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On Understanding the Nature of Scientific Knowledge

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One important goal of science education is to help students understand the nature of the scientific enterprise itself. We review data from several sources, indicating that middle school and high school students have a common sense epistemology of science at variance with the constructivist epistemology we advocate as the appropriate curricular goal. We sketch the student epistemology and discuss two attempts to induce changes in it through science education.

One important curricular goal of science education is to help students understand the nature of the scientific enterprise itself. This goal is important for several reasons. First of all, students can master only a small fraction of scientific knowledge in the course of their schooling, but as citizens they must adopt positions on public issues that turn on controversial points. Hence, the successful science curriculum will have fed an interest in science that underlies lifelong learning, a valuing of the kind of knowledge that is acquired through a process of careful experimentation and argument, as well as a critical attitude toward the pronouncements of experts. Involving students in the process of doing science and talking with them explicitly about its nature are thought to be central to cultivating these interests, values, and attitudes.

In addition, another quite different reason for teaching students about the nature of science has recently come to the fore. Because students come

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to science class with theories and concepts that are different from the scientists', the successful science curriculum will have involved students in making difficult conceptual changes. An open question is the relation between student understanding of the nature of scientific knowledge and student success in learning from curricula designed to foster conceptual change. Making students aware of the process of conceptual change may help them succeed at it.

Exactly what view of the nature of science do we wish to give to students? It is common practice for current textbooks to portray scientists as engaged in a process that depends on careful observation and experiment and to teach students some of the skills involved in careful experimentation. However, overlooked in these accounts is any discussion of the role of the scientists' theories in this process. Instead, mention is only made of scientists' specific hypotheses or beliefs about the world. In some accounts, these hypotheses are seen to be a simple consequence of unbiased observation and experiment, whereas in others it is acknowledged that scientists may have hypotheses that motivate their doing a particular experiment. However, in both cases, these hypotheses are thought to be tested in unproblematic and straightforward ways by the data of critical experiments, and scientific knowledge is portrayed as the steady accumulation of a set of confirmed hypotheses. As Hodson (1985, 1988), Nadeau and Desautels (1984), and Strike and Posner (1985) claimed, such a view is essentially an inductivist or empiricist view: The origin of scientific knowledge lies solely in data about the world.

We argue (along with the just-mentioned authors) that it is important to present students with a more constructivist epistemology of science: one in which students develop an understanding that scientists hold theories that can underlie the generation and interpretation of specific hypotheses and experiments. We want them to come to understand that our knowledge of regularity in nature is a consequence of successful conjecture, rather than its precursor, and that an adequate theoretical perspective is essential to both observation and experimentation. Thus, without challenging students' faith that theories may ultimately reflect reality, we may be able to help them see that theories are large-scale intellectual constructions that constitute the scientists' understanding and guide the day-to-day activities of scientists. Such an understanding would help students understand why scientists do experiments, why there can be legitimate controversies in science, and even why learning science is difficult.

In this article, we first review the evidence that seventh-grade students come to science class with an epistemology that is at odds with the constructivist epistemology we wish to teach. We then go on to consider how that epistemology is changed as a consequence of an explicit attempt to teach them about the constructive nature of science.

STUDENT EPISTEMOLOGY

Hodson (1985, 1988) and Nadeau and Desautels (1984) assumed that the existing science curricula reinforce students' own common sense views about the nature of scientific knowledge: one that sees knowledge acquisition driven solely by the data at hand. But what is the evidence for this assumption? Surprisingly, most of the evidence regarding this point is indirect. In this section, we review the evidence from three quite separate literatures that potentially can bear on this issue.

Common Sense Epistemology

The first literature concerns common sense epistemology in general, not particularly an epistemology of science. Several authors have used clinical interviews to probe adolescent and adult views of the nature of knowledge and its source and justification (e.g., Broughton, 1978; Chandler, 1987; Kitchener & King, 1981; Kuhn, Amsel, & O'Loughlin, 1988; Perry, 1970). Emerging from these clinical interview studies is some consensus on the stages ordinary people go through in developing their epistemological views, although the exact number of stages and the timing of transitions has been subject to some dispute. In reviewing this literature, we focus on two related developments that we regard as important: a conception of a theory or interpretative framework and an appreciation that theoretical knowledge is acquired through indirect arguments from evidence.

Relating to the first theme, some have claimed that young children begin with a common sense epistemology in which they see knowledge arising unproblematically (and directly) from sensory experiences and see knowledge as simply the collection of many true beliefs (e.g., Chandler, 1987; Kitchener & King, 1981; Kuhn et al., 1988). At this point, there is no notion that beliefs themselves are organized in intuitive theories or interpretative frameworks or that one's intuitive theory can influence one's beliefs and observations.

A study by Kuhn et al. (1988) provides support for this claim. They presented subjects with two accounts of a fictitious war called the Fifth Livian War, told by a historian from each of the different sides. In each account, the two historians, among other things, each claimed victory for their side. Subjects were then asked to describe in their own words what happened in the Fifth Livian War, whether the two historians' accounts were different in any important ways, and whether both accounts could be right.

Responses were coded into six stages: All sixth graders and over three quarters of the ninth graders were at the lowest three stages. A key feature of the lowest stages is that students show no awareness of "theoretical interpretation as having played a role in the construction of the accounts and as a vehicle for reconciling them" (Kuhn et al., 1988, p. 213). Instead they deal primarily on the level of objective fact, at most seeing the accounts as differing in the facts chosen for presentation. This may be due to the historians being in different places at different times or having had different motives or purposes (i.e., they may have lied or exaggerated to make their side look good). However, students at this point still assume there is a simple truth to the situation which can be known to a careful impartial observer.

In contrast, older adolescents, college, and graduate students tended to be at the highest three stages. At these stages, students are increasingly aware that the two historians have different points of view and that determining the reality of the situation is not so simple as determining who lied and who told the truth. Some believe there may in fact be multiple individual realities, whereas others acknowledge an elusive objective reality that can only be known approximately.

At the same time children are moving from a common sense epistemology that sees knowledge arising unproblematically from observations to one that sees a role for interpretative frameworks in knowledge acquisition, they are also developing more complex conceptions of how beliefs are justified. This point is nicely illustrated in Kitchener and King's (1981) studies. Like Kuhn et al. (1988), Kitchener and King presented students with dilemmas about differences of opinion; one difference was that they then probed students about how they would decide what to believe. They found that the younger adolescents justified beliefs primarily in terms of perceptual experiences or what they were told by authorities. Sometime in late adolescence (especially for students who go to college), students become aware of genuine differences in the interpretation of the same facts and, consequently, that even authorities may disagree. This leads to an epistemological crisis, a period in which students are radical relativists and hold there is no true knowledge and everybody is free to believe whatever they want. Finally, in the college years, some people reach a mature epistemology that not only recognizes the relativity of belief to interpretative frameworks, but also recognizes that there are canons of rational justification of belief. Beliefs need to be justified in terms of arguments from patterns of data, and some beliefs are better justified than others.

Although these data certainly indicate likely differences between the epistemological beliefs of young adolescents and adults, other data indicate that these authors may not have done full justice to the complexity of the beliefs of young adolescents. For example, in Kuhn et al.'s (1988) earliest stage, it is asserted that students fail to make a distinction between the account of an event and the event itself; similarly, in Kitchener and King's (1981) earliest stage, there is no awareness that one's own beliefs can be false or different from an expert's. Both of these stages are thought to characterize a number of young adolescent children. Yet, there is now very good evidence (using a different methodology that calls for less formal and verbalized understandings) that even 3-year-olds can make distinctions between their beliefs about reality and reality itself and understand that people can have false beliefs (see, e.g., the work of Wellman, 1990).

Another example of an oversimplification in Kitchener and King's (1981) account of early adolescent epistemology concerns their claims that students view perceptual experience and expert testimony as the sole sources of belief and that students do not realize that the same facts can be given different interpretations or that there can be legitimate differences in opinion. Again, however, there is now good evidence that even 6-year-olds understand that inference is a genuine source of knowledge (Sodian & Wimmer, 1987). In addition, Taylor, Cartwright, and Bowden (1991) showed that by age 6, children are beginning to understand that the same visible stimulus might be interpreted differently by different people, depending on their background knowledge. (Although presumably only one interpretation is right; the other interpretations are wrong due either to misinformation or ignorance.) Finally, Flavell, Flavell, Green, and Moses (1990) demonstrated that even 3-year-olds are aware that people can have differences of opinion especially about questions of value.

An adequate characterization of young students' epistemology must integrate findings from these diverse methodologies. Appendix A sketches our preliminary attempt to give a richer account of students' early epistemology and to contrast it with a later epistemology which makes clear use of a notion of theory. Both are constructivist epistemologies in the sense that they acknowledge that one's present beliefs can affect one's observations and subsequent knowledge. And both are realist in the sense that both assume the existence of an objective reality. However, in the first (dubbed *knowledge unproblematic*), it is assumed knowledge of reality can be obtained with enough diligent observation, whereas in the second (dubbed *knowledge problematic*), reality can be known only through successive approximations via a process of critical inquiry. We offer these, tentatively, as the beginning point and one relatively sophisticated possible endpoint for school-aged children's epistemologies. Clearly, there are many intermediate steps between these two points.

Process Skills

The second literature that bears indirectly on students' epistemology of science concerns attempts to construct scientific arguments. These are studies of the so-called science process skills (e.g., Dunbar & Klahr, 1989; Inhelder & Piaget, 1958; Kuhn et al., 1988). Many studies show that preadolescents and young adolescents do not appreciate the logic of argumentation from experimental results. Dramatic deficiencies in designing experiments and/or drawing conclusions from experimental evidence are amply documented in Inhelder and Piaget's (1958) classic work exploring the development of scientific reasoning and in more recent work by Kuhn et al. (1988) and Dunbar and Klahr (1989).

There may be at least two distinct deficiencies underlying children's problems on such tasks. On the one hand, students may genuinely lack knowledge of aspects of the logic of hypothesis testing. For example, Kahneman, Slovic, & Tversky (1982) documented errors in statistical reasoning that are made even by quite sophisticated adults. On the other hand, students' difficulties may in part reflect their commitment to a naive epistemology that makes no clear distinction between theory, specific hypothesis, and evidence. Such an epistemology leads them to expect a more direct relation between hypothesis and experiment than exists, to overlook the role of auxiliary assumptions in testing hypotheses, and to reach more certain conclusions from their data than the data in fact allow. In this way, some of the literature on deficiencies in process skills may indirectly support the existence of the knowledge unproblematic epistemology of young children.

Kuhn et al. (1988) reported a series of studies in which they looked at students' abilities to modify their initial theories (e.g., about the causes of colds) in light of experimental evidence that was presented to them. Subjects of all ages, even adults, found their tasks difficult. That is, even lay adults were poor at drawing proper conclusions from patterns of statistical evidence. However, Kuhn et al. also argued that the way young children responded indicated that they did not have a clear notion of theory which they distinguished from evidence. In particular, they noted that fewer than one third of the sixth graders spontaneously referred to evidence when answering whether the scientist's data showed that a given variable makes a difference to some outcome. What subjects did instead of referring to the evidence was to restate their theory or elaborate it with a mechanism. When the evidence was at odds with their theory, only graduate students were likely to distinguish what they thought from what the scientists' evidence showed. Instead subjects changed their hypotheses and only later mentioned evidence. When their theory was compatible with the evidence, Kuhn et al. (1988) described the subjects as regarding the evidence as "equivalent to *instances* of the theory that serve to illustrate it, while the theory in turn serves to explain the evidence. . . . The two meld into a single representation of 'the way things are' " (p. 221).

We believe Kuhn et al.'s (1988) findings are consistent with young adolescents' knowledge unproblematic epistemology: one in which they do not yet distinguish between theory and belief and one in which they do not yet see the importance of indirect, multistepped arguments in specific hypothesis testing. At the same time, note that the kinds of findings just presented, although consistent with this hypothesis, do not provide strong evidence for it, for two reasons. First, it is hard to disentangle how much of their difficulty is with the specific statistical inferences they are asked to draw and how much is because of their holding the more limited epistemology which makes it hard for them to appreciate what it means to test a hypothesis. Second, note that the studies do not assess a concept of "theory" in the sense of an interpretative framework; the theories tapped by these studies are simply beliefs about causal relations among single variables.

Epistemology of Science

A third literature derives from more direct study of students' verbalizable epistemology of science. Two of the most ambitious standardized tests (Test of Understanding Science, Klopfer & Carrier, 1970; the Nature of Scientific Knowledge Scale, Rubba & Anderson, 1978) probe for an understanding of science as a set of theories built up through a process of critical inquiry. Results reveal that young adolescents have much to learn about science in this regard but make steady progress toward such understanding throughout secondary school and college, especially as a result of specific instruction (Rubba & Anderson, 1978). However, these standardized tests were not designed to probe for the existence of an alternative epistemology in students. To remedy this limitation, two clinical interviews of seventh-grade students' epistemology of science were conducted.

In the first study, students were asked about the nature and purpose of science, the role of experiments in a scientist's work, and the relations among ideas, experiments, and results/data (see Carey, Evans, Honda, Jay, & Unger, 1989, for further details). Interview questions were divided into six sections, and students' responses on each section were coded into categories that reflected three general levels of understanding. Appendix B summarizes the three general levels that were coded in this study, ranging from Level 1, in which the goal of science is seen simply in terms of gathering specific facts about the world, to Level 3, in which the goal of science is seen in terms of a process of generating ever deeper explanations of the natural world.

Twenty-seven of the seventh-grade students were interviewed prior to their curriculum unit on the nature of science, and the overall mean level was 1.0. Only 4 students had an overall mean score over 1.5. Perhaps the most critical feature of Level 1 is the absence of an appreciation that ideas are distinct, constructed, and manipulable entities that motivate the scientist's more tangible experimental work. In Level 1 understanding, nature is there for the knowing. Accordingly, scientists "discover" facts and answers that exist, almost as objects "out there." Scientists' ideas themselves, however, are never the object of scrutiny.

In the second interview study (Grosslight, Unger, Jay, & Smith, 1991), researchers probed students' conceptions of science in quite a different manner, but the results were quite similar. Students were asked questions such as, "What comes to mind when you hear the word *model,* What are models for?, What do you have to think about when making a model?, How do scientists use models?," and "Would a scientist ever change a model?" In addition, a number of physical items such as a toy airplane, a subway map, and a picture of a house were presented, and the students were asked to explain whether these could be called models. As in the nature of science interview, three general levels in thinking about models were identified. These differ in how students talk about the relation of models to reality and the role of ideas in models. Appendix C gives a characterization of the dominant ideas at each level, ranging from a Level 1 understanding, in which models are seen as little copies of reality, to a Level 3 understanding, in which models are seen as tools used in the construction and testing of scientists' theories about the world.

In this study (Grosslight et al., 1991), both seventh and eleventh graders were interviewed. Levels were assigned based on six separately scored dimensions (the role of ideas, the use of symbols, the role of model makers, communication, testing, and multiplicity of models). Each student was given six scores, corresponding to each dimension. A student scoring at the same level across five or six dimensions was assigned that level; all students with mixed levels straddled two adjacent levels and were assigned mixed levels (e.g., Level 1/2). Using this scheme, Grosslight et al. found that the majority (67%) of seventh graders were at Level 1. Only 12% of the seventh graders were at Level 2, and 18% had Level 1/2 scores. Turning to the eleventh graders, Grosslight et al. found that only 23% were pure Level 1's. The rest were split evenly between Level 1/2 (36%) and Level 2 (36%).

Overall, the reliability in scoring the levels was moderate in Study 1 (74%) and quite high in Study 2 (84%). One problem in the first study was that the interview was not designed to clearly probe the difference between Level 2 and Level 3 understandings. In retrospect, this is a significant shortcoming, because both Level 1 and 2 understandings may fall within the knowledge unproblematic epistemology (described in Appendix A), whereas Level 3 calls for a more mature constructivist epistemology, closer to the knowledge problematic epistemology (described in Appendix A). Currently, revisions are being made to the interview and scoring system to handle these shortcomings. Although in both studies no students gave evidence of a Level 3 epistemology, some validation of its existence came from interviews of a group of expert scientists using the nature of models interview. All the scientists clearly showed Level 3 understanding.

Certainly further work is needed to clarify the nature of these levels and to determine how consistent student epistemology is, both within and across domains. For example, it is possible that students may be more advanced in their common sense epistemology than in their epistemology of science. Yet the results from the three different literatures are all consistent with the claim that seventh-grade students have an alternative epistemology that they bring to science class that is at odds with the constructivist epistemology that we wish to teach.

Levels and Development

Suppose that we have correctly characterized the junior high school students' common sense epistemology of science. Two questions of urgent importance to educators now arise. First, in what sense are these levels developmental? Is there something else we know about 12-year-olds that would help us understand these levels? Second (and distinctly), do these levels provide barriers to grasping a constructivist epistemology if such is made the target of science curricula?

We do not believe these levels reflect stages in Piaget's sense (see Carey, 1985a, for a review of these issues). That is, they are unlikely to reflect some other, more abstract, cognitive failing of the child. The approach we favor is to characterize knowledge acquisition and knowledge reorganization within cognitive domains. So, for example, we have characterized changes in the child's intuitive biology (Carey, 1985b) and in the child's intuitive theory of matter (Carey, 1991; Smith, Carey, & Wiser, 1985). We see epistemology as part of one such domain—an intuitive theory of mind—that has a specific developmental history (e.g., Wellman, 1990). Understanding why junior high school students have these particular epistemological views consists of understanding their construction of a theory of mind, a process that begins in infancy.

That the levels probably do not reflect stages in Piaget's sense does not mean that they do not provide important constraints on student understanding. Domain-specific knowledge acquisition often involves large-scale reorganization and genuine conceptual change (Carey, 1985b, 1991). It is an open question whether a transition from Level 2 to Level 3 epistemology requires such a reorganization. The levels are not yet well enough characterized to even hazard a guess. One source of evidence relevant to the issue is the success of curricula designed to foster this transition. Insofar as the curricular ideas are sound, the students' failure to grasp Level 3 ideas would suggest that Level 1 and Level 2 epistemologies provide constraints on understanding Level 3 points.

EFFECTS OF CURRICULAR INTERVENTION ON STUDENT EPISTEMOLOGY

At the junior high school level, curricular interventions concerning metaconceptual lessons about science have focused primarily on process skills. Although such skills are an important component of scientific inquiry, their mastery constitutes only a small part of the goals for student understanding of scientific knowledge just outlined. In this section, we first contrast two approaches to teaching seventh-grade students about the nature of science: a traditional approach with its emphasis on teaching process skills out of context and our approach with its emphasis on teaching these skills in the context of genuine scientific inquiry. We argue that only the latter approach has a chance at challenging the entrenched knowledge unproblematic epistemology that students bring with them to science classes. Then we discuss briefly the results of using this more innovative unit with seventh graders and raise a series of questions that need to be addressed in subsequent research.

The Standard Curricular Approach to Teaching About Inquiry

Much of current educational practice grows out of curriculum reform efforts that have emphasized the teaching of the process skills involved in the construction of scientific knowledge with such diverse skills as observation, classification, measurement, conducting controlled experiments, and constructing data tables and graphs of experimental results. These skills are typically covered in the junior high school science curriculum, beginning with the introduction of the scientific method in the seventh grade. The standard curricular unit on the scientific method, for example, contains many exercises to teach students about the design of controlled experiments, such as identifying independent and dependent variables in experiments and identifying poorly designed experiments in which variables have been confounded. Although in the best of these curricula, students go on to design and conduct controlled experiments, typically, the possible hypotheses and variables for a given problem are prescribed by the curriculum. Indeed, because students are testing disembodied hypotheses, this curriculum would be expected to move students toward Level 2 understanding on the nature of science interview (i.e., toward an understanding of the role of experimentation in testing hypotheses) but not toward Level 3 understanding with its notions of theory and indirect argument.

Certainly, process skills are important elements of a careful scientific methodology. Junior high school students do not spontaneously measure and control variables or systematically record data when they first attempt experimental work. Yet the standard curriculum fails to address the motivation or justification for using these skills in constructing scientific knowledge. Students are not challenged to utilize these process skills in exploring, developing, and evaluating their own ideas about natural phenomena. Rather, instruction in the skills and methods of science is conceived outside the context of genuine inquiry. Thus, there is no context for addressing the nature and purpose of scientific inquiry or the nature of scientific knowledge.

A Theory-Building Approach to Teaching About Inquiry

We assume, but at present have no evidence for our assumption, that process skills will be more easily and better learned if they are embedded in a wider context of metaconceptual points about the nature of scientific knowledge. Such metaconceptual knowledge is important in its own right, and it can be gained only by actively constructing scientific understanding and reflecting on this process. These assumptions motivate a curricular approach that emphasizes theory building and reflection on the theory-building process. Carey et al. (1989), therefore, developed and tested an instructional unit to replace the typical junior high school unit on the scientific method.

This instructional unit begins with the question of what makes bread rise and ends with designing a research program aimed at discovering why combining yeast, sugar, and water produces a gas, and, ultimately, the nature of yeast. The metaconceptual points in this curriculum concerned how scientists decide what experiments are worth doing, how the answer to each question we ask raises still deeper questions, how one's theories of chemistry and biology constrain the experiments one does and the interpretations of results, and how unexpected results require changes in those theories.

As a result of the yeast unit, seventh-grade students' overall mean score on the nature of science clinical interview increased from 1.0 on the preinstruction interview to 1.55 on the postinstruction interview ($p < .001$, Wilcoxon Signed Ranks Test). Every student improved, and improvement averaged one half a level. Now 16 of the 27 students achieved overall scores of 1.5 or better (as opposed to 4 students on the preinterview), and 5 scored Level 2 or better—a score nobody achieved on the preinterview. Although these results are certainly in the right direction, movement was toward consolidating Level 2 responses; there was little evidence that students appreciated the Level 3 metaconceptual lessons included in the curriculum that called for a notion of theory and indirect argument.

The results of curricular interventions aimed at changing students' conceptions of models are even more discouraging. At Harvard's Educational Technology Center, Smith and Wiser have developed curricula using computer-implemented interactive models to foster conceptual change in two domains: the theory of matter, especially weight/density differentiation (Smith, Snir, & Grosslight, 1992); and thermal theory, especially heat/temperature differentiation (Wiser, Kipman, & Halkiadakis, 1988). Although conceptual change in the respective domains of physics was the purpose of these model-based curricula, discussion of various metaconceptual points about the nature and use of models in science was included in each of the curricular units: in particular, the ideas that models can be used to develop and test ideas, that multiple models are possible, and that models are evaluated in terms of their usefulness or how well they serve a given purpose. There was no noticeable effect of this discussion on the postinstruction clinical interviews about models. The seventh grades scored the same on the postinstruction interviews as on the preinstruction interviews. And although the eleventh graders improved significantly to a solid Level 2 understanding, the improvement was just as great in a control group that did not have the modeling curriculum. Apparently, simply having thought about the issues as a result of the preinterview was sufficient to lead eleventh graders to better articulate their views on the postinterview.

CONCLUSIONS AND FURTHER QUESTIONS

It may be that it would be impossible for junior high school students to attain Level 3 understanding of the nature of scientific knowledge. Such understanding may have to await developments in more general epistemological beliefs and may require confronting head-on the relativism that characterizes the transition between the first and second senses of constructivism in the normal, untutored course of development. However, we do not take our failures to date as warranting this conclusion. We feel it is possible that scientific knowledge could well be an arena in which young adolescents could acquire some aspects of a constructivist epistemology in the knowledge problematic sense, in an optimal curricular environment. The curricular interventions we tried so far are far from optimal. They were both designed before we had fully appreciated the differences between students' starting epistemology and the epistemology we wished to teach, and the modeling curriculum had much less metaconceptual content than it would be possible to include. We take it to be very much an open question whether junior high school students can grasp the more sophisticated constructivism depicted in Appendix A.

Another extremely important issue for exploration is the relation between students' epistemiological beliefs and conceptual change in science content.

Although many have speculated that students' epistemological beliefs interfere with successful learning of science and mathematics, there is little empirical evidence on this point. We know of no studies, for example, that show that changes in students' epistemological views affect their success in learning content. Of course, such studies will not be possible until the research program just outlined is brought to further fruition. That is, we will need accurate and detailed descriptions of student epistemology, as well as curricula that advance their epistemological views, before such studies will be possible.

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APPENDIX A

Two Contrasting Constructivist Epistemologies

Knowledge unproblematic

Knowledge consists of a collection of true beliefs. The sources of beliefs are perception, testimony, and one-step inference. Individuals may draw different conclusions from the same perceptual experience due to differences in prior knowledge or motives; individuals may have different opinions in matters of value and personal taste. Individuals with this epistemology believe there is only one objective reality that is knowable in a straightforward way by making observations. Hence, when individuals disagree about reality, it is possible for only one of them to be correct. Ultimately, ignorance, misinformation, or deceit are the causes of having false beliefs.

Knowledge problematic

Knowledge consists of theories about the world that are useful in providing a sense of understanding and/or predicting or explaining events. Individuals actively develop their theories through a process of critical inquiry. Conjectures derived from interpretative frameworks merit testing; the results constitute evidence for or against the interpretative framework and associated specific beliefs. Different people may draw different conclusions from the same perceptual experiences because they hold different theories that affect their interpretation of evidence. Reality exists, but our knowledge of it is elusive and uncertain. Theories are judged to be more or less useful, not strictly right or wrong. Canons of justification are framework relative. In addition to false beliefs due to ignorance and misinformation, beliefs can be in error for much deeper reasons: Theories can be on entirely the wrong track, positing incorrect explanations of accurate beliefs and positing entities and causal mechanisms that do not even exist.

APPENDIX B

Three Levels of Understanding in the Nature of Science Interview

Level 1

The students make no explicit distinction between ideas and activities for generating ideas, especially experiments. A scientist tries "it" to see if it works. The nature of "it" remains unspecified or ambiguous; "it" could be an idea, a thing, an invention, or an experiment. The motivation for an activity is the achievement of the activity itself, rather than the construction of tested ideas. The goal of science is to discover facts and answers about the world and to invent things.

Level 2

Students make an explicit distinction between ideas and experiments. The motivation for experimentation is to test an idea to see if it is right. There is an understanding that the results of an experiment may lead to the abandonment or revision of an idea. However, an idea is still a guess; it is not a prediction derivable from a general theory. (Indeed, students may not yet have the general idea of a theory.) There is yet no appreciation that the revised idea must now encompass all the data, the new and the old, and that if a prediction is falsified, the theory may have to be revised.

Level 3

As in Level 2, students make a clear distinction between ideas and experiments, and they understand that the motivation for experiments is verification or exploration. Added to this is an appreciation of the relation between the results of an experiment (especially unexpected ones) and the theory leading to the prediction. Level 3 understanding recognizes the cyclic, cumulative nature of science, and identifies the goal of science as the construction of ever deeper explanations of the natural world.

APPENDIX C

Three Levels of Understanding in the Nature of Models Interview

Level 1

Models are thought of as either toys or as simple copies of reality. Models are considered to be useful because they can provide copies of actual objects or actions. If students acknowledge that aspects or parts of objects can be left out of the model, they do not express a reason for doing so beyond the fact that one might not want or need to include it.

Level 2

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 needs to match the real world object exactly. 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. Tests of the model are thought of as tests of the workability of the model itself, not of the underlying ideas.

Level 3

At Level 3 understanding is characterized by three important factors. First, the model is now constructed in the service of the development and testing of ideas, rather than as serving as a copy of reality itself. Second, the modeler takes an active role in constructing the model, using symbols freely and evaluating which of several designs could be used to serve the modeler's purpose. Third, models can be manipulated and subjected to test in the service of informing ideas.