: Purpose of models. Table 2 summarizes students' answers to the questions: "What are models for? What is the purpose of models? What can you do with a model? Can you use them in science?" Responses from both groups touched on a wide range of purposes including observation, communication, learning and understanding, providing references and examples, making things clear and accessible, making and building, and testing. However, differences between the groups were apparent both in terms of articulation and area of focus.

Approximately half of both groups said that models were for showing an object (e.g., what it looks like). The groups then diverged with the mixed-ability 7th graders saying that the purpose of models was to give you an example or demonstration of what something is or does, and that models were basically for looking at and playing with. In contrast, many honors 11th graders thought the purpose of models was to help someone understand and to teach, as well as to make things more accessible or convenient to see and/or use. Ways of accomplishing this purpose were highlighting, simplifying, and omitting information from the model or changing the size, location, time, or view of the referent.

Table 3: Designing and creating models. Table 3 summarizes students' answers to the question: "When making a model, what do you have to keep in mind or think about?" Both groups felt that one would have to think about "the real thing" and try to make the model as close as possible to the exact size, shape, and proportion of the

Table 1
Classification of Student Answers to Questions about Kinds of Models

Classification	Percentage of students	
	Mixed 7th ($N = 33$)	Honors 11th ($N = 22$)
Examples of models		
(1) Objects and people	97	95
Fashion models; Toy models; Living models; Replicas; Role models; Architectural models		
(2) Visual models (on paper; computer)	30	68
Pictures or Drawings (2D; 3D); Diagrams; Blueprints; Graph; Map		
(3) Verbal	12	0
Example (instructions)		
(4) Abstract	3	14
Idea; Representation; Theoretical model; Mathematical model		
Type of thing modeled		
(1) Objects	91	86
Clothes; Buildings; Airplanes		
(2) Abstractions	9	5
Ideal behavior; An idea (of how to build); A concept or species (model of a frog. . .)		
Relationship		
(1) Exactly alike	15	9
(2) Visually similar	3	5
(3) Alike, except different scale	42	77
(4) Relationally similar (works the same)	6	14
Awareness of modeler (mentions modeler spontaneously in describing models)	12	5
Other	0	5

Table 2
Classification of Student Answers to Questions about the Purpose of Models

Collapsed: Mixed 7th (*N* = 33)	Collapsed: Honors 11th (*N* = 22)	Classification	By item: Mixed 7th (*N* = 33)	By item: Honors 11th (*N* = 22)
61	82	Communication		
		(1) unelaborated	6	5
		(2) to show an object—what it looks like or is going to look like	52	50
		(3) to show an action—what it does, how it works	18	23
		(4) to show an idea	3	0
		(5) to teach, to help someone understand	6	41
		(6) to get a message across, a specific purpose or point; may have different models depending on the purpose	0	14
52	27	Observation		
		(1) unelaborated	0	5
		(2) to look at, to watch	30	18
		(3) to touch	3	5
		(4) to play with	24	0
52	14	Making, building		
		(1) unelaborated	12	14
		(2) to put together, to make	36	0
		(3) to build something	3	0
33	59	Learning, understanding		
		(1) unelaborated	27	36
		(2) to learn about what something looks like	15	9
		(3) to learn about how something works, functions	6	23
		(4) to help understand and form an explanation about why it works	3	14
36	41	Testing		
		(1) unelaborated	3	14
		(2) to test, to try something out on an object and what happens	12	14
		(3) to test, to try something out on an object—can revise the object	9	0
		(4) to test, try out before the "real" one is finalized	15	14
		(5) to test what would happen in different situations	0	9
		(6) to test an idea	3	0
58	41	Reference or example		
		(1) unelaborated	3	0
		(2) reference—it shows you something, you refer to it (e.g., a map shows you how to get somewhere)	15	14
		(3) plan, blueprint, guide, instructions—it shows you what you are supposed to do or what you are going to make	12	14
		(4) example, demonstration—it demonstrates or enacts what to do (can be a person/role model, object, or procedure)	42	23
21	86	Accessibility or Clarity		
		(1) unelaborated	0	5
		(2) to make more accessible or convenient to see or use by changing location, time, size, by using different media, or by having different views, or angles	21	77
		(3) to make something more clear, easier to understand by highlighting, simplifying, omitting	0	23

Note. The "by item" column shows the percentage of students who replied to a given question or set of questions in a particular way. The "collapsed" column shows the percentage of students who replied in at least one way within a particular category.

Table 3

Classification of Student Answers to the Initial Question about Designing and Creating Models

Collapsed: Mixed 7th (N = 33)	Collapsed: Honors 11th (N = 22)	Classification	By item: Mixed 7th (N = 33)	By item: Honors 11th (N = 22)
61	59	What the real thing is		
		(1) unelaborated	27	36
		(2) has to be close to exact, proportionate, size, shape (as possible)	30	32
		(3) pay attention to basic shape, attributes	3	0
		(4) pay attention to how the real thing works; relations	9	9
6	9	The model itself		
		(1) unelaborated	0	5
		(2) what you want the model to look like	3	0
6	36	General criteria in model building		
		(1) simplicity	0	14
		(2) validity	3	23
		(3) match with purpose	3	14
12	50	Communication		
		(1) unelaborated	0	5
		(2) what you're trying to get across	3	9
		(3) understandable/clear to self or others	6	41
		(4) do not mislead others	3	5
		(5) viewer's perspective (put yourself in other person's shoes)	3	18
30	9	Modeler's role		
		(1) unelaborated	3	0
		(2) passive (copies)	9	0
		(3) active (makes choices)	9	5
		(4) concentrate, know what you are doing	12	5
6	0	Other		

Note. The "by item" column shows the percentage of students who replied to a given question or set of questions in a particular way. The "collapsed" column shows the percentage of students who replied in at least one way within a particular category.

real thing. Although this was the most popular response for the mixed-ability 7th graders, the most popular response for the honors 11th graders was that the model should be understandable to yourself and/or others. Here again, the honors 11th graders demonstrate a greater explicit concern with the communicative capabilities of models. Not only were honors 11th graders far more inclined to talk about the importance of a model being understandable, they were also beginning to be aware of some general criteria for model making (e.g., validity and simplicity).

Table 4: Designing and creating models (continued). Table 4 summarizes students' answers to the questions: "How close does a model have to be to the thing itself? How do you know what's important to include?" About half of both groups thought that the model should be exact, smaller, or proportional to the real thing and that one decides what to include by considering "basics and details" or what is "major and minor." Honors 11th graders were more likely to elaborate on the meaning of "major and minor" in terms of the importance of "the main idea." Three-quarters of the honors 11th graders thought that "what you're talking about or working on" is important, whereas only 15% of the mixed-ability 7th graders explicitly referred to this sense of purpose. The mixed-ability 7th graders talked mainly about including or scaling physical attributes and reflected less on why one would do this.

Table 5: Changing a model. Table 5 summarizes students' answers to the question: "Would a scientist ever change a model?" The overwhelming majority of students agree that a scientist could change a model. There are some differences, however, in the ways both groups describe the conditions leading to such a change. The mixed-ability 7th graders remained rather vague, saying that they would change the model if it "wasn't right" or something was "wrong." They were also more likely than the honors 11th graders to say that a model would be changed if the reality itself changed.

The honors 11th graders had more to say in response to this question. About half of the honors 11th graders said that models would be changed in light of new information that showed the model to be wrong and they could articulate some ways that this new information could be found, i.e., through research, experimentation, or discovery. It is important to note, however, that the honors 11th graders did not imply that the model itself would be used in any way for this research.

Table 6: Multiple models. Table 6 summarizes students' answers to the question: "Can a scientist have more than one model for the same thing?" Again, both the mixed-ability 7th and honors 11th graders thought that this was possible, with the majority of both groups saying that the scientist could have different views of the same entity. Although the honors 11th graders had more to say than the mixed-ability 7th graders, most of the time, both groups meant that one would have a literally different view, i.e., of the inside or the outside or a view from a different angle. In addition, about a third of the honors 11th graders also thought one could emphasize different aspects of the entity—omitting or highlighting certain things to provide greater clarity (e.g., showing the blood vessels or the skeleton of the human body). Thus, the honors 11th-grade theme of clarifying and making things accessible first encountered in the question about the purpose of models is echoed in the responses to this question. It was rare for students to say that there could be different models to explain or conceptualize something. No student spoke of using different models to test rival hypotheses; the few students who mentioned testing referred to testing different versions of a real thing to see which worked.

Table 4
Classification of Student Answers to Further Questions about Designing and Creating Models

Collapsed: Mixed 7th (N = 33)	Collapsed: Honors 11th (N = 22)	Classification	By item: Mixed 7th (N = 33)	By item: Honors 11th (N = 22)
52	45	Should be exact, smaller, proportional		
		(1) unelaborated	36	36
		(2) pretty close, almost exact	15	18
18	9	Depends on the view		
		(1) need what you see	9	0
		(2) inside/outside, physical perspective inside/outside	12	9
48	45	Depends on what is major/minor, basics/details, little things/big things, main things		
		(1) unelaborated	39	27
		(2) basic shape (and other as above)	9	5
		(3) different views or aspects of same entity (implies omission of some things to provide greater clarity)	6	9
		(4) main idea (captures essentials of the subject)	6	27
15	73	Depends on what you're talking about, working on		
		(1) unelaborated	9	23
		(2) subject	6	32
		(3) get the message or point across	0	23
		(4) suit the purpose	6	27
3	5	Things for how it runs and functions, how it works, whether anything's going wrong, dynamics		
6	14	Other		

Note. The "by item" column shows the percentage of students who replied to a given question or set of questions in a particular way. The "collapsed" column shows the percentage of students who replied in at least one way within a particular category.

Table 5

Classification of Student Answers to Questions about Changing a Model

Collapsed: Mixed 7th (*N* = 33)	Collapsed: Honors 11th (*N* = 22)	Classification	By item: Mixed 7th (*N* = 33)	By item: Honors 11th (*N* = 22)
21	0	Unelaborated mention of something being wrong, not right		
39	18	Something wrong with model or how model was made		
		(1) unelaborated	21	5
		(2) something missing, not enough info, needs part, or something added that wasn't necessary	6	9
		(3) doesn't work (right), doesn't function	12	9
		(4) doesn't match reality, or what you want to make	9	5
		(5) test of model leads to change	3	5
39	82	Model not right because new information is found		
		(1) unelaborated	15	27
		(2) new info found through research, experimentation, or discovery (implies model was not used for finding this information)	0	45
		(3) new info has to be incorporated into the model, and specific example given (e.g., smaller particle in atom discovered, so make new/revise old model)	0	9
		(4) the thing itself/reality changed	15	0
		(5) found out idea wasn't right (vague)	3	14
		(6) model talked about in context of new or changing ideas and thoughts	6	14
		(7) someone else thinks its not right	3	5
12	0	Yes, for aesthetic reasons		
		(1) unelaborated (don't like it, want to make it look better, just want to change it)	12	0
		(2) someone else doesn't like it (e.g., boss)	3	0
9	32	Yes, model changes in accordance with how purpose or need was matched		
		(1) unelaborated	6	14
		(2) model must have what you need, suit need	3	5
		(3) to get some result or what you want (technologically speaking)	3	14
		(4) to test out or explore new idea	0	5
9	0	Other or "No"		

Note. The "by item" column shows the percentage of students who replied to a given question or set of questions in a particular [...] students who replied in at least one way within a particular category.

Table 6
Classification of Student Answers to Questions about Multiple Models

Collapsed: Mixed 7th (*N* = 33)	Collapsed: Honors 11th (*N* = 22)	Classification	By item: Mixed 7th (*N* = 33)	By item: Honors 11th (*N* = 22)
3	5	Unelaborated "yes"; there can be more than one		
45	73	Yes, to show different views of the same entity		
		(1) unelaborated	3	5
		(2) literally different views, different angles, inside/outside	24	55
		(3) different aspects (implies omission of some things to provide greater clarity or highlighting)	12	32
		(4) different levels of detail	9	18
9	9	Two or more different ideas or ways of explaining "it"		
		(1) unelaborated	3	5
		(2) different opinions or theories	6	5
15	18	Yes, there are different ways to show or represent the same thing		
		(1) unelaborated	6	0
		(2) same idea/subject	9	14
		(3) different mode/medium/symbols (e.g., visual rather than verbal, 3D rather than 2D)	3	5
15	9	Yes, you can make different models to test an entity		
		(1) unelaborated	3	5
		(2) different versions to see which is best, which works	9	5
		(3) make the same one again, make sure it works	3	5
12	0	Other		

Note. The "by item" column shows the percentage of students who replied to a given question or set of questions in a particular way. The "collapsed" column shows the percentage of students who replied in at least one way within a particular category.

Analysis of the Expert Responses

The purpose of the analysis of expert responses was to confirm that sophisticated answers could be elicited through the interview and to gain insights into the major differences and similarities among expert and student answers.

The answers expressed by the experts both coincided with some of the student responses and, not surprisingly, contained ideas which were altogether missing from the student interviews. The sheer volume of talk given by the experts was noticeably different: a student interview averaged about 6 pages of transcript, and an expert interview averaged about 15 pages in length. The adults had obviously thought about many of our questions previously, as their professions required, and hence articulated many ideas they had formulated before the interview. More sophisticated follow-up questions could thus be (and were) asked of the experts. However, none had been given a copy of the interview questions before hand, and there were times when particular follow-up questions sparked some thoughts they had not previously entertained.

Kinds of models. There was a striking difference between the expert and student responses when they were asked about what the word "model" brings to mind and whether they think there might be different types of models. All of the experts generalized about types of models, in that they fell into two basic categories: physical models that can be physically handled, and abstract models including mathematical equations and mental images. In contrast, at most only 14% of the total student sample referred to any abstract models at all, whereas virtually all of them talked about the physical type of model.

Purpose of models. The experts unanimously said that models existed as aids to understanding phenomena. Furthermore, they reported that this understanding can be checked or verified by comparing the results obtained by manipulating the model to observations obtained in the real world.

None of the students articulated a view that points as clearly to the use of models in helping the construction of scientific knowledge, although a few students had ideas that sounded similar to pieces of the expert view. Three percent of the mixed-ability 7th graders and 14% of the honors 11th graders mentioned that a model could help you understand and form an explanation about why something works. Some of the students (27% and 36%, respectively) mentioned some aspect of learning or understanding but did not elaborate what this meant.

Students were truly lacking the notion that one's understanding of phenomena can be tested by comparing the implications of the model to actual measurements or observations. Rather, students see models as communicating knowledge in a more accessible way. Any testable ideas are more akin to testable designs of objects than they are to testable formulations about the behavior of natural phenomena.

Designing and creating models. All the experts agreed that a primary guideline for making a model is to consider its purpose. Two of the experts were very specific about the kinds of purposes a model might serve and how the model's design would consequently be affected. They suggested that purposes would be mediated by the extent of one's interest in structure, function, explanation, precision, predictive power, communication, and/or scope. In contrast, only 3% and 14% of mixed-ability 7th and honors 11th graders (respectively) spontaneously said that the model should be designed with its purpose in mind. In general, mixed-ability 7th graders were more concerned with keeping the "real thing" in mind, and the honors 11th graders with the model's being understandable. When pushed to explain how they would know what was important to include in a model, the honors 11th graders were more apt to consider the model's purpose, whereas the mixed-ability 7th graders continued to be more focused on physical attributes and details of the real thing.

Multiple models for the same thing. All experts thought a scientist could have more than one model for the same thing because different models could be used to address different specific interests or questions about the referent. (Most experts discussed the issue of compatibility across models, as well). Typically, questions would involve functional aspects of or explanatory frameworks for the referent. Two adults made the additional point that there could be several competing models for the same thing which, in turn, would carry different implications or make different predictions. Very few (9% and 9%) of the mixed-ability 7th and honors 11th graders even hinted at this sense of multiple models by saying that there could be two or more ways of "explaining it."

Changing a model. None of the experts hesitated to say that scientific models could change, but there were some differences in how they focused their responses. Two of the four strongly stated that changing a model was not only possible, it was inevitable. One stated, "If we take the suggestion seriously that basically science is the game of predictive and explanatory model building and testing, then it almost is a point of definition that that's the case [i.e., models change]." The two other experts commented, more generally, that a model would be replaced by a better one (i.e., a better tool for answering questions) or by one that incorporated newer, more appropriate mathematics. Although the student ideas are somewhat consistent with expert views, they do not convey the sense in which models would be changed to aid our interpretation of reality. Most honors 11th graders thought that models could change if new information was found, and mixed-ability 7th graders were likely to think that a model could change if it wasn't made correctly. Thus, for students, changing a model is a matter of adding new information or replacing a part that was made wrong.

In summary, experts agree that (a) there are both physical and abstract models, (b) models help us understand or think about phenomena, (c) the validity of a model can be tested by comparing its implications to observations and measurements in the real world, (d) different models of the same phenomenon can be built to accommodate different purposes, and (e) scientific models can be replaced by better ones. Students tended to think that (a) models are physical or visual in nature, (b) they show or help communicate information about real things, (c) different models of the same thing show literally different aspects of real things, and (d) scientific models can change if they are made wrong or if new information is found. Thus, the experts tended to talk about models in terms of actively formulating and testing our ideas about reality, whereas students tended to point to a more immediate transparency between reality and models.

The Application of Criteria Analysis

One might argue that if one has a strong conception of what models are then one should have some articulated criteria that can be applied or at least considered across any number of instances. Here we analyze whether students and experts consistently used particular criteria for deciding whether certain physical items were models. Subjects were given a small metal toy airplane, a photograph of an old house, a schematic map of the Boston subway system, and a diagram of the water cycle from a middle school science textbook. All subjects were asked whether they could call each item a model, and to explain their answers. We then categorized their reasons and tallied the number of times they used the same criterion across items.

Only about half of each group (58% of mixed-ability 7th graders and 50% of honors 11th graders) applied a consistent criterion across three or more items, whereas all of the experts applied at least one criterion across all four items. This may mean that half of the students in each group do not have consistent notions of what models are; they invoked different criteria depending on what item they were shown.

There is a difference in the types of criteria that students in the two groups apply consistently. Among those students who did apply a consistent criterion, almost half (45%) of the honors 11th graders but none of the mixed-ability 7th graders appealed to whether the item would "help you," i.e., whether the item explained, simplified, taught you things, or made the real thing easier to understand. In contrast, almost half (42%) of the mixed-ability 7th graders and 9% of the honors 11th graders simply considered whether the items showed the real thing and its parts.

Other criteria were invoked by both the mixed-ability 7th and honors 11th graders, although less often. These included considering whether the item was a replica or miniature (16% and 9%, respectively), a representation per se (of something real) (16% and 18%), and whether it was three-dimensional and touchable or a two-dimensional picture or diagram (21% and 18%). In addition, a small number of honors 11th graders considered the item's accuracy needed for its purpose (9%), and if it could be used to design something, make something better, or see if it would work (also 9%).

Three of the adults consistently considered whether the item was itself a representation or not. The fourth adult (and one of the previous three) evaluated whether the item could be used to answer questions or obtain useful information.

Levels of Understanding Analysis

We could identify three general levels of thinking about models, reflecting different epistemological views about models and their use in science. The levels summarize the kind of understandings and conceptions of models that emerged from the interview as a whole. The three general levels differ in how one describes the relationship of models to reality and the role that ideas play with respect to models.

In a general level 1 understanding, models are thought of as either toys or simple copies of reality. Models are thought to be useful because they can provide copies of actual objects or actions. If students acknowledge that some aspects or parts of the real thing can be left out of the model, they do not express a reason for doing so beyond the fact that one might want or need to.

In a general level 2 understanding, 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.

Finally, a general level 3 understanding is characterized by three important factors. First, the model is now constructed in the service of developing and testing ideas rather than as serving as a copy of reality itself. Second, the modeler takes an active role in constructing the model, evaluating which of several designs could be used to serve the model's purpose. Third, models can be manipulated and subjected to tests in the service of informing ideas. Thus, they provide information within a cyclic constructive process.

General levels were assigned to students based on six separately scored dimensions. These six dimensions concern (a) the role of ideas, (b) the use of symbols; (c) the role of the modeler, (d) communication, (e) testing, and (f) multiplicity in model building. Students were scored as providing a level 1, 2, or 3 answer for each dimension. These scores, in turn, were used to derive a general level score for each student. A general level score is either "pure" or "mixed." A student scoring at the same level across five or six dimensions was considered "pure." Students scoring at one level across two, three, or four dimensions and the adjacent level for the remainder of the dimensions was given a "mixed" level score. Mixed level scores always involved adjacent levels. Three of the authors conducted the interviews and each scored approximately one third of the student interviews, assigned randomly. Twelve interviews were scored twice, independently by two researchers. Agreement in scoring levels of understanding was found to be 84%, a higher level than was attained by Carey et al.

Using this scheme, we found the majority (67%) of mixed-ability 7th graders had pure level 1 scores. Only 12% of the mixed-ability 7th graders had pure level 2 scores and 18% had mixed level 1/2 scores. Only 23% of the honors 11th graders had pure level 1 scores. The rest were divided evenly between the mixed level 1/2 (36%) and the pure level 2 (36%) scores. No student in either grade received enough level 3 scores to be given a mixed level 2/3 score. All of the expert interviews resonated with the three themes that we took as providing a general level 3 understanding. There were also interesting differences in the ideas with which each expert seemed most engaged. For example, one expert spoke about finding phenomena which would fit a new model or new mathematics. Another expert discussed how different representational codes might bear on a model's meaning.

Discussion

In this study, we have begun to assess students' conceptions of models and how models function in science by administering a clinical interview about models to a group of mixed-ability 7th and honors 11th grade students. The results appear promising in that (a) students do appear to have preconceptions about models, (b) certain themes regularly recur in individual interviews, (c) there are some interesting differences in the themes of mixed-ability 7th and honors 11th grade students, and (d) there are many differences between student interview themes and those of experts.

Implications for Understanding Students' Epistemologies of Science

As mentioned earlier, Carey et al. (1989) interviewed seventh graders about their

students' ideas about the nature and relationship of hypotheses, experiments, and unexpected results. Three different viewpoints were distinguished. In the present study, we have interviewed students about models and their use in science and have also identified a three-level series of viewpoints. Although our three levels may differ in nuance and specific detail from the three levels proposed by Carey et al., the two series do seem conceptually parallel.

In both our data and Carey's pretest data, the typical 7th grader exhibits a viewpoint that is consistent with a simple copy theory epistemology (level 1). Although students with a level 1 viewpoint about models do make some distinction between the model and the thing modeled, the students still essentially think of models as little copies of real-world objects. They believe that the purpose of the model is to be like the real thing and only vaguely appreciate that models may be wrong, i.e., when they do not work, are made wrong, or do not have enough information about the real thing in them. Thus, the level 1 student does not clearly distinguish the ideas and/or purposes underlying the model, the model itself, and the experimental data which would support or refute the validity or usefulness of the model. In a similar way, the level 1 student in the system of Carey et al. has a conception of an experiment that does not distinguish the hypothesis underlying the experiment, the experiment itself, and the data that would support or refute the hypothesis.

Because interviews in Carey et al. were given only to mixed-ability 7th graders, we cannot directly compare our data about 11th-grade honors students' conceptions of models to data about their general conceptions of science. We have found, however, that a number of honors 11th graders have what we describe as a level 2 viewpoint about models. At level 2, students distinguish between the ideas and/or purposes motivating the model and the model itself, and realize that the purpose of the model dictates some aspect of the form of the model. Further, level 2 students talk about how experimental evidence might show you that some aspect of your model was wrong and needs to be changed, and they imagine in a limited way how a model might have to be revised. These findings seem consistent with the characteristic level 2 advances described by Carey et al. in which students distinguish hypotheses and experimental data.

Three features of our level 2 understanding of models suggest that the level 2 viewpoint is still not a sophisticated constructivist one. First, our level 2 students still fundamentally see models as representations of real-world objects or events and not as representations of ideas about real-world objects or events. Second, different models are thought to capture different spatiotemporal views of the object rather than different theoretical views. And third, students see models primarily as a means to communicate information about real-world events rather than as a means to test and develop their ideas or theories about the world.

Unlike the students who were interviewed about models, the experts articulated clear level 3 viewpoints with respect to models. In particular, experts believe models are constructed in the service of developing and testing ideas and explanations about phenomena. They believe the modeler actively evaluates which of several designs will best suit the model's purpose. And they believe that the model can be manipulated and subjected to tests that provide information about how the model may need to be revised. These level 3 themes are similar to the level 3 themes in Carey's nature of science work where the belief emerges that ideas can be developed, not just directly tested, through a cumulative and cyclic process of experimentation, evaluation, and

In sum, we believe our work extends Carey's work in three main ways. First, we have extended the range of populations studied to include 11th-grade honors students and experts. Our analysis of expert responses provided evidence that expert beliefs are consistent with level 3 viewpoints. (Such viewpoints were hypothesized to exist when both coding systems were constructed but were virtually absent from gathered student reponses.) Second, although the 11th-grade honors sample was in many ways more sophisticated that the mixed-ability 7th-grade sample, it is instructive to see how far short the 11th graders still fell from the expert conception: in many ways the 11th-grade honor student's conception was closer in spirit to the 7th-grade conception. Third, for the 7th graders there is a consistency in epistemological position expressed across the two types of interviews.

Implications for Curriculum Development

The results of our student interviews suggest ways to build on student ideas for helping them develop a more sophisticated constructivist epistemology. First, it seems easier for students to make a distinction between models and the thing modeled than for them to grasp the distinction between scientists' ideas and the reality those ideas are about. This distinction is possibly easier to make because many models are themselves tangible and can be directly observed and compared with their referents. Second, it seems that prior to understanding the role of interpretative or theoretical frameworks in model construction, students understand that model construction is influenced by certain intentions and purposes and that there can be multiple models for a given reality. These purposes include teaching, highlighting, explaining, and communicating rather than simply playing or showing. Thus, giving students chances to use or design models for multiple purposes may be a natural way to lead them to reflect on a variety of epistemological concerns including the purpose of one's inquiry, the nature of what one wishes to communicate, explain, or understand, how one is informed, and the interplay between reality and one's ideas about it.

The interviews also revealed that, in general, students seem to have had very limited experiences with scientific models. When asked to give examples of models, the 7th graders rarely mentioned any type of scientific model, and often confused equipment such as microscopes and telescopes with models. At best, the 11-grade honors students gave some examples of standard textbook models such as the diagrams of atoms and the circulatory system. It appears that the 11th-grade honor student's greater educational experience did not in fact lead the students to become more familiar with models as "testers" of interpretive frameworks, as bases from which to draw inferences and make predictions, nor as aids for forming explanations of phenomena. Rather, these students have retained that models basically transmit information about the world as it really is and make such information more understandable.

Clearly, if we want students to develop a richer conception of models, then it is important for the science curriculum to provide students with more extensive experiences with models and more time to reflect about those experiences. In light of what we have learned about student preconceptions, we identify some experiences we believe are particularly important to provide. First, it is important to provide students with experiences using models to solve intellectual problems. In this way students would have the opportunity to learn that a model can be used as a tool of inquiry and that it is not simply a package of facts about the world that needs to be memorized.

Second, students need experiences with multiple models of the same phenomena and with revising and/or modifying models as they encounter new phenomena. In presenting multiple models, it is especially important to think, of models that do not just provide physically different spatiotemporal views of the object but different conceptual vantage points. In this way, students may come to realize what a conceptual vantage point is and how it can influence one's thinking. It could be useful to encourage students to develop models that reflect their own conceptual vantage point as well as to present them with models developed by others. In the course of recognizing multiplicity, the problem of developing criteria for mediating among the diversity also arises. Students can see how models must be evaluated in part in terms of one's purpose and also how, given a single purpose, there can be several valid models for the same phenomenon. Also, in pursuing a sustained investigation across a variety of related problems, students have the opportunity to consider how well a model handles not just what one wishes to communicate but also one's questions and predictions about phenomena. This experience would further provide an opportunity to consider the importance of the scope and predictive and explanatory power of a model in its overall evaluation.

Finally, we feel students not only need extensive experience playing with and working with models but also reflecting on the nature of models themselves. Thus some class time is needed for verbalizing "metaconceptual" lessons about models embodied in the curriculum.

Future Directions and Further Work

We now see ways that our interview could be modified in order to (a) test whether more sophisticated answers could be elicited from students; and (b) further test our description of the three levels of understanding models. In order to probe student understandings of abstract models, we plan to provide students with a richer set of examples to work from and think about, including mathematical equations and graphs. We will also probe student conceptions of predictive and explanatory models more thoroughly. We plan to give the Carey et al. nature of science interview and our nature of models interview to the same students, to further investigate the consistency of student epistemologies of science across tasks. It will be interesting to discover in further work how far secondary students would be able to progress in their understanding of the constructive nature of science when provided with innovative curricula designed to build on their current insights about models.

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